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(54) **PRE-CODING IN MULTI-USER MIMO**

(71) Applicant: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

(72) Inventor: **Steve Shattil**, Cheyenne, WY (US)

(73) Assignee: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

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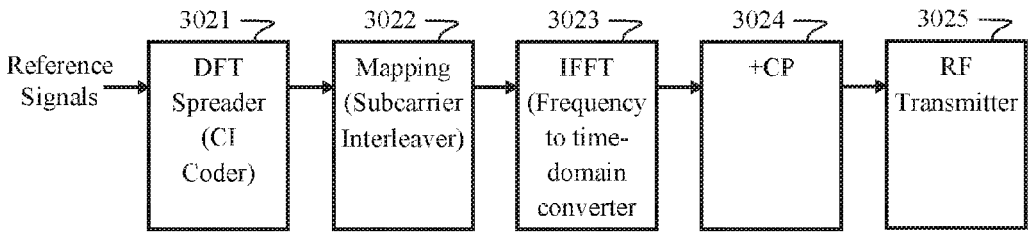
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Primary Examiner — Dac Ha
(74) *Attorney, Agent, or Firm* — Steven J Shattil

(57) **ABSTRACT**

In a multi-user communication system, a pre-coder in a transmitter comprises a Discrete Fourier Transform (DFT) spreader configured to spread data symbols with Fourier coefficients to generate DFT-spread data symbols. An OFDM modulator, such as an inverse-DFT, modulates the DFT-spread data symbols onto OFDM subcarriers to produce a pre-coded OFDM transmission signal. The DFT spreader is configured to reduce the transmission signal's peak to average power.

29 Claims, 33 Drawing Sheets



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Non-Final Office Action dated Jun. 23, 2017 from corresponding U.S. Appl. No. 15/489,664.

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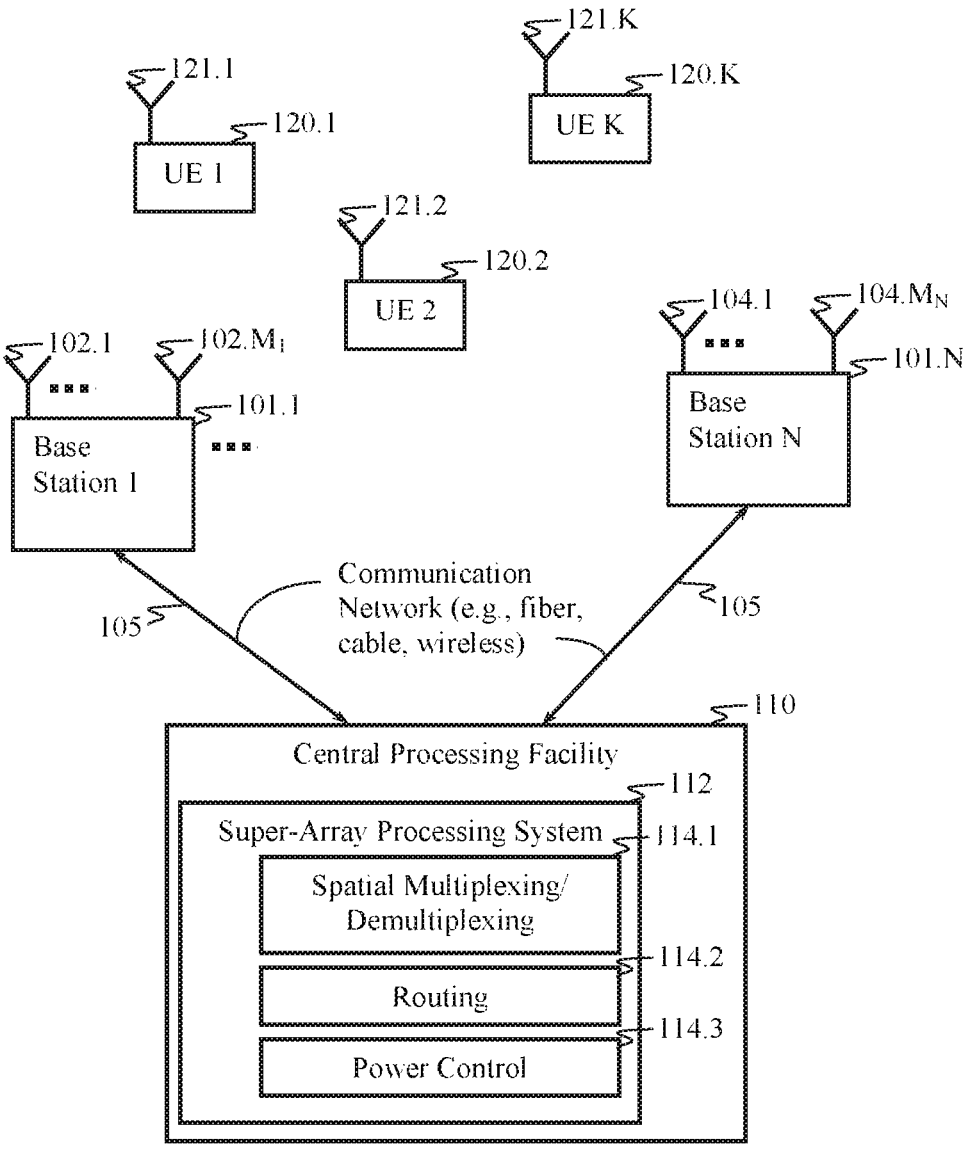

121.K
120.K
UE K
121.1
120.1
UE 1
121.2
120.2
UE 2
104.1
104.M_N
101.N
Base Station N
102.1
102.M_1
101.1
Base Station 1
105
Communication Network (e.g., fiber, cable, wireless)
105
110
Central Processing Facility
112
Super-Array Processing System
114.1
Spatial Multiplexing/ Demultiplexing
114.2
Routing
114.3
Power Control

Figure 1

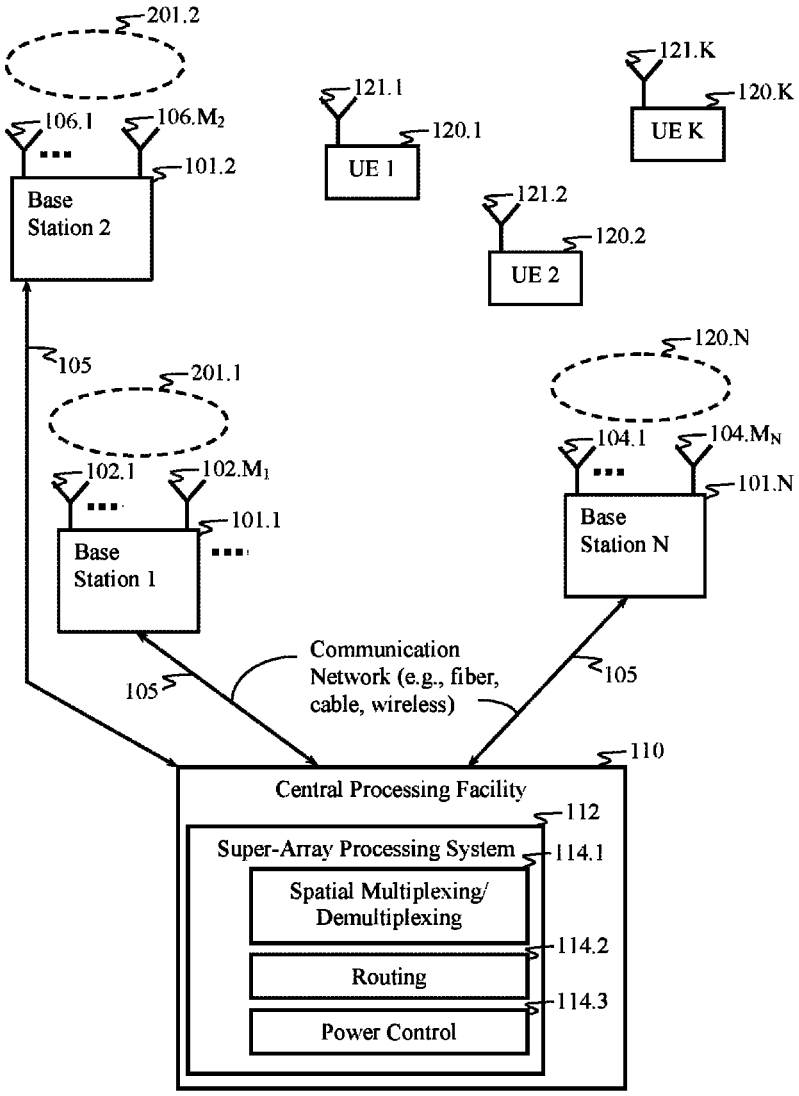

201.2
106.1
106.M2
101.2
Base Station 2
121.1
120.1
UE 1
121.K
120.K
UE K
121.2
120.2
UE 2
105
201.1
102.1
102.M1
101.1
Base Station 1
120.N
104.1
104.MN
101.N
Base Station N
105
Communication Network (e.g., fiber, cable, wireless)
105
110
Central Processing Facility
112
Super-Array Processing System
114.1
Spatial Multiplexing/ Demultiplexing
114.2
Routing
114.3
Power Control

Figure 2

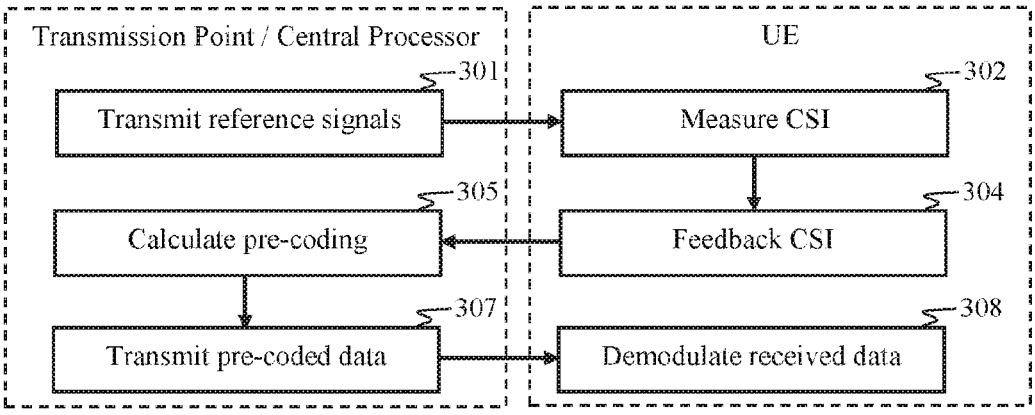


Figure 3A

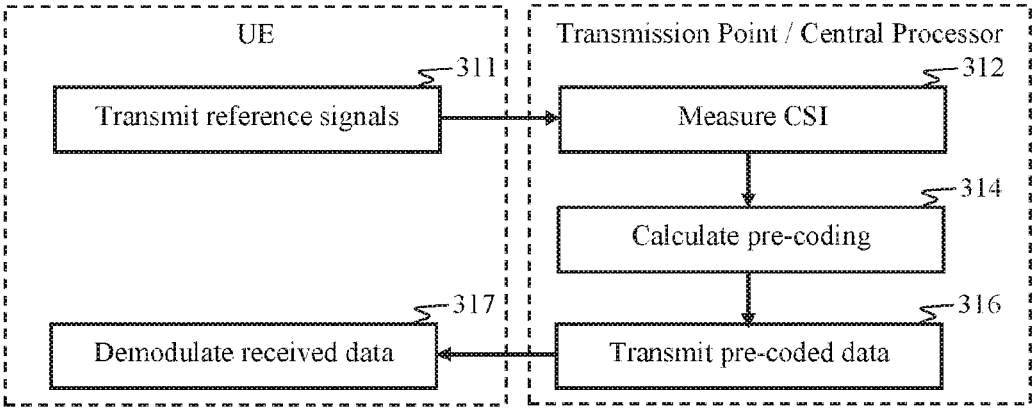


Figure 3B

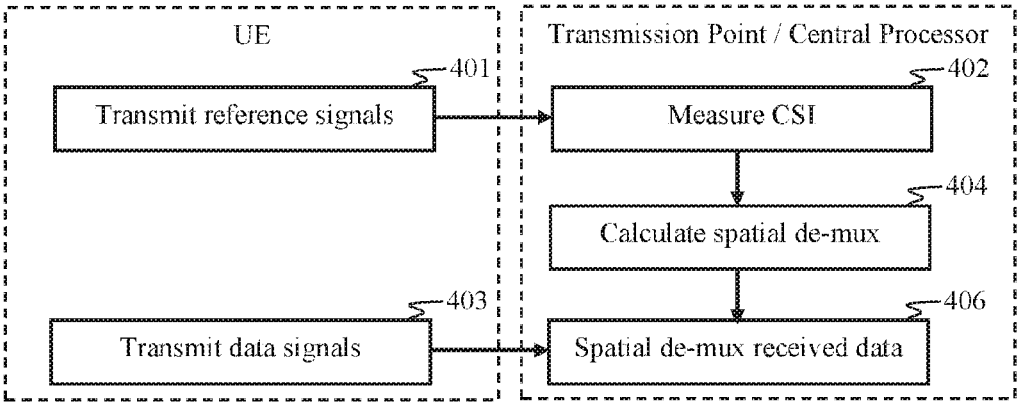


Figure 4A

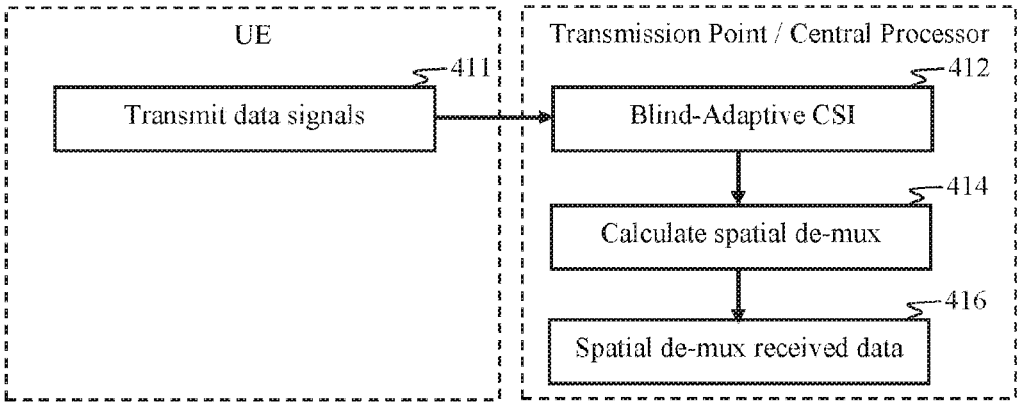


Figure 4B

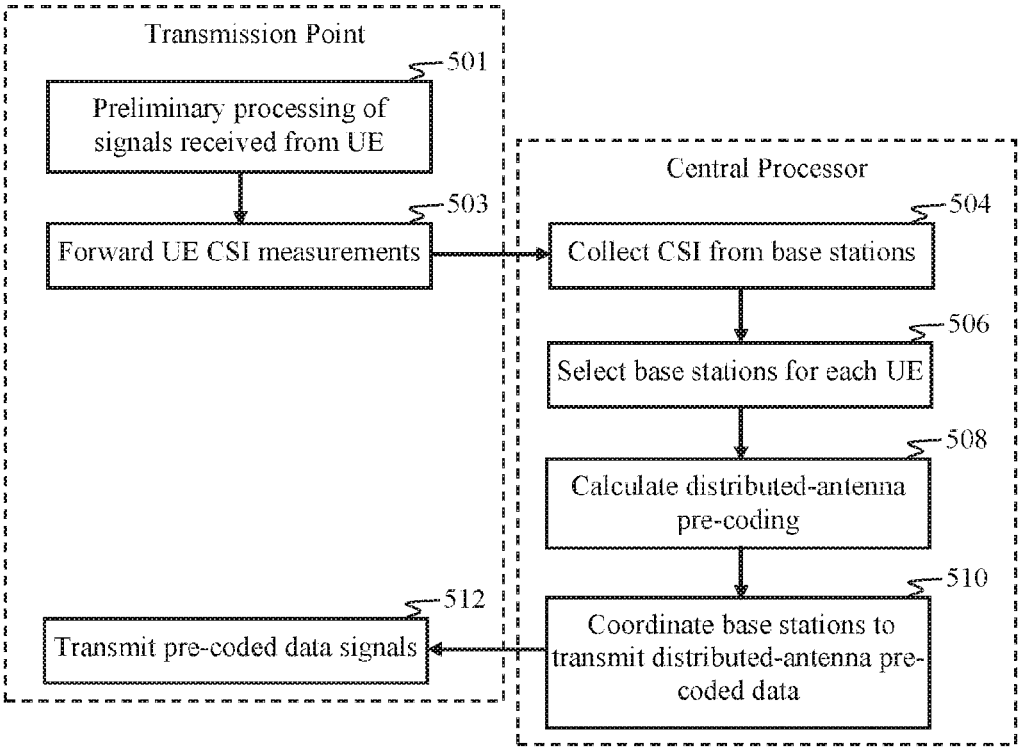

Transmission Point
501
Preliminary processing of signals received from UE
503
Forward UE CSI measurements
512
Transmit pre-coded data signals
Central Processor
504
Collect CSI from base stations
506
Select base stations for each UE
508
Calculate distributed-antenna pre-coding
510
Coordinate base stations to transmit distributed-antenna pre-coded data

Figure 5

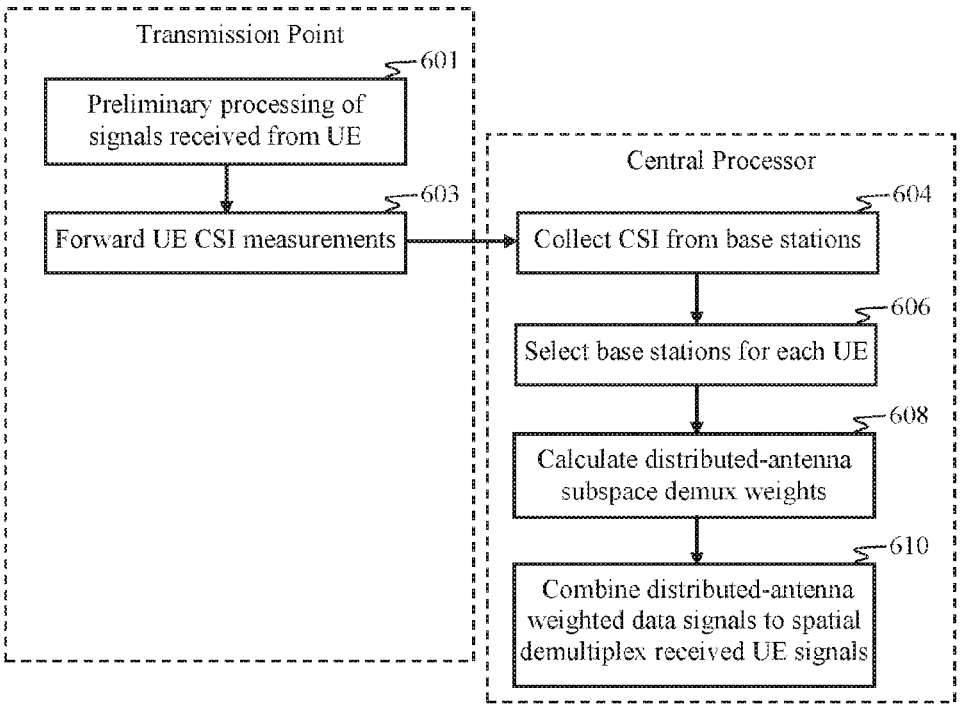

Transmission Point
601
Preliminary processing of signals received from UE
603
Forward UE CSI measurements
Central Processor
604
Collect CSI from base stations
606
Select base stations for each UE
608
Calculate distributed-antenna subspace demux weights
610
Combine distributed-antenna weighted data signals to spatial demultiplex received UE signals

Figure 6

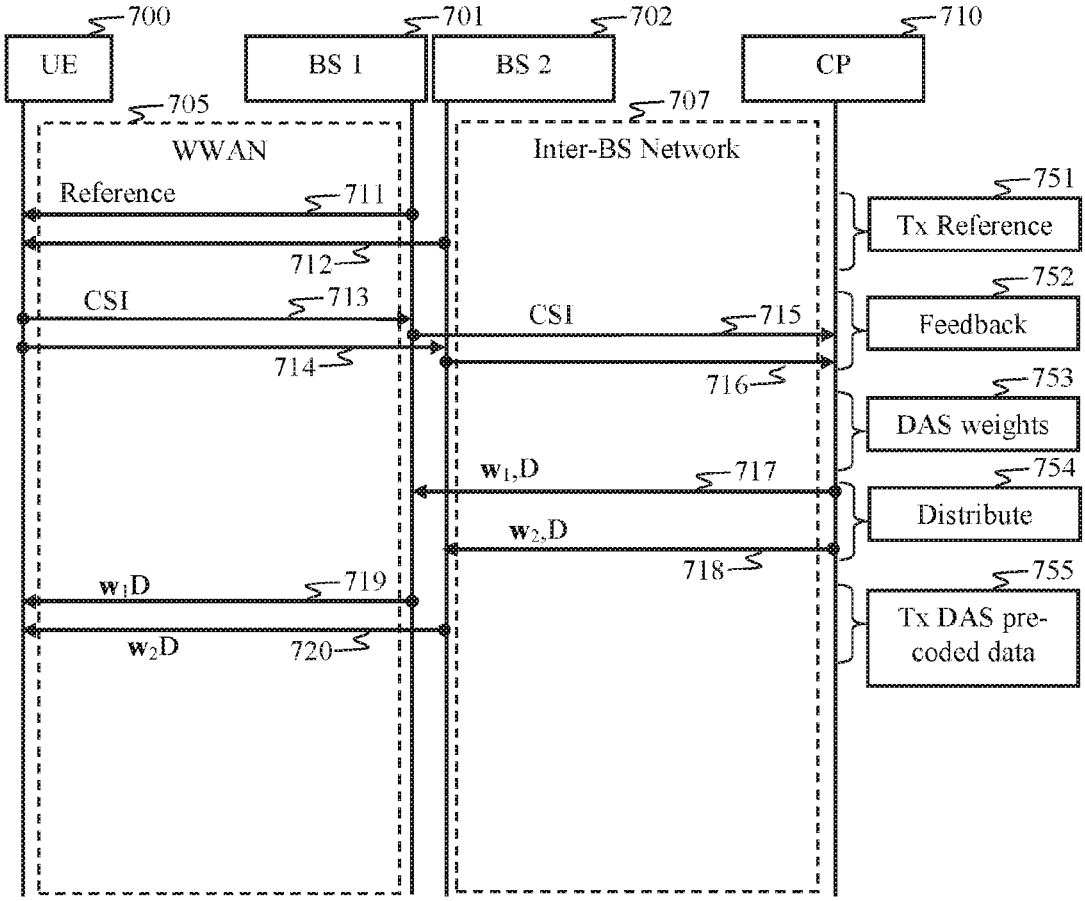

700
UE
701
BS 1
702
BS 2
710
CP
705
WWAN
707
Inter-BS Network
Reference
711
712
CSI
713
714
CSI
715
716
751
Tx Reference
752
Feedback
753
DAS weights
754
Distribute
755
Tx DAS pre-coded data
w1.D
717
w2.D
718
w1D
719
w2D
720

Figure 7

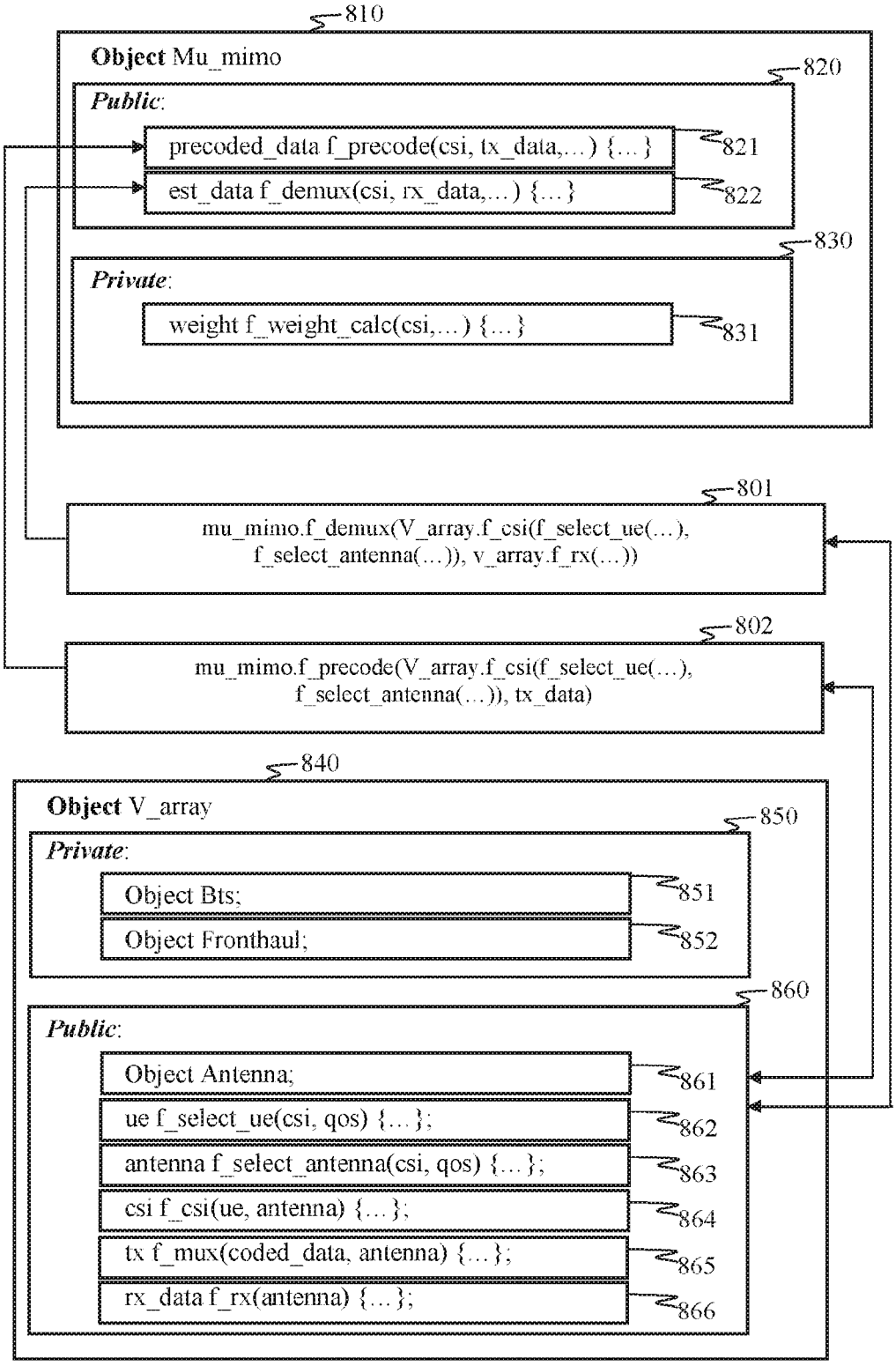

810
Object Mu_mimo
820
Public:
precoded_data f_precode(csi, tx_data,...) {...}
821
est_data f_demux(csi, rx_data,...) {...}
822
830
Private:
weight f_weight_calc(csi,...) {...}
831
801
mu_mimo.f_demux(V_array.f_csi(f_select_ue(...), f_select_antenna(...)), v_array.f_rx(...))
802
mu_mimo.f_precode(V_array.f_csi(f_select_ue(...), f_select_antenna(...)), tx_data)
840
Object V_array
850
Private:
Object Bts;
851
Object Fronthaul;
852
860
Public:
Object Antenna;
861
ue f_select_ue(csi, qos) {...};
862
antenna f_select_antenna(csi, qos) {...};
863
csi f_csi(ue, antenna) {...};
864
tx f_mux(coded_data, antenna) {...};
865
rx_data f_rx(antenna) {...};
866

Figure 8

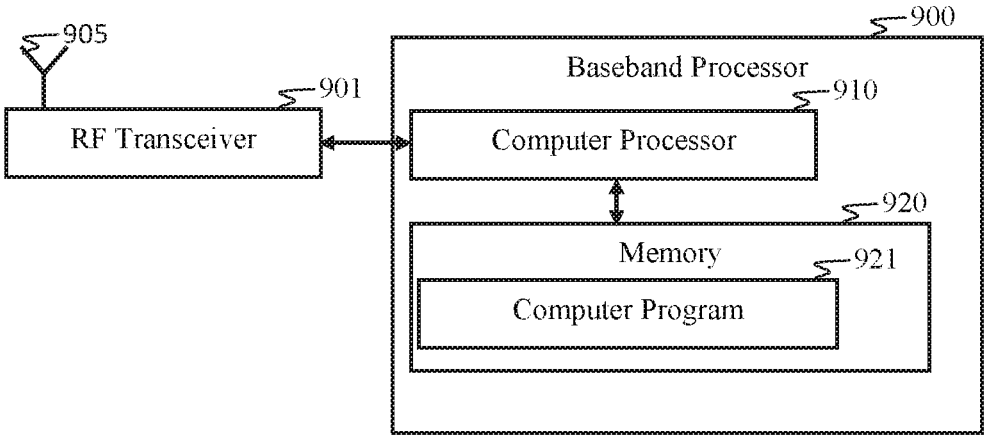

905
900
Baseband Processor
901
910
RF Transceiver
Computer Processor
920
Memory
921
Computer Program

Figure 9

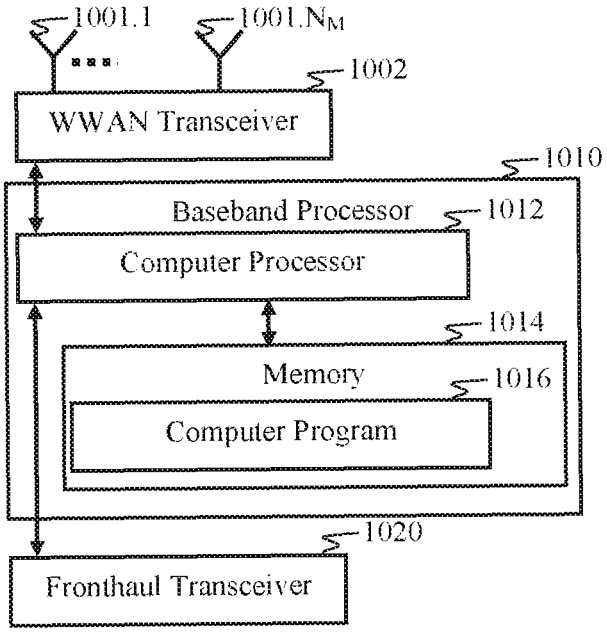

1001.1
1001.N_M
1002
WWAN Transceiver
1010
Baseband Processor
1012
Computer Processor
1014
Memory
1016
Computer Program
1020
Fronthaul Transceiver

Figure 10

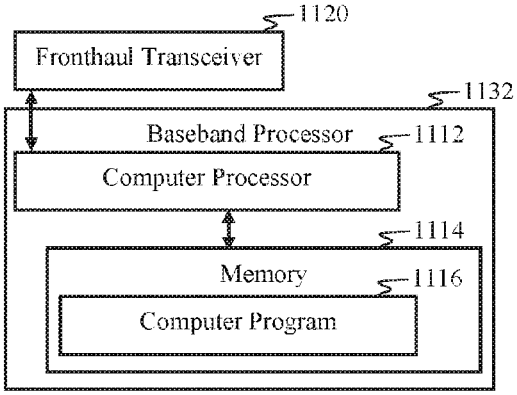


Figure 11A

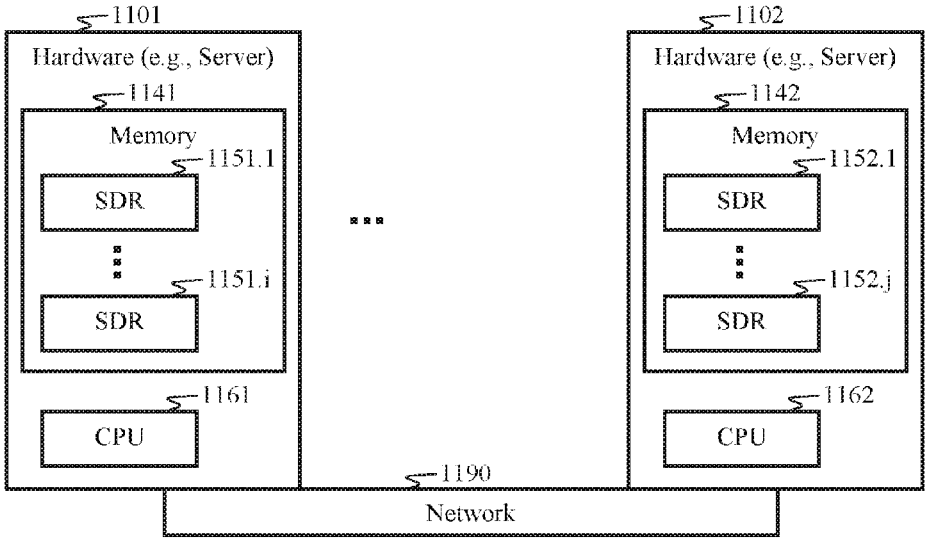


Figure 11B

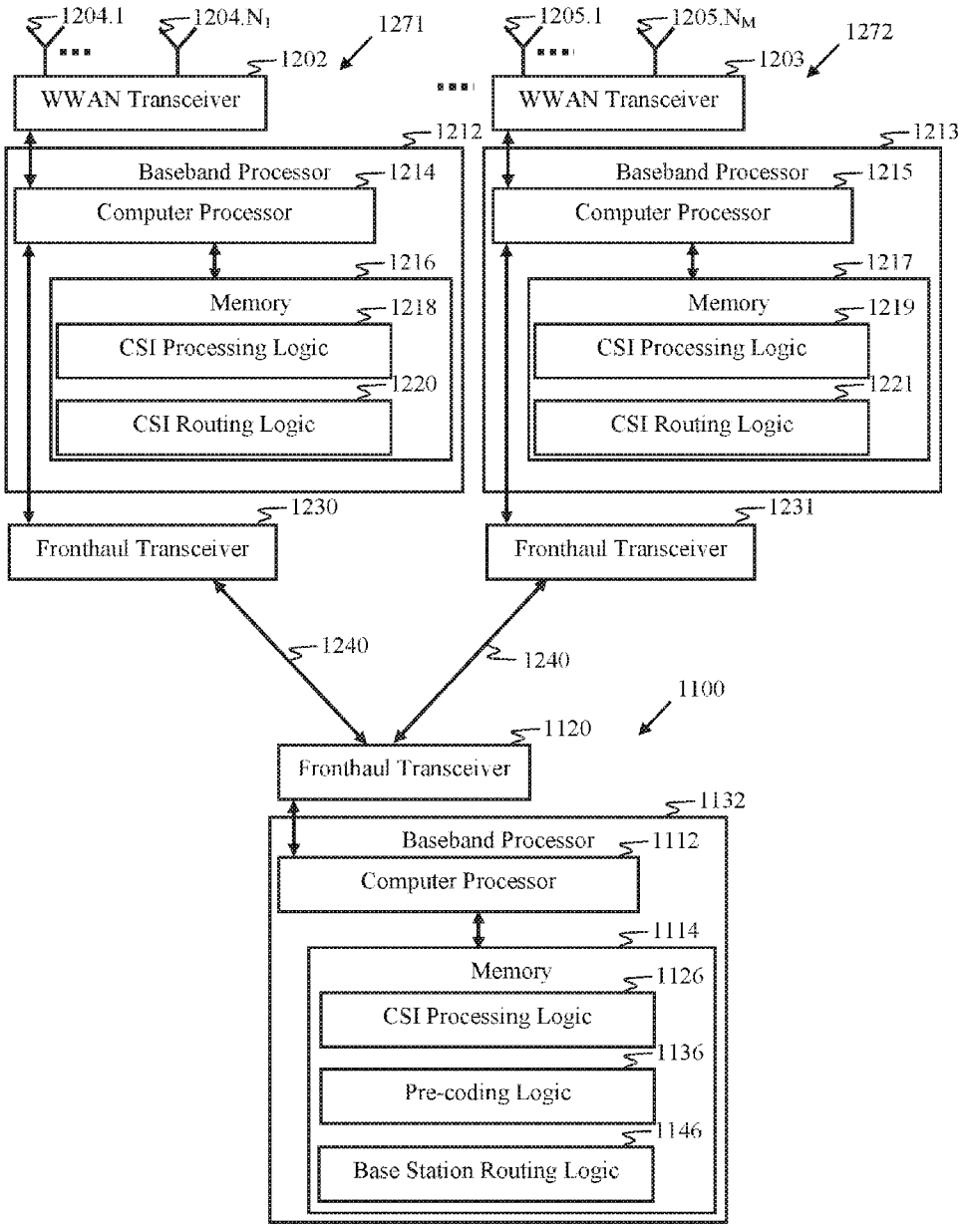

1204.1
1204.N1
1271
1205.1
1205.NM
1272
1202
1203
WWAN Transceiver
WWAN Transceiver
1212
1213
Baseband Processor
1214
Computer Processor
Baseband Processor
1215
Computer Processor
1216
1217
Memory
1218
CSI Processing Logic
1220
CSI Routing Logic
Memory
1219
CSI Processing Logic
1221
CSI Routing Logic
1230
1231
Fronthaul Transceiver
Fronthaul Transceiver
1240
1240
1100
1120
Fronthaul Transceiver
1132
Baseband Processor
1112
Computer Processor
1114
Memory
1126
CSI Processing Logic
1136
Pre-coding Logic
1146
Base Station Routing Logic

Figure 12

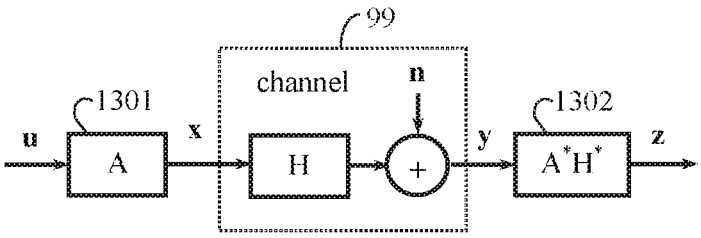


Figure 13A

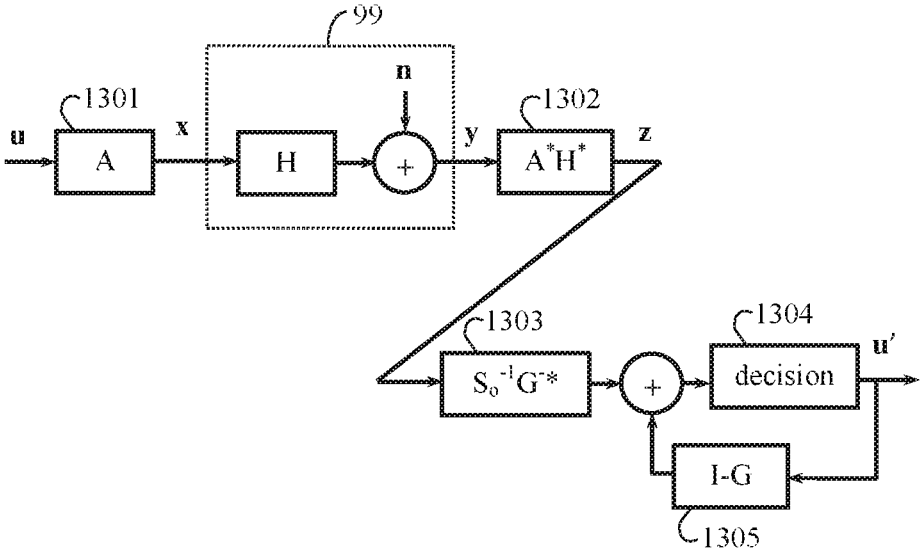


Figure 13B

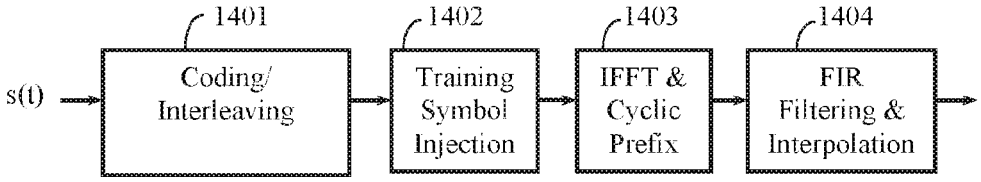


Figure 14A

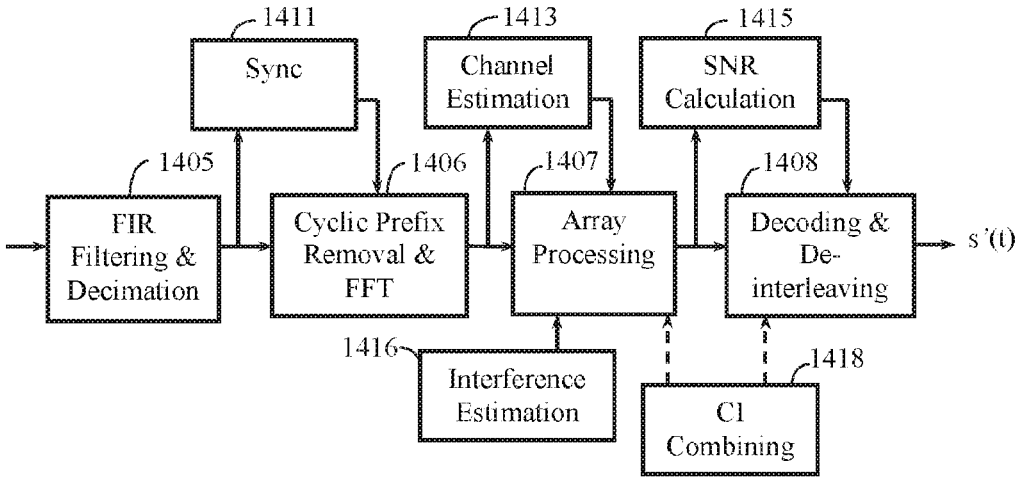


Figure 14B

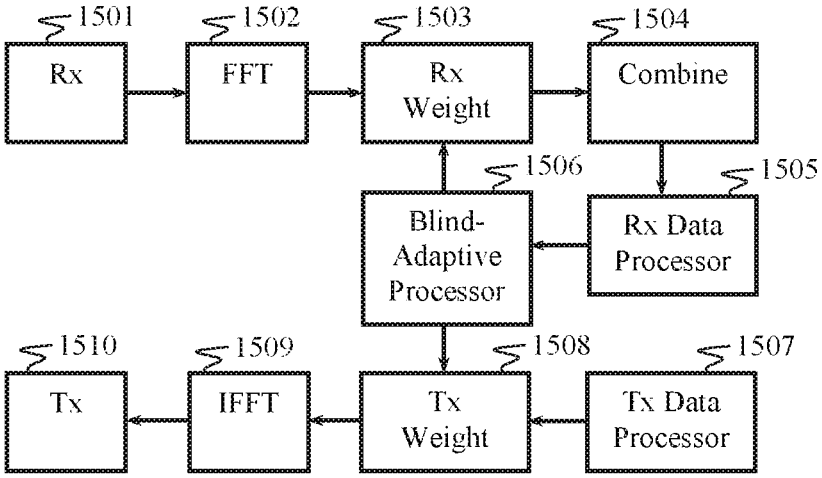

1501
Rx
1502
FFT
1503
Rx Weight
1504
Combine
1506
Blind-Adaptive Processor
1505
Rx Data Processor
1510
Tx
1509
IFFT
1508
Tx Weight
1507
Tx Data Processor

Figure 15

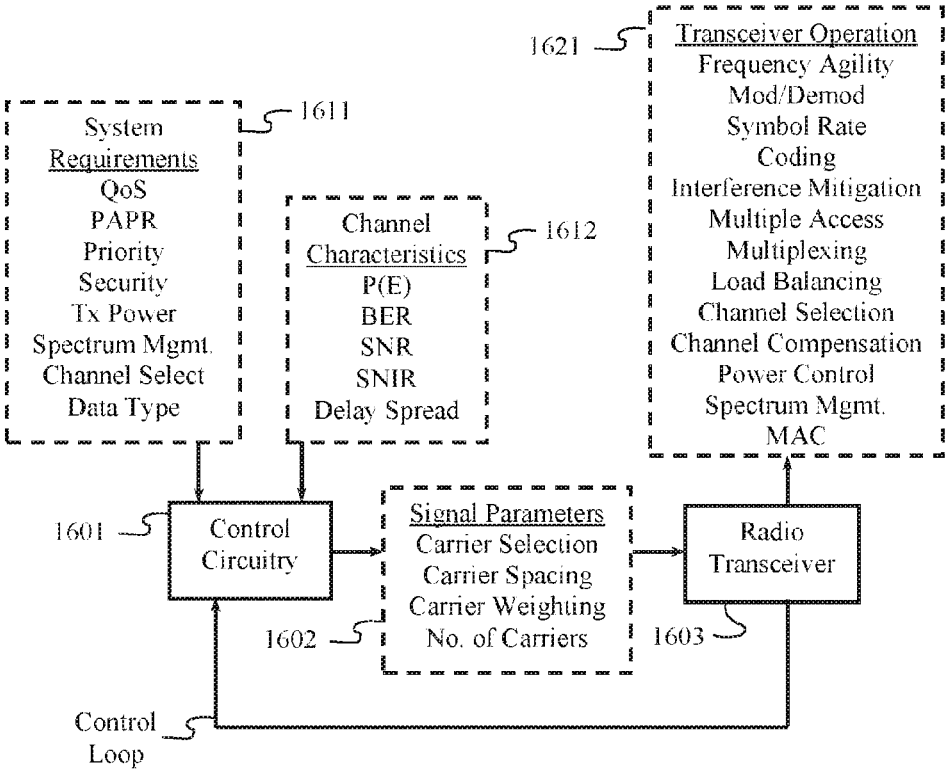

1621
Transceiver Operation
Frequency Agility
Mod/Demod
Symbol Rate
Coding
Interference Mitigation
Multiple Access
Multiplexing
Load Balancing
Channel Selection
Channel Compensation
Power Control
Spectrum Mgmt.
MAC
1611
System
Requirements
QoS
PAPR
Priority
Security
Tx Power
Spectrum Mgmt.
Channel Select
Data Type
Channel
Characteristics
P(E)
BER
SNR
SNIR
Delay Spread
1612
1601
Control
Circuitry
Signal Parameters
Carrier Selection
Carrier Spacing
Carrier Weighting
No. of Carriers
Radio
Transceiver
1602
1603
Control
Loop

Figure 16

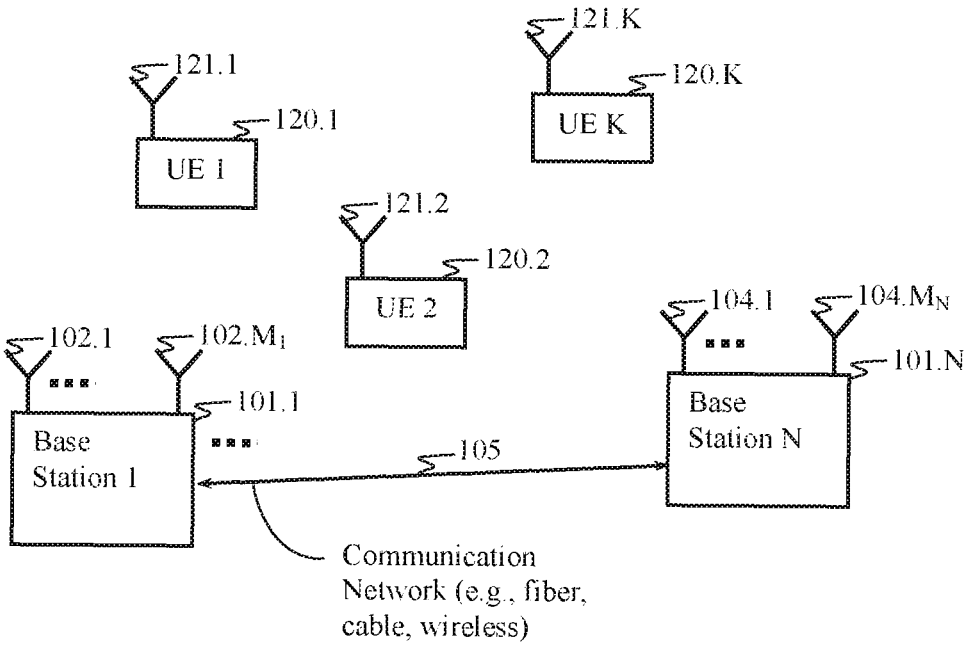

121.K
120.K
UE K
121.1
120.1
UE 1
121.2
120.2
UE 2
104.1
104.M_N
101.N
102.1
102.M_1
101.1
Base Station 1
Base Station N
105
Communication Network (e.g., fiber, cable, wireless)

Figure 17

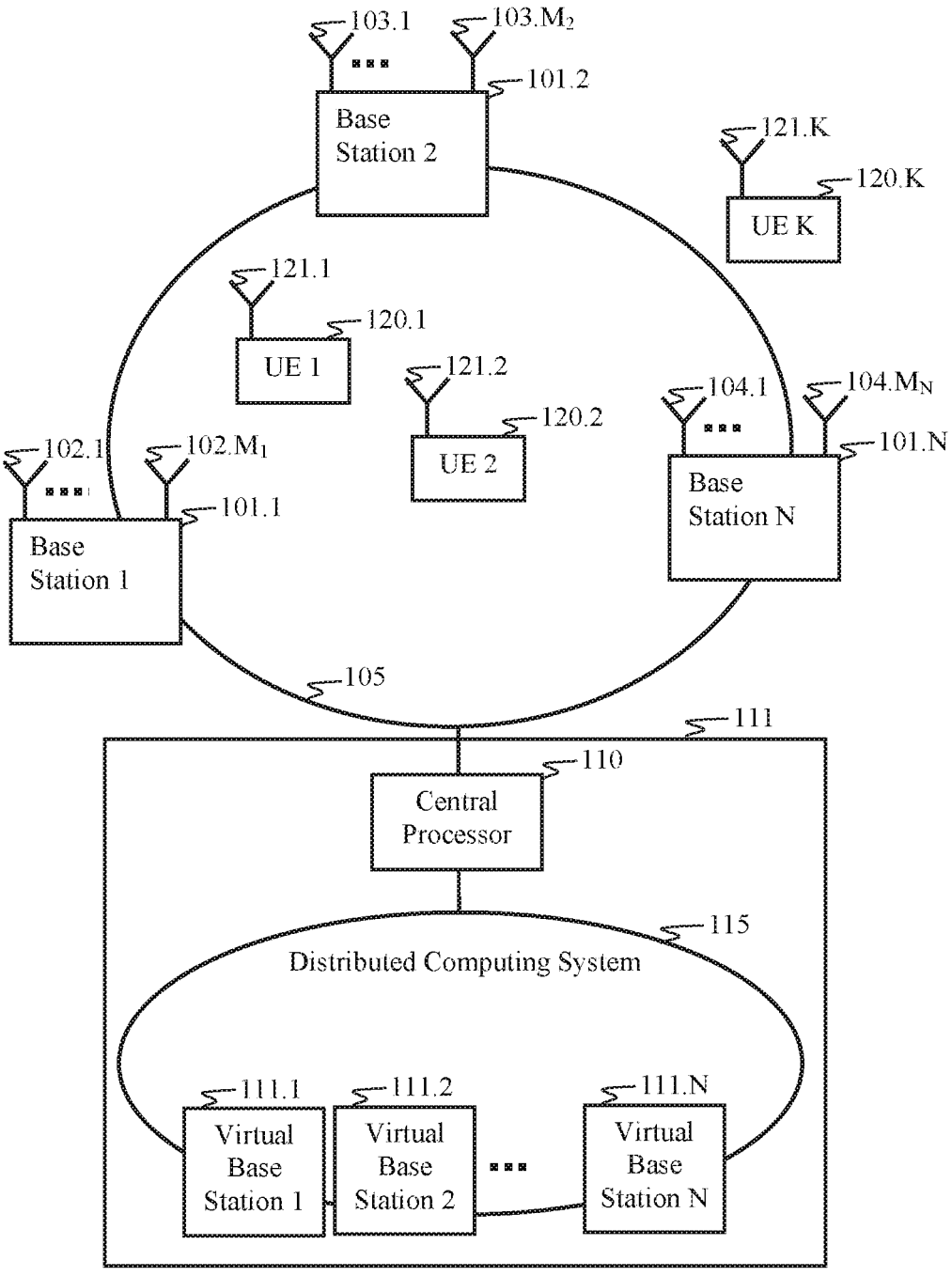

103.1
103.M2
101.2
Base Station 2
121.K
120.K
UE K
121.1
120.1
UE 1
121.2
120.2
UE 2
104.1
104.MN
101.N
Base Station N
102.1
102.M1
101.1
Base Station 1
105
111
110
Central Processor
115
Distributed Computing System
111.1
111.2
111.N
Virtual Base Station 1
Virtual Base Station 2
Virtual Base Station N

Figure 18

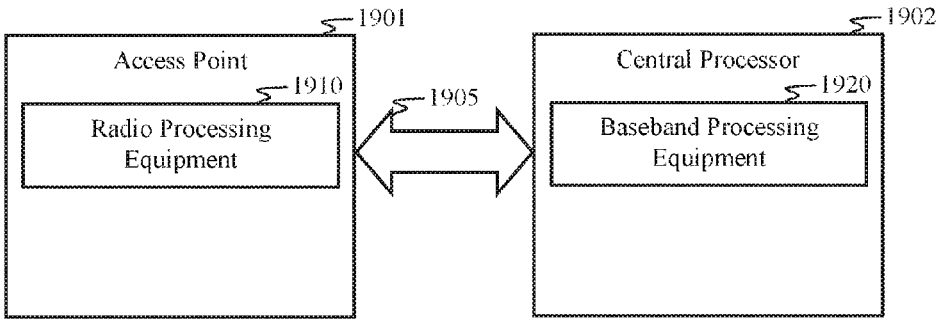

1901
Access Point
1910
Radio Processing Equipment
1905
1902
Central Processor
1920
Baseband Processing Equipment

Figure 19

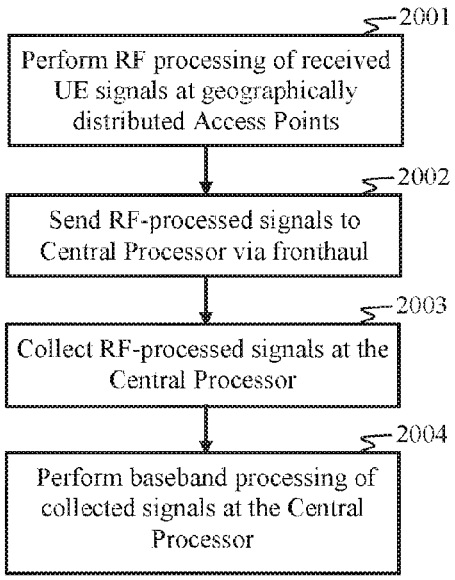


Figure 20A

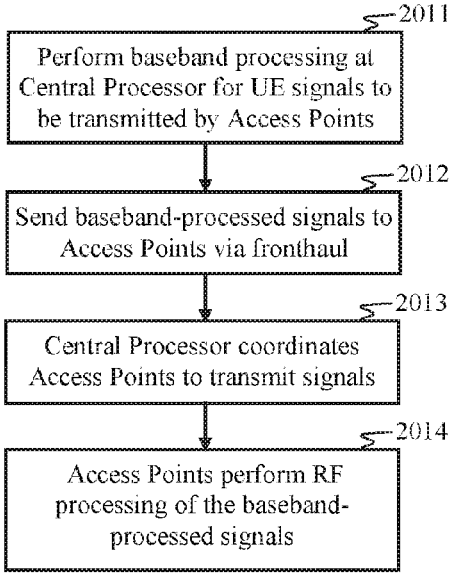


Figure 20B

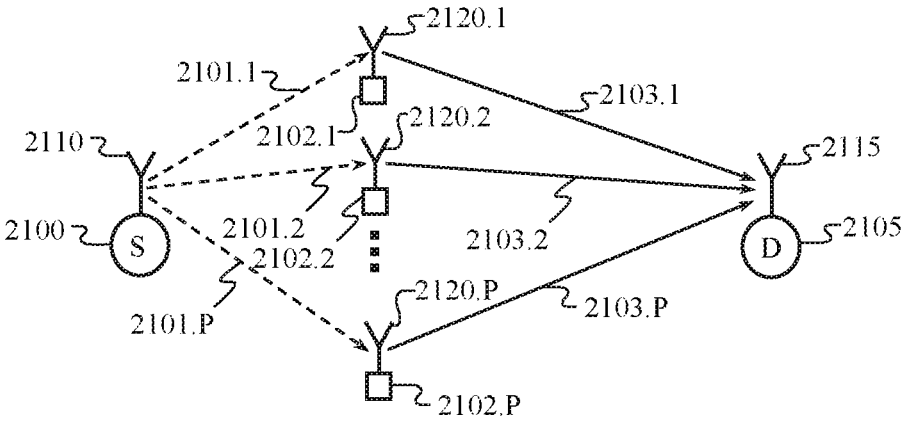

2120.1
2101.1
2103.1
2102.1
2120.2
2110
2115
2100
S
2101.2
2102.2
2103.2
D
2105
2120.P
2103.P
2101.P
2102.P

Figure 21

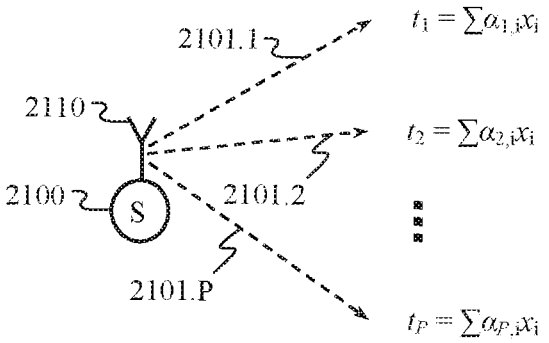


Figure 22A

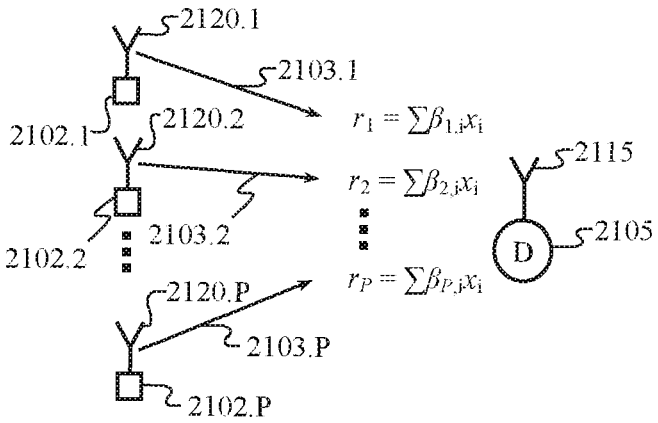


Figure 22B

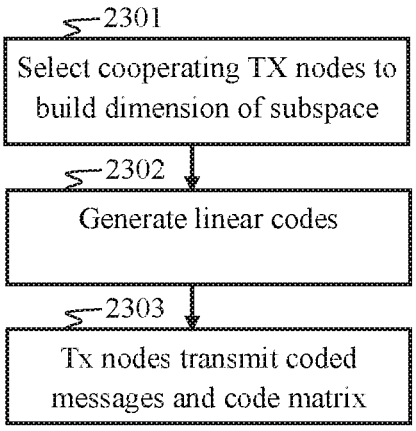


Figure 23A

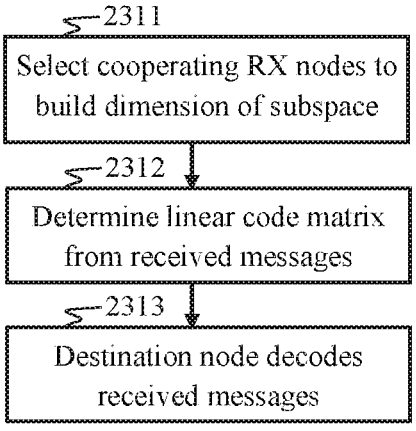


Figure 23B

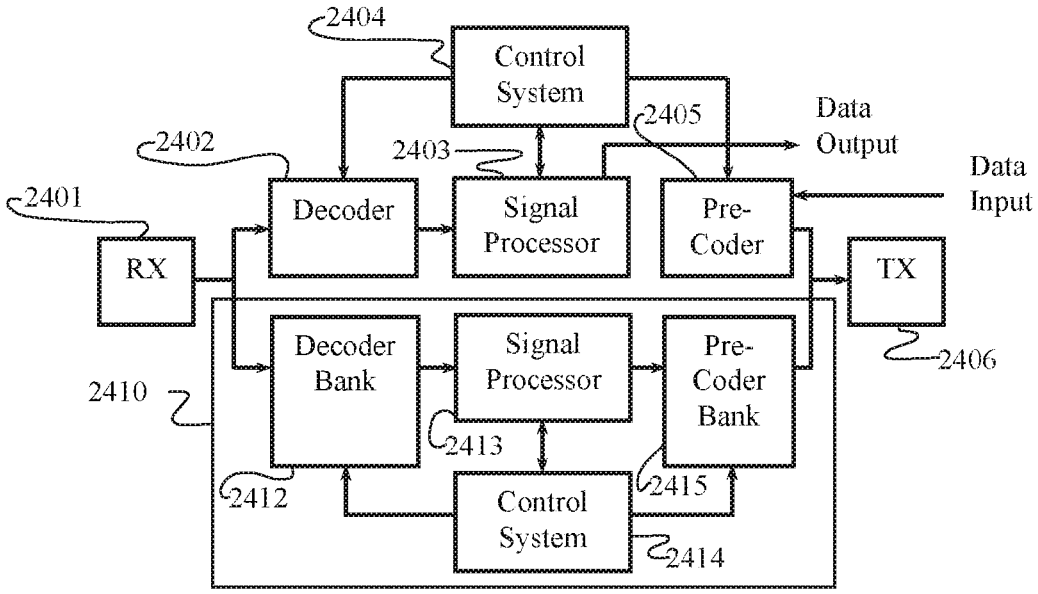


Figure 24A

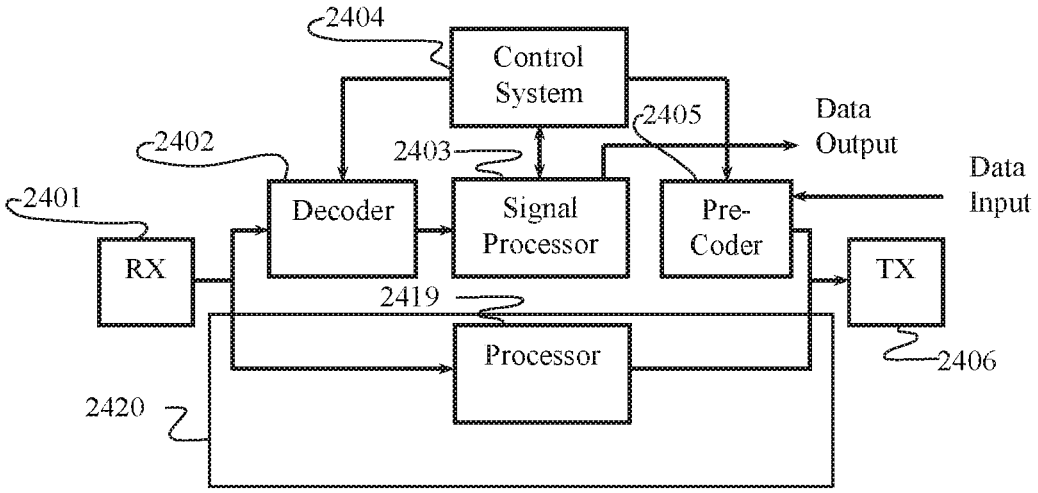


Figure 24B

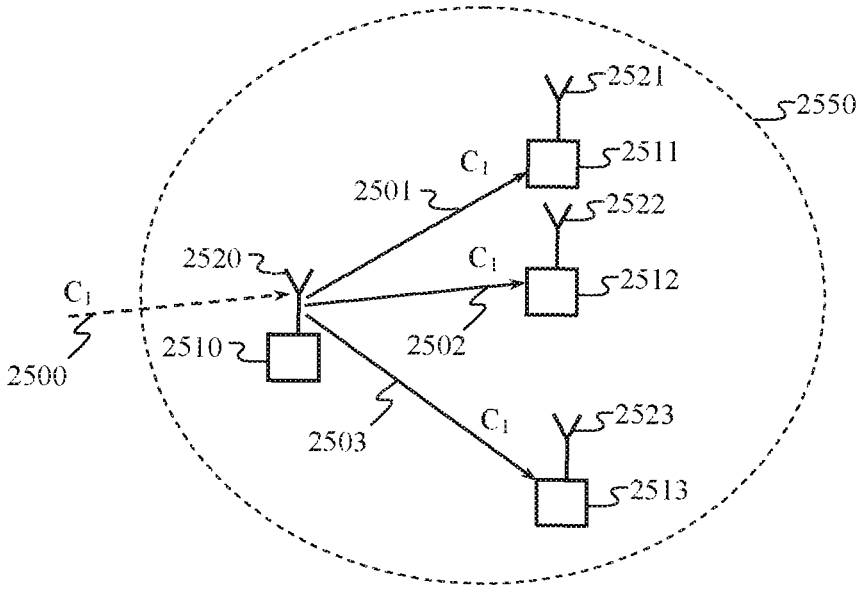


Figure 25A

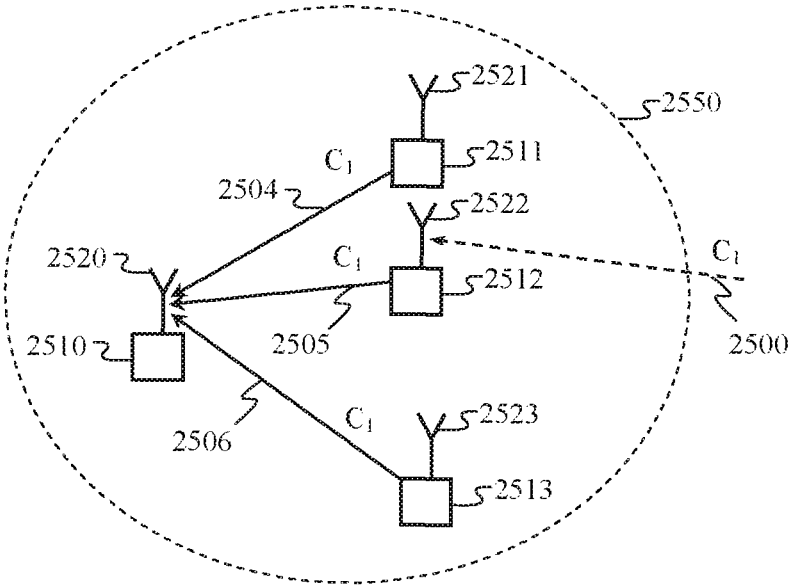


Figure 25B

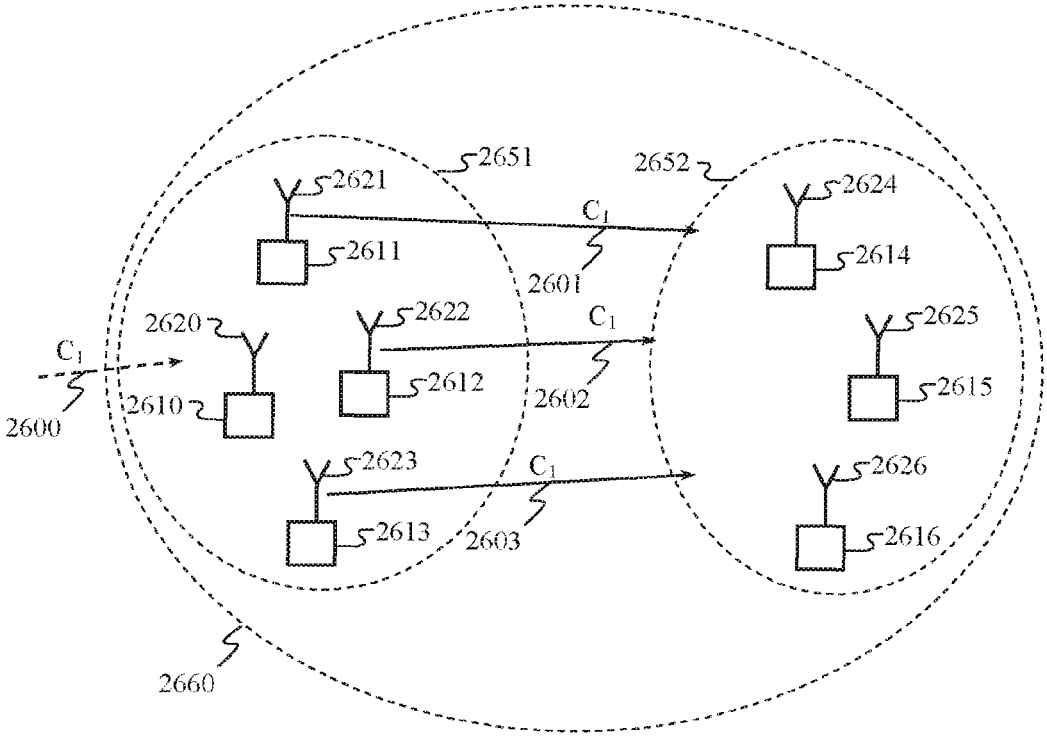

2651
2652
2621
2624
C_1
2611
2614
2601
2620
2622
C_1
2625
C_1
2610
2612
2615
2600
2602
2623
C_1
2626
2613
2603
2616
2660

Figure 26

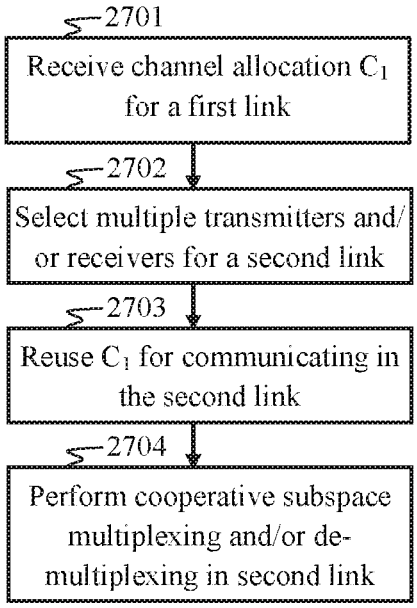

2701
Receive channel allocation C_1 for a first link
2702
Select multiple transmitters and/or receivers for a second link
2703
Reuse C_1 for communicating in the second link
2704
Perform cooperative subspace multiplexing and/or de-multiplexing in second link

Figure 27

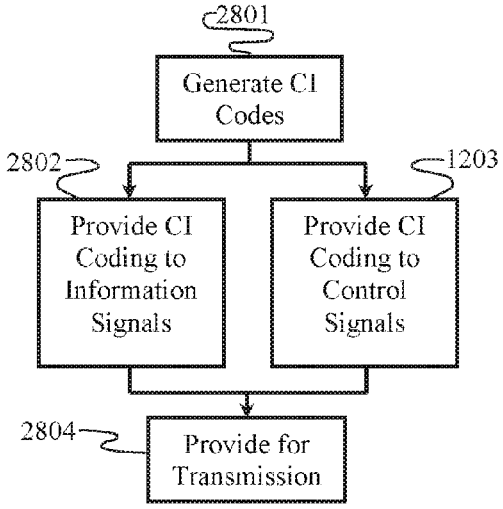


FIG. 28A

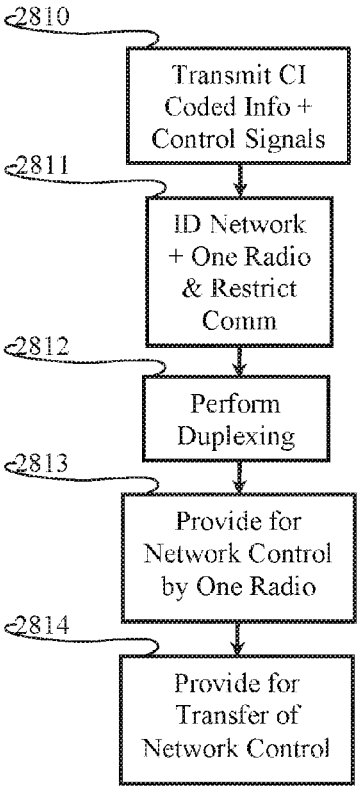


FIG. 28B

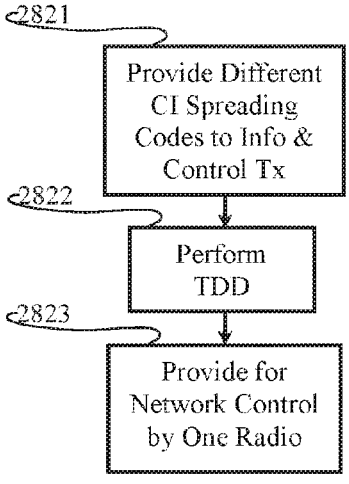


FIG. 28C

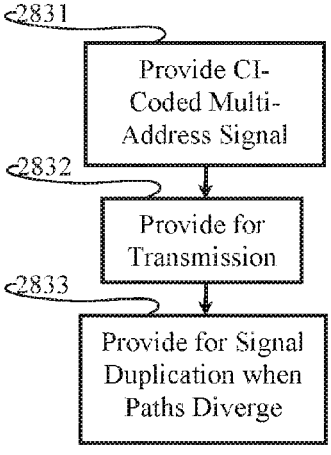


FIG. 28D

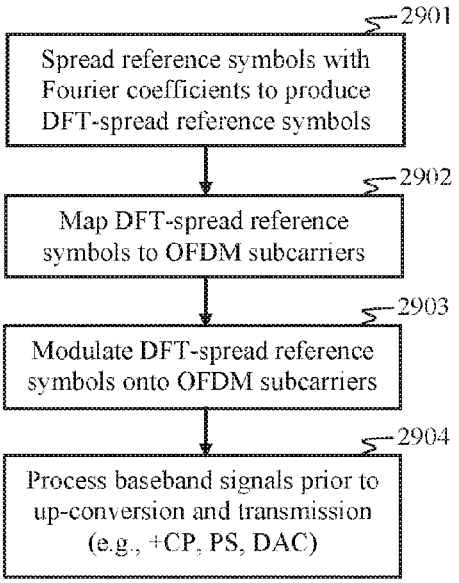


Figure 29A

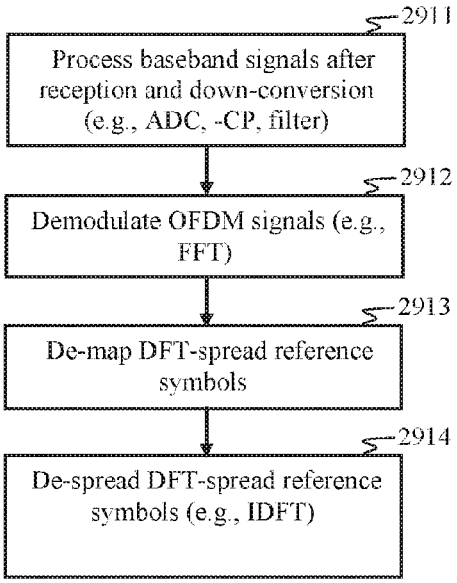


Figure 29B

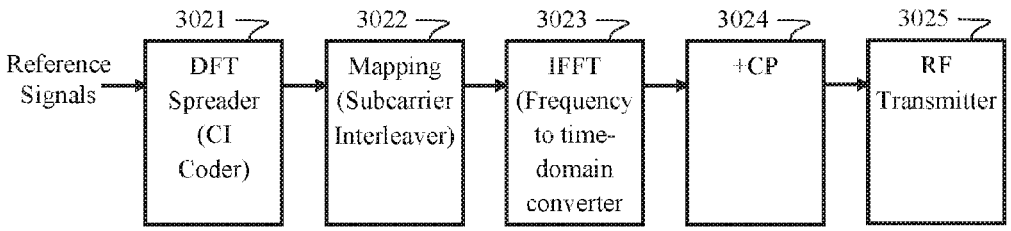


Figure 30A

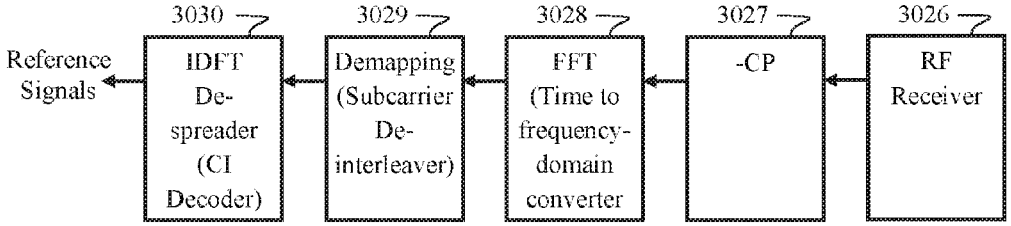


Figure 30B

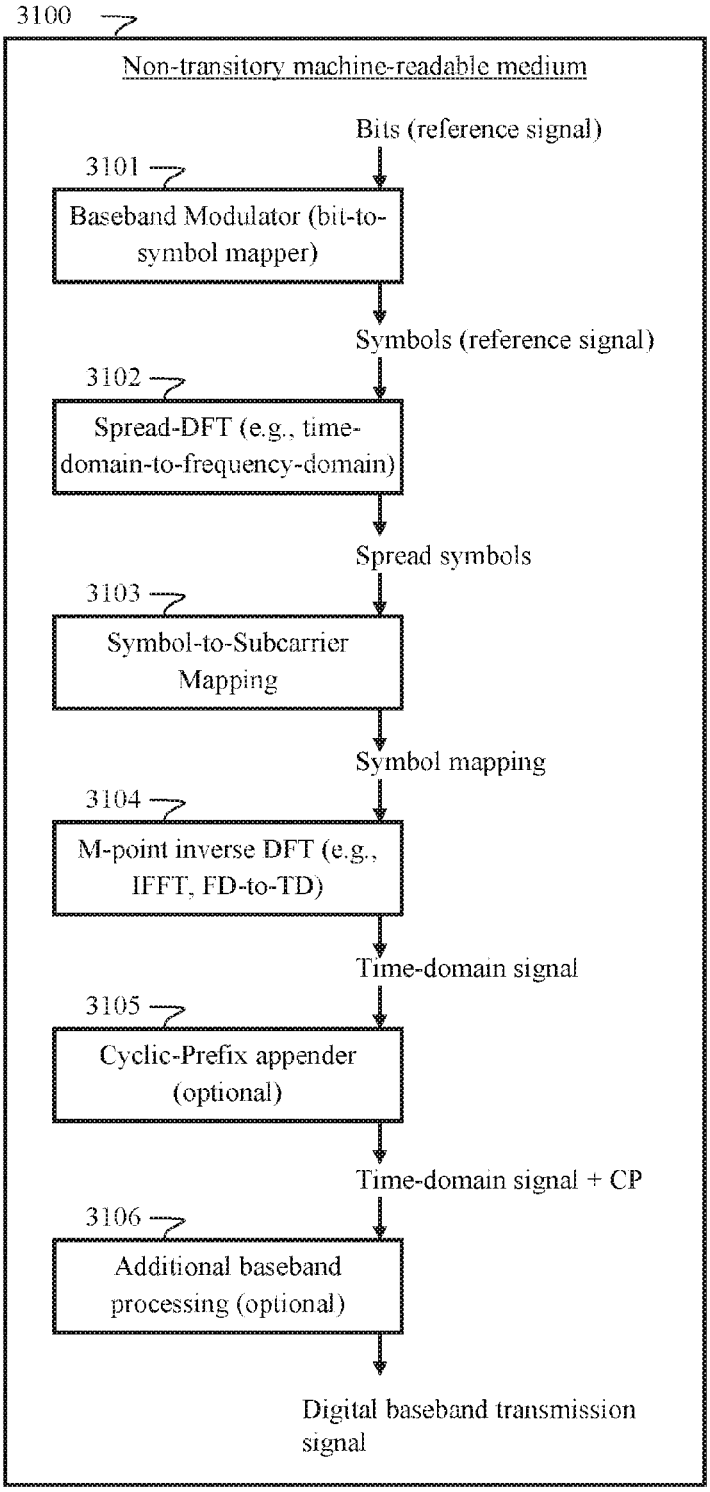

3100
Non-transitory machine-readable medium
Bits (reference signal)
3101
Baseband Modulator (bit-to-symbol mapper)
Symbols (reference signal)
3102
Spread-DFT (e.g., time-domain-to-frequency-domain)
Spread symbols
3103
Symbol-to-Subcarrier Mapping
Symbol mapping
3104
M-point inverse DFT (e.g., IFFT, FD-to-TD)
Time-domain signal
3105
Cyclic-Prefix appender (optional)
Time-domain signal + CP
3106
Additional baseband processing (optional)
Digital baseband transmission signal

Figure 31

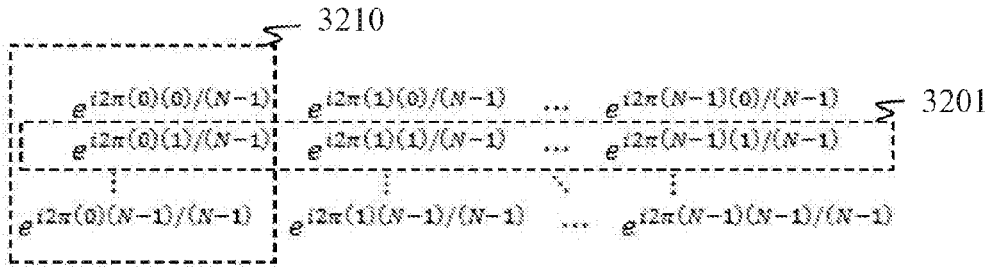

3210
3201
$e^{i2\pi(0)(0)/(N-1)}$ $e^{i2\pi(1)(0)/(N-1)}$ ... $e^{i2\pi(N-1)(0)/(N-1)}$
$e^{i2\pi(0)(1)/(N-1)}$ $e^{i2\pi(1)(1)/(N-1)}$ ... $e^{i2\pi(N-1)(1)/(N-1)}$
$e^{i2\pi(0)(N-1)/(N-1)}$ $e^{i2\pi(1)(N-1)/(N-1)}$ ... $e^{i2\pi(N-1)(N-1)/(N-1)}$

Figure 32

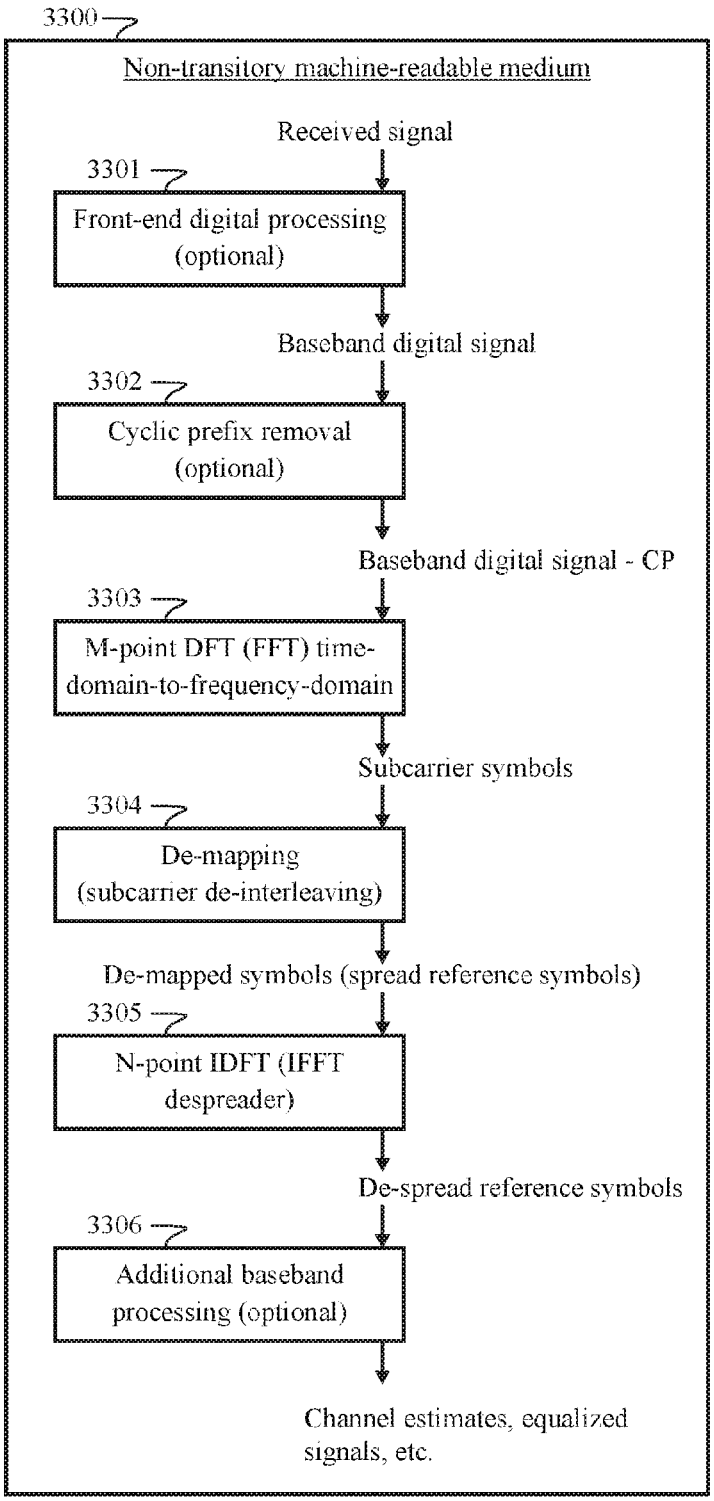

3300
Non-transitory machine-readable medium
Received signal
3301
Front-end digital processing (optional)
Baseband digital signal
3302
Cyclic prefix removal (optional)
Baseband digital signal - CP
3303
M-point DFT (FFT) time-domain-to-frequency-domain
Subcarrier symbols
3304
De-mapping (subcarrier de-interleaving)
De-mapped symbols (spread reference symbols)
3305
N-point IDFT (IFFT despreader)
De-spread reference symbols
3306
Additional baseband processing (optional)
Channel estimates, equalized signals, etc.

Figure 33

PRE-CODING IN MULTI-USER MIMO

RELATED APPLICATIONS

This application is a Continuation of U.S. patent application Ser. No. 14/967,633, filed Dec. 14, 2015, which is a Continuation-in-Part of U.S. patent application Ser. No. 14/168,466 filed Jan. 30, 2014, which is a Continuation-in-Part of U.S. patent application Ser. No. 11/187,107 filed Jul. 22, 2005, now U.S. Pat. No. 8,670,390, which claims priority to Provisional Appl. No. 60/598,187, filed Aug. 2, 2004, and which is a Continuation-in-Part of U.S. patent application Ser. No. 10/145,854, filed May 14, 2002. The patent applications, U.S. patent application Ser. No. 13/116,984, filed May 26, 2011, U.S. patent application Ser. No. 12/328,917, filed Dec. 5, 2008, now U.S. Pat. No. 7,965,761, U.S. patent application Ser. No. 11/621,014 filed Jan. 8, 2007, now U.S. Pat. No. 7,593,449, U.S. patent application Ser. No. 10/131,163 filed Apr. 24, 2002, now U.S. Pat. No. 7,430,257, and U.S. Provisional Application 60/286,850, filed Apr. 26, 2001 are expressly incorporated by reference in their entireties.

BACKGROUND

I. Field

The present invention relates generally to wireless communication networks, and more specifically to spread Orthogonal Frequency Division Multiplexing.

II. Background

The background description includes information that may be useful in understanding the present inventive subject matter. It is not an admission that any of the information provided herein is prior art or relevant to the presently claimed inventive subject matter, or that any publication, specifically or implicitly referenced, is prior art.

Communication over the spatial modes of a point-to-point MIMO channel was developed in the early 90s [e.g., S. J. Shattil, U.S. Pat. No. 6,211,671] then gradually extended to multi-user (MU-) MIMO channels [e.g., S. J. Shattil, U.S. Pat. No. 6,008,760].

In a conventional cellular communication system, transmissions to different users are formed independently. Hence, the transmission to one user can act as interference to other users. Because the system forms the transmission to each user independently, the system has no way of knowing how a transmission to a particular user will impact other users in the vicinity. As a result, interference between cells is a main factor limiting the performance of current cellular systems. For users near a cell boundary, inter-cell interference is especially problematic.

Fading and interference are the two key challenges faced by designers of mobile communication systems. While fading puts limits on the coverage and reliability of any point-to-point wireless connection, e.g., between a base station and a mobile terminal, interference in prior-art networks restricts the reusability of the spectral resource (time, frequency slots, codes, etc.) in space, thus limiting the overall spectral efficiency expressed in bits/sec/Hz/base station.

The conventional approach to interference mitigation is spatial reuse partitioning, which prevents any spectral resource from being re-used within a certain cluster of cells. Typically, the frequency re-use factor is much less than unity such that the level of co-channel interference is low. Thus, interference is controlled by fixing the frequency reuse pattern and the maximum power spectral density levels of each base station. Some CDMA systems allow for full frequency re-use in each cell, but at the expense of severe interference at the cell edge, resulting in a significant data rate drop at the terminals and a strong lack of fairness across cell users. Some interference mitigation can be achieved via limited inter-cell coordination, such as soft handover techniques. Inter-cell interference is typically treated as noise at the receiver side and is handled by resorting to improved point-to-point communications between the base station and the mobile station using efficient coding and/or single-link multiple-antenna techniques.

Some of the proposals for increasing the capacity of cellular networks include using more spectrum, increasing the number of transmit/receive antennas on each station, using dedicated beams to serve users, and micro-cell deployment. However, none of these approaches adequately address inter-cell interference, which is a primary bottleneck for spectral efficiency.

In the traditional cellular architecture, each base station only connects to a fixed number of sector antennas that cover a small area and only provide transmission/reception in its coverage area. Ideally, in such networks, the coverage areas of different base stations do not substantially overlap, as the system capacity is limited by interference. In these networks, interference makes it difficult to improve spectrum efficiency and network capacity. Another drawback to traditional cellular systems is that the base stations are built on proprietary platforms as a vertical solution.

Operators of prior-art cellular systems are faced with many challenges. For example, the high complexity of traditional base stations requires costly initial investment, site support, site rental, and management support. Building more base station sites imposes substantial infrastructure and operational expenses on the network operator. Furthermore, since the base stations can't share processing power with each other, network energy efficiency, processing efficiency, and infrastructure utilization efficiency are low because the average network load is typically far lower than the peak load. Specifically, each base station's processing capability can only benefit the active users in its cell. Thus, a base station's processing capability is wasted when the network load within its cell is low, while at other times it may be oversubscribed. Also, an idle or lightly loaded base station consumes almost as much power as it does under peak loads.

These and other drawbacks of the prior art can be reduced or eliminated by exemplary aspects of the disclosure.

As explained above, prior-art broadband wireless technologies are band-limited or interference-limited, meaning that their spectral efficiency reaches an upper limit set by the laws of Physics, such as indicated by the Shannon formulas. While the spatial domain adds another dimension to exploit via cell planning and sectoring, increasing the cell density (e.g., micro-cells, pico-cells, femto-cells) beyond a certain point fails to mitigate the performance decline as more users demand services. This is because smaller cells result in increased inter-cell interference, which establishes a practical upper bound for cell density. While the spectral efficiency of prior-art technologies is limited by the laws of Physics, the demand for data bandwidth keeps growing. As a result, today's cellular networks are already experiencing declining data rates per user.

Thus, there is a compelling need in the broadband wireless industry for systems and methods of wireless communications in which network performance is not hard-limited by the laws of Physics, but rather increases according to advances in computer processing technologies, such as

indicated by Moore's law. Only systems and methods such as disclosed herein can meet the growing demands for broadband wireless data services.

SUMMARY

Aspects of the disclosure describe cooperative-MIMO processing which comprise MIMO processing wherein the multiple input (MI) comprises downlink transmissions from multiple base transceiver stations and the multiple output (MO) comprises uplink transmissions to multiple base transceiver stations. Aspects of the disclosure also indicate that cooperative-MIMO processing can employ user equipment (UEs). In accordance with some aspects, combinations of base transceiver stations and UEs are configured for cooperative-MIMO processing.

In accordance with the deficiencies of the prior art, some aspects of the disclosure can eliminate problems due to inter-cell interference near cell boundaries by simply eliminating the cell boundaries. For example, unlike soft hand-off in which two base stations merely employ the same radio channel to serve a handset at a cell boundary, geographically distributed base stations can be coordinated to function together as a distributed antenna system with overlapping coverage areas and configured to perform subspace antenna array processing. Since subspace antenna array transmissions can produce constructive and destructive interference zones (i.e., amplified-signal and cancelled-signal zones) in a rich scattering environment, provisioning of radio resources in accordance with networks and methods disclosed herein can benefit from types of spatial reuse that far outperform cellular-based (e.g., honeycomb) spatial reuse schemes that rely on signal attenuation via path loss.

Whereas prior-art cellular systems strive to reduce inter-cell and intra-cell interference, aspects of the disclosure exploit interference to achieve substantial performance gains. Some exemplary aspects dramatically improve system performance, including throughput, coverage, signal quality, and spectral efficiency, by exploiting inter-cell (and/or intra-cell) interference. Furthermore, since capacity in a downlink multi-user MIMO system depends on the number of transmitting antennas, coordinating multiple geographically distributed base transceiver stations to cooperatively perform multi-user MIMO processing can effectively increase the number of transmitting antennas, and thus, downlink system capacity (which can translate into a combination of serving more users, increasing data rates per user, and improving quality metrics of the communication links). Some aspects of the disclosure produce similar benefits for uplink performance in a multi-user MIMO system.

In some aspects, radio transceivers operating in networks disclosed herein can perform either or both client and server operations. By way of example, a UE may be configured to operate as a base transceiver antenna in a Cooperative-MIMO configuration with one or more base transceiver systems, thereby increasing the rank of the channel matrix, which enables more subspace channels to be employed in the uplink and/or downlink. The UE may be coordinated with the one or more base transceiver systems via a fronthaul network, including the radio access network (e.g., the WWAN). By way of example, a base transceiver system may be configured to operate as a UE in a local group of UEs organized in a Cooperative-MIMO configuration. The base transceiver can be configured to communicate with the local group via a local area network (e.g., a UE fronthaul network used to coordinate the group of UEs) in order to increase the rank of the channel matrix employed for uplink and/or downlink subspace processing.

Aspects of the disclosure may be provided for achieving a large number of objectives and applications which are too numerous to list herein. Therefore, only some of the objects and advantages of exemplary aspects are discussed in the Summary and in the Detailed Description. In some aspects of the disclosure, interference is dealt with using cooperative MIMO so as to increase the number of co-channel links that can coexist with acceptable quality of service. For example, in the high-SNR regime, this figure of merit corresponds to the maximum number of concurrent interference-free transmissions, which is referred to as the multiplexing gain of the network, or the number of degrees of freedom in the information-theoretic terminology.

Some aspects of the disclosure provide various types of interference-aware multi-cell coordination. For example, in some aspects, base stations no longer tune separately their physical and link/MAC layer parameters (power level, time slot, subcarrier usage, beamforming coefficients, etc.) or decode independently of one another, but instead coordinate their coding and/or decoding operations on the basis of global channel state and user data information exchanged over fronthaul (e.g., backhaul) links among multiple cells. Coordination protocols can exploit existing fronthaul links (e.g., WiMax, 4G LTE, optical fiber) or may require a design upgrade to accommodate additional overhead. There are various degrees of cooperation, offering a trade-off between performance gains and the amount of overhead placed on fronthaul and/or other channels, including over-the-air feedback channels.

In some aspects of the disclosure, such as disclosed in the '850 application, certain network control functions are performed in a cooperative fashion by a central processing unit for a set of cooperating base transceiver stations. The central processing unit can be incorporated in one of the cooperating base transceiver stations, which can be connected with any of the other cooperating base transceiver stations via a low-latency, high-capacity fronthaul network. Various network control functions can be performed by the central processing unit, including resource allocation (e.g., scheduling) and power control.

In some aspects of the disclosure, antenna array processing performed by the central processing unit can mitigate inter-cell interference caused by simultaneous transmissions scheduled on the same frequency resource by nearby base transceiver stations. In one aspect, the central processing unit coordinates beamforming (e.g., calculates array-processing weights from channel measurements and coordinates transmissions of the base transceiver stations) such that one base transceiver station provides for coherent combining of its transmissions at a target UE while at least one other base transceiver station produces transmissions that destructively combine at the target UE. In another aspect, the central processing unit is configured to perform joint processing of subspace signals for coordinated multi-point transmissions, wherein multiple base transceiver stations serve a target UE with subspace-coded transmissions. For example, multiple base transceiver stations can be provided with subspace pre-coding weights calculated from channel measurements, and their transmissions can be coordinated such that the set of base transceiver stations functions jointly as an array of transmitters that produces multiple non-interfering subspace channels. Specifically, first portions of subspace-coded transmissions from antennas on multiple ones of the base transceiver stations combine coherently at the target UE to produce at least a first data

stream, whereas at least second portions of the subspace-coded transmissions from different ones of the base transceiver stations combine destructively at the target UE to cancel at least a second data stream, wherein the at least second data stream is intended for at least one other UE. Subspace processing in the disclosed aspects can include various techniques, including, but not limited to, maximum ratio combining (MRC), zero-forcing (ZF), and minimum mean square error (MMSE) techniques.

In one aspect of the disclosure, a network of M connected J-antenna base stations can serve a total of MJ terminals in an interference-free manner simultaneously, regardless of how strong the interference is. To achieve this remarkable result, multi-user spatial pre-coding and decoding can be employed on the downlink and uplink, respectively.

In accordance with some aspects of the disclosure, a cloud radio access network (C-RAN) comprises multiple geographically distributed base transceiver stations, a high-bandwidth low-latency optical transport network (e.g., a fronthaul network), and a central processor. The base transceiver stations are connected to the central processor via the fronthaul network. Furthermore, the central processor may comprise distributed computing resources. For example, the central processor may comprise (or be communicatively coupled to) high-performance programmable processors and real-time virtualization technology. Some aspects employ a software defined radio (SDR) platform.

In one aspect of the disclosure, a C-RAN system comprises base transceiver stations that operate solely as radio units (e.g., remote radio heads), while the RAN baseband processing is performed at a central processor within the operator's network. Fronthaul links, such as fiber optic links or wireless links, connect each base transceiver station to the central processor. The centralization of both uplink and downlink baseband processing at the central processor enables many benefits, including allowing the central processor to perform cancellation of the downlink-uplink interference, since the downlink signal is known at the central processor.

Centralized signal processing disclosed herein greatly reduces the amount of base transceiver equipment needed to cover the same area. Cooperative processing, such as Cooperative-MIMO in a distributed antenna system, provides higher spectrum efficiency. Real-time cloud infrastructure (which can be based on an open platform and utilize base station virtualization) enables processing aggregation and dynamic resource allocation, reducing the power consumption and increasing the infrastructure utilization rate. This network architecture is advantageous for LTE-Advanced, which requires tight coordination between neighboring cells, as such coordination is facilitated at the central processor where RAN baseband functions of the base transceiver stations are pooled.

In another aspect of the disclosure, methods for providing C-RAN communications comprise performing RAN baseband processing at a central processor, while a distributed antenna system comprising a network of geographically distributed base transceiver stations acts solely as down-converters in the uplink and up-converters in the downlink. The fronthaul links carry baseband information. In one aspect, in the uplink, UE signals received by the base transceiver stations are forwarded to the central processor, which performs joint decoding. In another aspect, in the downlink, the central processor performs pre-coding and then communicates the resulting baseband signals via the fronthaul links to the base transceiver stations. Each base transceiver station simply up-converts the baseband signal and transmits it to the UEs.

With centralized processing of the C-RAN architecture, power consumption due to air conditioning and other equipment at the base transceiver sites can be reduced. In many aspects, the distance from the base transceiver stations to the UEs can be decreased, since Cooperative-MIMO processing can mitigate the effects of interference between base transceiver stations, allowing for a much higher density of base transceiver stations. With smaller cells, the power required for signal transmission is reduced, which can decrease power consumption in both the RAN and the UEs. Furthermore, because baseband processing is implemented via a shared resource among a large number of base transceiver stations, more efficient utilization of processing resources and lower power consumption can be achieved.

In aspects of the disclosure, the base station baseband processors and site support equipment are aggregated in a centralized location. This centralized management and operation can be far more efficient than managing a large number of base station sites in a traditional RAN network. If each base transceiver station's functionality is simpler, the size, cost, and power consumption can be reduced. Thus, base transceiver stations can be smaller, less expensive, and easier to deploy with minimum site support and management requirements. Centralized operation also facilitates sharing of the control signaling, traffic data, and channel state information in the system, which can enable joint processing and scheduling to mitigate inter-cell interference and improve spectral efficiency.

In some aspects of the disclosure relating to non-transitory computer-readable medium with instructions stored thereon, the term "virtual" is used. While virtualization typically refers to the abstraction of computer resources in which the physical characteristics of a computing platform are hidden from users and/or applications, the term, virtual, can also relate to an abstraction of a network configuration wherein signal-processing functions do not require certain details of a distributed antenna system. In some aspects, portions of methods and systems that provide for channel characterization and calculating antenna array weights for subspace multiplexing and/or demultiplexing do not require certain information about the distributed antenna system. For example, some of the signal-processing functions can be independent of whether the system comprises a conventional antenna array or a plurality of separate RAN transceivers communicatively coupled together via a fronthaul network. Some signal-processing functions can be independent of whether they are performed at a base transceiver station or at a central processor to which the base transceiver station is communicatively coupled. This enables MIMO and other baseband processing to be performed at the central processor.

In some aspects of the disclosure, central processing comprises distributed computing. Thus, a network operator can dynamically allocate processing resources within a centralized baseband pool to different virtualized base stations and different air interface standards. This allows the operator to efficiently support a variety of air interfaces and adjust to varying network loads across different geographical areas. Within a centralized baseband pool, physical layer processing resources can be efficiently managed and allocated via real time virtualization. Thus, a base station instance can be adapted through the flexible resource combination, which can adjust, allocate, and re-allocate resources based on each virtualized base station's require-

ments in order to meet its demands. This provides Cooperative-MIMO operations with the required processing resources dynamically. Furthermore, centralizing the hardware platform can provide cost effectiveness for managing, upgrading, and expanding the base station network.

In accordance with some aspects of the disclosure, a plurality of transmitting nodes is employed by a source node to build the dimension of the subspace spanned by the coded transmissions. In one aspect, the plurality of transmitting nodes is selected to ensure that a set of pre-coded transmissions is characterized by sufficient rank to allow a destination node to decode received signals. For example, selecting a sufficient number of transmitting nodes and encoding (e.g., pre-coding) original data signals can produce a sufficient number of linearly independent (i.e., algebraically unique) combinations of the original data signals to permit the destination node(s) to resolve the original data signals. The transmitting nodes can be selected based on channel measurements and/or their geographic locations such as to ensure that their transmissions are uncorrelated. Each of the transmitting nodes transmits a subset of a total number (i.e., plurality) of subspace-coded components and a corresponding code matrix, wherein at least one of the transmitting nodes has a rank that is insufficient for decoding the plurality of subspace coded components (e.g., a destination node needs to receive signals from a plurality of the transmitting nodes in order to achieve sufficient rank for decoding the received signals). The corresponding code matrix can take the form of a preamble (or header) that comprises the code matrix. When the codes comprise channel-specific codes based on the naturally random channel, then the codes comprise random codes.

As disclosed in some aspects herein, the transmitting nodes can function as routers, relays, repeaters, etc., configured to encode received signals prior to retransmission or simply pass through received signals prior to retransmission. In some aspects, the transmitting nodes can combine multiple signals to be transmitted. In some aspects, the naturally random channel provides random linear coding to transmissions, such as when transmitting nodes are selected to produce transmissions with uncorrelated multipath effects (e.g., fading).

In accordance with some aspects of the disclosure, a destination node can employ a plurality of receiving nodes to cooperatively receive a plurality of subspace-coded components and their corresponding code vectors, wherein the rank of at least one of the receiving nodes is insufficient for decoding the coded components. Thus, receiving nodes can function as routers, relays, repeaters, etc. The destination node builds up the dimension of the subspace spanned by code vectors it collects from the receiving nodes so it can decode the coded components. For example, the destination node can receive signals from multiple receiving nodes in order to decode the subspace-coded components. The receiving nodes can be selected to provide uncorrelated channels.

As disclosed herein, intervening nodes can function as either or both transmitting nodes and receiving nodes. Whereas in conventional routing, intervening nodes simply replicate and forward their received packets, cooperative network coding (such as disclosed in the '163 application) enables relay nodes to combine information received from multiple links for subsequent transmissions. The '163 application discloses various types of linear network codes, including polyphase codes derived from a discrete Fourier transform and random codes, such as derived from the natural randomness of wireless multipath channels, and combinations thereof.

In some aspects of the disclosure, assigned wireless network channels (such as network channels allocated to a particular frequency band and time interval) are reused. For example, cooperative subspace processing (e.g., Cooperative-MIMO) generates a plurality of parallel subspace channels that can simultaneously occupy the same spectral resource. If OFDM is employed, this means that multiple parallel spatial subchannels can occupy the same set of OFDM subcarriers, or tones. In some aspects, cooperative subspace processing provides for communicatively coupling together multiple geographically distributed transceivers (e.g., base transceiver stations and/or wireless client devices) via a fronthaul network to enable joint processing operations.

In some aspects of the disclosure, a network channel is allocated to a transceiver operating in a first network, wherein the transceiver is part of a group of transceivers comprising a second network. The network channel is reused by the group of transceivers for communicating in the second network in a manner that avoids interfering with the first network. By way of example, the group of transceivers employs spatial multiplexing, such as cooperative subspace processing, to mitigate interference between the first network and the second network.

In one aspect of the disclosure, a transceiver employs a channel allocation for a first communication link in a first group of transceivers comprising a first network. A second group of transceivers that is different from the first group but comprises the transceiver reuses the channel allocation for communicating in at least a second communication link. The second group is configured to employ any of various interference-mitigation techniques that permit the reuse of the channel allocation while minimizing co-channel interference with the first network. In some aspects, the second group is configured to employ interference-mitigation techniques that mitigate the effects of co-channel interference in the second link due to transmissions in the first link.

By way of example, if the channel allocation is for a downlink channel, the second group can perform either or both transmit-side and receive-side spatial multiplexing to cancel interference from transmissions in the first link that could interfere with one or more receivers in the second link. If the channel allocation is for an uplink channel, the second group can perform transmit-side spatial multiplexing to cancel interference from transmissions in the second link that could interfere with receivers employing the first link. The second group can perform either or both transmit-side and receive-side spatial multiplexing to cancel interference due to transmissions in the first link that could interfere with one or more receivers employing the second link.

As described throughout the '163 application, aspects disclosed herein can be implemented in a cloud-based SDR platform.

In some aspects of the disclosure, an OFDM transmitter is configured to produce a CI-OFDM transmission signal, such as a Discreet Fourier Transform (DFT)-spread OFDM signal. For example, an OFDM spreader (such as a CI coder) is configured to spread a plurality of reference-signal symbols with Fourier coefficients to generate a DFT-spread reference signal. A mapper is configured to map DFT-spread reference symbols to a plurality of OFDM subcarriers. An OFDM modulator modulates the DFT-spread reference symbols onto the OFDM subcarriers to produce an OFDM transmission signal, which can have low peak to average

power ratio (PAPR). Various techniques, such as interleaving the OFDM subcarriers, combining the spreading with spatial precoding, and pulse shaping are also disclosed.

Groupings of alternative elements or aspect of the disclosed subject matter disclosed herein are not to be construed as limitations. Each group member can be referred to and claimed individually or in any combination with other members of the group or other elements found herein. One or more members of a group can be included in, or deleted from, a group for reasons of convenience and/or patentability. When any such inclusion or deletion occurs, the specification is herein deemed to contain the group as modified, thus fulfilling the written description of all Markush groups used in the appended claims.

All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided with respect to certain embodiments herein is intended merely to better illuminate the inventive subject matter and does not pose a limitation on the scope of the inventive subject matter otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the inventive subject matter.

Additional features and advantages of the invention will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The features and advantages of the invention may be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims. These and other features of the invention will become more fully apparent from the following description and appended claims, or may be learned by the practice of the invention as set forth herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Flow charts depicting disclosed methods comprise "processing blocks" or "steps" may represent computer software instructions or groups of instructions. Alternatively, the processing blocks or steps may represent steps performed by functionally equivalent circuits, such as a digital signal processor or an application specific integrated circuit (ASIC). The flow diagrams do not depict the syntax of any particular programming language. Rather, the flow diagrams illustrate the functional information one of ordinary skill in the art requires to fabricate circuits or to generate computer software to perform the processing required in accordance with the present disclosure. It should be noted that many routine program elements, such as initialization of loops and variables and the use of temporary variables are not shown. It will be appreciated by those of ordinary skill in the art that unless otherwise indicated herein, the particular sequence of steps described is illustrative only and can be varied. Unless otherwise stated, the steps described below are unordered, meaning that the steps can be performed in any convenient or desirable order.

FIG. **1** is a block diagram of a communication system architecture in accordance with an exemplary aspect of the invention.

FIG. **2** illustrates a network configuration for super-array processing in accordance with some aspects of the invention.

FIG. **3**A is a flow diagram of a super-array processing method in accordance with an aspect of the invention.

FIG. **3**B is a flow diagram of a super-array processing method in accordance with an aspect of the invention in which channel information is estimated from measurements of reference signals transmitted by the UEs. The reciprocal nature of the channel can enable channel estimation of received uplink signals to be used to calculate pre-coding for the downlink channel.

FIGS. **4**A and **4**B are flow diagrams depicting spatial demultiplexing implemented via multi-cell MIMO cooperation in wireless networks.

FIG. **5** is a flow diagram depicting a method in accordance with an aspect of the disclosure in which multiple geographically distributed transmission points are coupled to a central processor via a fronthaul network, and the central processor calculates pre-coding weights for spatial multiplexing and coordinates the transmission points to transmit subspace pre-coded downlink signals to multiple UEs.

FIG. **6** is a flow diagram depicting a method in accordance with an aspect of the disclosure in which multiple geographically distributed transmission points are coupled to a central processor via a fronthaul network, and the central processor is configured to perform spatial demultiplexing of UE uplink transmissions received by the distributed transmission points.

FIG. **7** is a flow diagram depicting messages passed between UEs, base transceiver stations, and a central processor corresponding to a super-array processing method.

FIG. **8** comprises pseudo-code that depicts data structures and processing functions that can be implemented by a computer processor programmed to perform methods, such as super-array processing methods, in accordance with aspects of the disclosure.

FIG. **9** is a block diagram of a UE that can be configured to operate in accordance with aspects of the disclosure.

FIG. **10** is a block diagram of a base transceiver station that can be configured to operate in accordance with aspects of the disclosure.

FIG. **11**A is a block diagram of a central processor that can be configured to operate in accordance with aspects of the disclosure.

FIG. **11**B is a block diagram that depicts a cloud-based software-defined radio, which can be implemented in accordance with many different aspects of the disclosure.

FIG. **12** is a block diagram of a super-array processing system comprising a central processor communicatively coupled to multiple geographically distributed base transceiver stations via a fronthaul network.

FIG. **13**A is a flow diagram of a subspace processing method configured in accordance with some aspects of the disclosure.

FIG. **13**B is a flow diagram of a subspace processing method that employs decision feedback configured in accordance with some aspects of the disclosure.

FIGS. **14**A and **14**B are block diagrams that illustrates method and apparatus implementations of radio transceivers in accordance with aspects of the disclosure.

FIG. **15** is a block diagram of a transceiver in accordance with some aspects of the disclosure.

FIG. **16** is a block diagram depicting functional aspects of transceivers according to aspects of the disclosure.

FIG. **17** depicts a network comprising multiple geographically distributed base transceiver stations communicatively coupled together via a fronthaul network. The base transceiver stations are configurable to jointly process signals in a radio access channel that serves multiple UEs. In some aspects of the disclosure, at least one of the base transceiver stations coordinates joint processing.

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FIG. **18** depicts a cloud radio access network comprising multiple geographically distributed base transceiver stations communicatively coupled to a central processor via a fronthaul network, wherein the central processor comprises a distributed computing system. In such aspects, combinations of central processing and distributed computing can provide for pooling and virtualizing base station processing, such as via an SDR.

FIG. **19** depicts a coordinated multipoint network wherein a plurality of access points are communicatively coupled to a central processor via a fronthaul network, and wherein at least some of the access points' signal processing functions (such as RAN baseband processing) are pooled at the central processor. Apparatus implementations corresponding to this aspect of the disclosure include providing for relocating access point baseband processing equipment to the central processor, which can greatly reduce the capital expense and operating expense associated with the access point network.

FIGS. **20**A and **20**B are flow charts depicting methods wherein geographically distributed access points perform RF processing in a radio access network and a central processor performs corresponding RAN baseband processing. In some aspects the corresponding RAN baseband processing is performed by a distributed computing system.

FIG. **21** depicts a network topology comprising a source node, a destination node, and a plurality of intervening nodes. This and other network topologies shown herein depict some aspects of the disclosure, including cooperative-MIMO, cooperative subspace coding along multiple network paths, simultaneously employing multiple network paths as a single communication link, providing for reusing spectral resources across multiple links, etc.

FIGS. **22**A and **22**B depict signal transmissions propagating in a network with multiple intervening nodes between a source node and a destination node. Selecting the intervening nodes as part of a transmit and/or receive cooperative subspace processing operation can build the rank of the subspace coding matrix of coded signals propagating through the network, thus providing a sufficient number of linearly independent combination of original data to permit subspace demultiplexing at the destination node.

FIG. **23**A is a flow diagram that illustrates aspects of the disclosure pertaining to cooperative subspace multiplexing.

FIG. **23**B is a flow diagram that illustrates aspects of the disclosure pertaining to cooperative subspace demultiplexing.

FIGS. **24**A and **24**B are block diagrams depicting transceiver apparatus and method aspects configured to perform routing and/or relaying.

FIGS. **25**A and **25**B are block diagrams that depicts channel reuse, such as may be configured between a plurality of networks.

FIG. **26** depicts a cooperative-MIMO network configured to employ channel reuse.

FIG. **27** is a flow diagram that depicts channel reuse methods in accordance with some aspects of the disclosure.

FIG. **28**A is a flow diagram that depicts a method for producing CI-coded transmissions of user data and control signals. Such methods may be performed by a UE for uplink transmissions in a radio access network.

FIG. **28**B is a flow diagram depicting a method that employs CI spreading codes to spread user data and control signals.

FIG. **28**C is a flow diagram that depicts a method that employs CI spreading codes and time division duplexing.

FIG. **28**D is a flow diagram that depicts a routing method that employs CI spreading and is configurable for operating in cooperative, peer-to-peer, multi-hop, and mesh networks.

FIG. **29**A is a flow diagram that depicts a CI signal generation method in accordance with some aspects of the disclosure. A UE can be configured to perform such methods to generate an uplink transmission.

FIG. **29**B is a flow diagram that depicts a CI signal processing method in accordance with some aspects of the disclosure. A base transceiver station or a central processor may employ such methods for processing received transmissions comprising DFT-spread uplink signals transmitted by a UE.

FIG. **30**A is a block diagram of a CI-OFDM transmitter according to some aspects of the disclosure, and FIG. **30**B is a block diagram of a CI-OFDM receiver configured in accordance with some aspects of the disclosure.

FIG. **31** is a block diagram that depicts a non-transient computer-readable memory comprising a set of instructions stored therein and executable by a processor to perform methods in accordance with aspects of the disclosure.

FIG. **32** illustrates an invertible transform matrix that can be employed in some aspects of the invention.

FIG. **33** is a block diagram that depicts a non-transient computer-readable memory comprising a set of instructions stored therein and executable by a processor to perform methods in accordance with aspects of the disclosure.

DETAILED DESCRIPTION

The terms "backhaul" and "fronthaul" can be used interchangeably in some aspects of the disclosure. A fronthaul is similar to a backhaul, which, at its simplest, links a radio access network to a wired (e.g., cable or optical fiber) network. A fronthaul can comprise a backhaul, or a portion of a backhaul. For example, a fronthaul can comprise a connection between one or more centralized controllers and remote stand-alone radio heads. A fronthaul connects a central processor to multiple base transceiver stations. A fronthaul connects multiple base transceiver stations together when one or more of the base transceiver stations functions as a central processor. As used herein, a fronthaul may comprise a traditional backhaul network. For example, a fronthaul can comprise at least a portion of S1 and/or X2 interfaces. A fronthaul may be part of a base station network. In Pat. Appl. Ser. No. 60/286,850, it is disclosed that a fronthaul can comprise optical fiber, wired, and/or radio networks. In one aspect of the disclosure, point-to-point fiber links provide high bandwidth and low latency. In another aspect, radio (e.g., microwave) links can provide high bandwidth and low latency, and can be substantially less expensive to implement than fiber. Furthermore, wireless links enable mobile radios and/or other radio transceivers (e.g., remote radio equipment) to be networked together via a radio fronthaul, such as disclosed in patent application Ser. No. 10/131,163. Accordingly, a fronthaul can comprise any combination of wireless, wired, and optical fiber links that communicatively couple together a group of radio transceivers configured to perform cooperative MIMO. Here, a group of radio transceivers is also referred to as a "micro-cell" and a "pico-cell" in the '163 application, and as a "local group" and a "micro-network" in patent application Ser. No. 11/187,107, all of the patents and patent applications mentioned herein being incorporated by reference in their entireties.

Pre-coding is defined herein to comprise its ordinary and customer meaning known to those of ordinary skill in the art.

By way of example, in the '163 application, pre-coding is described in the context of antenna array transmission systems with the terms, "pre-transmission processing," "pre-distortion," "channel compensation," "transmit filtering," "spatial interferometry multiplexing," and "subspace processing." The '163 application also discloses directive and retro-directive adaptation methods for calculating antenna array weights for transmission in a distributed antenna system. In one example, subspace pre-coding weights are calculated from measurements of received signals, the measurements comprising channel state information.

User Equipment (UE), as used herein, may be fixed or mobile and comprises any device used directly by an end user (or client device) to communicate in a radio access network. For example, a UE can be a cellular handset, a laptop equipped with a mobile broadband adaptor, a wearable computer, a PDA, a tablet, or any other user device configured to communicate with a Wireless Wide Area Network (WWAN). A WWAN is also referred to as a radio access network (RAN). A UE comprises an RF transceiver for fixed and/or mobile clients receiving data streams over the downlink channel of the WWAN and transmitting data via the WWAN's uplink (UL) channel. While a UE is defined in the Universal Mobile Telecommunications System (UMTS) and 3GPP Long Term Evolution (LTE) as any device that connects to a base station NodeB or eNodeB as specified in the ETSI 125/136-series and 3GPP 25/36-series of specifications, UEs include equivalent devices, such as mobile stations in GSM systems and client devices in other wireless networks. As used herein, a UE may also be referred to as a subscriber device, mobile terminal, user terminal, wireless terminal, subscriber terminal, client terminal, subscriber unit, mobile unit, subscriber device, mobile device, wireless device, client device, client terminal, client unit, mobile network device, mobile handset, wireless handset, or some other terminology indicating a WWAN-enabled client device.

In general, the various embodiments of the UE can include, but are not limited to, cellular mobile devices, personal digital assistants (PDAs) having wireless communication capabilities, portable computers having wireless communication capabilities, image capture devices such as digital cameras having wireless communication capabilities, gaming devices having wireless communication capabilities, music storage and playback appliances having wireless communication capabilities, Internet appliances permitting wireless Internet access and browsing, as well as portable units or terminals that incorporate combinations of such functions. Examples of UEs are provided in 3GPP technical specification (TS) 36.306, Release 8, the disclosure of which is incorporated herein by reference in its entirety.

A Base Transceiver Station interfaces the fronthaul network with the WWAN channel. Base transceiver stations of one embodiment comprise access points consisting of a Digital-to-Analog Converter (DAC)/Analog-to-Digital Converter (ADC) and a radio frequency (RF) chain to convert the baseband signal to RF. A base transceiver station contains radio frequency transmitter(s) and receiver(s) for communicating directly with UEs. In some cases, the base transceiver station is a simple RF transceiver equipped with a power amplifier/antenna, and the RF signal is carried to the base transceiver station via RF-over-fiber technology as disclosed in the '850 and '163 applications. In other aspects, base transceiver stations are equipped to perform at least some RAN baseband processing operations, such as disclosed in the '850 and '163 applications. Additional features and aspects of base transceiver stations are described throughout the disclosure and in the aforementioned patent applications, which are incorporated by reference. As used herein, a base transceiver station may also be referred to as a base station, an access point, a NodeB, an evolved NodeB (eNodeB), or some other terminology. In accordance with some aspects of the disclosure, a base transceiver station is a network node.

A "network node" or "node," as used herein, is an active electronic device that is communicatively connected to a network via one or more connectors and is configured for sending, receiving, and/or forwarding information over a communication channel. A node can have multiple network connectors for a given network. For example, a node can have multiple antennas. A single device, such as a base station or a user terminal, with multiple network connectors is a single node. In a distributed network, nodes can be clients, servers, and/or peers. A peer can sometimes serve as a client and sometimes as a server. Nodes can include super nodes, which route data for other networked devices as well as themselves.

A Central Processor can include one or more servers interfacing the Internet (or other external networks) with the fronthaul. In a hierarchical network architecture, a central processor couples to the base transceiver stations and provides coordination and control for those stations. One or more base transceiver stations may function as a central processor, such as in a flat network architecture. In an LTE network, eNodeB(s) and/or access gateways can be configured to perform central processor functions. In some aspects of the disclosure, network control functions typically performed by a central processor may be assigned to any of various nodes in the network, including UEs.

In some aspects of the disclosure, the central processor computes the multi-user MIMO baseband processing and sends pre-coded data to geographically distributed base transceiver stations for downlink transmission. In some aspects, the central processor computes the multi-user MIMO baseband processing to provide spatial demultiplexing of uplink signals received by the geographically distributed base transceiver stations. In some aspects, the central processor can comprise a particular type of base transceiver station designed for certain specialized features, such as transmitting training signals for time/frequency synchronization of the base transceiver stations and/or the UEs, receiving/transmitting control information from/to the UEs, receiving the channel state information or channel quality information from the UEs, etc. In some aspects, a central processor is also referred to as a central processing facility, a cloud computing center, a cloud, a data center, a data center cloud, a central controller, a radio network controller, or a central control hub. In some aspects, a central processor can comprise multiple data centers.

Various aspects of the disclosure are described below. It should be apparent that the teachings herein may be embodied in a wide variety of forms and that any specific structure, function, or both being disclosed herein are merely representative. Based on the teachings herein one skilled in the art should appreciate that an aspect disclosed herein may be implemented independently of any other aspects and that two or more of these aspects may be combined in various ways. For example, an apparatus may be implemented or a method may be practiced using any number of the aspects set forth herein. In addition, such an apparatus may be implemented or such a method may be practiced using other structure, functionality, or structure and functionality in addition to or other than one or more of the aspects set forth herein.

The use of any and all examples, or exemplary language (e.g. "such as") provided with respect to certain embodiments herein is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention otherwise claimed. No language in the specification should be construed as indicating any non-claimed element essential to the practice of the invention. The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment or aspect described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments or aspects.

In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the invention. It should be understood, however, that the particular aspects shown and described herein are not intended to limit the invention to any particular form, but rather, the invention is to cover all modifications, equivalents, and alternatives falling within the scope of the invention as defined by the claims.

FIG. **1** is a block diagram of a communication system architecture in accordance with an exemplary aspect of the invention. A plurality N of base stations **101.1-101**.N are communicatively coupled to a central processing facility **110** (i.e., a central controller) via a communication network **105**. Each base station **101.1-101**.N comprises an antenna system for communicating with one or more mobile units (e.g., User Equipment) **120.1-120**.K. For example, the first base station **101.1** may comprise a first antenna array comprising a plurality M_1 of antennas **102.1-102**.M_1, and the Nth base station **101**.N may comprise an Nth antenna array comprising a plurality M_N of antennas **104.1-104**.M_N. A plurality K of mobile units **120.1**, **120.2**, and **120**.K are shown, each having its own antenna system **121.1**, **121.2**, and **121**.K, respectively. Each antenna system **121.1**, **121.2**, and **121**.K may comprise one or more antennas. The communication network **105** that communicatively couples the base stations **101.1-101**.N to the central processing facility **110** may comprise a fiber network, a cable (i.e., wired) network, a wireless network, or any combination thereof.

In one aspect of the invention, the signal-processing architecture provides base stations **101.1-101**.N that are essentially "dumb terminals." For example, many of the signal processing operations typically performed at a base station **101.1-101**.N may be transferred to a central processor (e.g., the central processing facility **110**) that is connected to the plurality of base stations **101.1-101**.N. In some aspects of the invention, a minimal amount of signal processing is performed at each base station **101.1-101**.N. For example, each base station **101.1-101**.N can perform basic signal-processing tasks, such as amplification, RF filtering, frequency conversion (e.g., frequency up-conversion and/or frequency down-conversion), and/or other RF signal-processing functions. After basic signal processing, signals received by one or more antennas at each base station **101.1-101**.N are coupled into at least one communication channel (e.g., network **105**) linked to the central processing facility **110**. Functions of the base station **101.1-101**.N may be limited to cleaning up the received RF signal, amplifying it, and processing the signal with respect to coupling it into the network **105**. Signals from different antennas **102.1-102**.M_1 and **104.1-104**.M_N may be transmitted on different channels (e.g., on different waveguides), or they may be multiplexed onto the same channel (e.g., with respect to wavelength division, time division, frequency division, polarization division, subspace, phase space, code division, mode division, directionality, etc.).

The central processing facility **110** processes each of the received signals from the communication channel(s). For example, the central processor **110** removes the individual signals from one or more communication channels. The removal process can include demultiplexing the signals on the channel(s). In some aspects, the central processor **110** frequency-converts the received signals to baseband, intermediate, or radio-frequency signals prior to processing. Beam-forming can be performed in RF, IF, and/or after conversion to baseband.

Thus, in some aspects of the invention, by relocating most (or all) of the base station processing operations to the central processing facility, the capital expenditures and operating costs of the radio access network can be greatly reduced. This can also facilitate rapid and less costly network upgrades and expansion. In one aspect, all the RF processing of the radio access network signals is performed at the base transceiver stations, whereas baseband processing is performed at the central processing facility. Baseband signals of the radio access network are communicated between the base transceiver stations and the central processing facility via a fronthaul radio network, some other wireless network, waveguide (e.g., cable), an optical fiber network, or a combination thereof. RF processing of the fronthaul network signals (which is different than RF processing of the radio access network signals) may be performed by the base transceiver stations and the central processing facility.

As depicted in FIG. **1**, signal-processing operations performed at the central processing facility **110** can include spatial multiplexing and/or spatial demultiplexing **114.1**, routing **114.2**, and power control **114.3**. The central processing facility **110** can be configured to perform super-array processing. In one aspect of the invention, the central processing facility **110** comprises a super array processing system **112**. In some aspects of the invention, the super array processing system **112** comprises one or more subsystems or modules, such as a spatial multiplexing/demultiplexing system **114.1**, a routing system (e.g., router) **114.2**, and a power control system **114.3**.

In one aspect of the invention, the super array processing system **112** comprises one or more general-purpose computers programmed to function as a special-purpose computer configured to perform various aspects of the disclosure, such as Cooperative-MIMO processing in a distributed antenna system. In another aspect, the super array processing system **112** comprises one or more special-purpose processors, such as integrated circuits, discrete circuits, and/or other specialized hardware configured to perform Cooperative-MIMO processing. As disclosed herein, a distributed computing system may be employed for implementing aspects of the invention, such as spatial multiplexing, spatial demultiplexing, and/or baseband signal processing operations typically performed by base transceiver stations. Such distributed computing systems may comprise a network of general-purpose computers (programmed to function as a special-purpose computers), such as servers, located in one or more data centers. A distributed computing system may comprise a network of special-purpose processors or a combination of special-purpose processors and general-purpose computers. Similarly, components of system **112**, as well as any other components, processors, systems, and devices mentioned in the disclosure, may each comprise one or more general-purpose computers, one or more special-purpose processors, or combinations thereof, and may optionally comprise a distributed computing platform.

In accordance with some aspects of the invention, the centralized architecture simplifies physical-layer system upgrades, since processing equipment used for multiple base stations **101.1-101**.N resides at a common location (i.e., the central processing facility **110**). Upgrades to improved modulation schemes, new receiver combining techniques, enhanced array-processing, etc. can be provided at the central processing facility **110** instead of at each base station **101.1-101**.N. Similarly, adding or upgrading base station antennas (e.g., antennas **102.1-102**.M_1 and **104.1-104**.M_N) is simplified since the antennas installed at each base station **101.1-101**.N may simply be coupled to the central processing facility **110** via the communication network **105**. Adding base stations to the network can be quick and less costly due to the low cost and complexity of each base station **101.1-101**.N. Thus, any signal-processing upgrade associated with the base stations **101.1-101**.N is performed at the central processor **110**.

In aspects of the invention that employ spatial multiplexing/demultiplexing, the system capacity scales linearly with the number of base station antennas (e.g., antennas **102.1-102**M_1 and **104.1-104**.M_N) within range of the UEs **120.1-120**.K. This is because the spatial multiplexing gain (i.e., the number of independent data streams that can be sent concurrently over MIMO subchannels) is proportional to the number of antennas **102.1-102**M_1 and **104.1-104**.M_N serving the UEs **120.1-120**.K.

Unlike conventional MIMO in which all of the transmitting antennas reside on a single device (e.g., a single base station), a cooperative-MIMO transmitting system in accordance with aspects of the disclosure comprises antennas residing on multiple devices (e.g., the base stations **101.1-101**.N). The super array processing system **112** coordinates the base stations **101.1-101**.N to synthesize an antenna system comprising geographically distributed antennas, which provides superior decorrelation of the transmission paths between transmitting antennas and receiving antennas in the MIMO system. Since MIMO antennas in prior-art systems reside on a single device, the length of the MIMO array is only a few wavelengths, which is usually insufficient for providing the spatial selectivity required to match the spatial multiplexing gain to the number of transmitting antennas. Thus, in prior-art MIMO systems, the rank of the MIMO channel matrix is typically less than its dimension. Adding more antennas to a prior-art MIMO system almost always results in diminishing levels of return with respect to capacity, whereas aspects of the invention solve this problem.

Since the system (depicted in FIG. **1**) capacity scales linearly with the number of base station antennas, particularly if the antennas are geographically distributed, it is advantageous to add more base stations as UE density increases. There are several benefits to doing this. Unlike prior-art cellular systems, inter-cell interference is not a problem in the radio access network depicted in FIG. **1**. Rather, it is exploited for spatial multiplexing gain, whereas enormous effort is made in today's cellular systems to avoid inter-cell interference, particularly for smaller cells. In aspects of the invention, base stations can be added in the general vicinity of increased user density without cell planning and extensive modifications to the radio access network. The central processing facility **110** immediately adapts to the new radio access network architecture to add capacity to the target area.

Since optimal spatial multiplexing gain is typically achieved when SNR is high (e.g., close to a MIMO base transceiver station), distributed antenna systems disclosed herein can provide closely proximal base transceivers for UEs throughout the coverage area that provide both high SNR and spatial selectivity. Unlike prior-art cellular systems in which each UE is linked to a single base station until it is handed off to another base station, aspects of the invention provide for maintaining concurrent links between the UE and multiple base stations throughout the UE's session. Thus, as the UE moves through the coverage area, it maintains a consistently high SNR. In other aspects of the invention, Cooperative-MIMO processing on the client side can provide distributed antenna systems comprising cooperating UEs that enable similar MIMO benefits.

In some aspects of the disclosure, all of the base station processing is performed in the central processing facility **110** (which may be an offsite data center as long as latency constraints are met) instead of by the individual base stations **101.1-101**.N. Thus, even at very high densities of UEs, not only can all UEs remain connected to the network, but the UEs do not incur the overhead normally incurred by large numbers of UEs sharing one base station in a cell.

The central processing facility **110** could be scaled indefinitely to accommodate increasing UE density and data demands. As the number of UEs and demand grows, not only is it easy to deploy additional base stations, as described above, but it is easy to expand the computing capability in the central processing facility **110** to accommodate the added base stations.

In accordance with some aspects of the invention disclosed in the '163 application, a distributed (e.g., cloud) computing environment may be employed to perform the base station processing.

Also, the '163 application discloses that the base station processing may be performed in an SDR. Thus, the implementation of the base station processing may occur entirely on general-purpose CPUs. One implementation of the central processing facility **110** in accordance with previously cited disclosure could include a data center comprising multiple switches and general-purpose servers that connect to the fronthaul network **105** via general-purpose digital links, such as 10 GbE or other links.

FIG. **2** illustrates a network configuration for super-array processing in accordance with some aspects of the invention. In one aspect, multiple mobile units (e.g., UEs **120.1-120**.K) are each serviced by multiple base stations (e.g., base stations **101.1-101**.N) simultaneously. In one aspect of the invention, each base station **101.1-101**.N comprises an antenna array. For example, the first base station **101.1** comprises an M_1-element array **102.1-102**.M_1, a second base station **101.2** comprises an M_2-element array **106.1-106**.M_2, and the Nth base station **101**.N comprises an M_N-element array **104.1-104**.M_N. In super-array processing, the base station arrays (e.g., arrays **102.1-102**.M_1, **106.1-106**.M_2, and **104.1-104**.M_N) are configured to work together to exploit the propagation environment, such as to enhance signal reception for each mobile user **120.1-120**.K, reduce power transmission requirements, and mitigate undesired interference.

For the purpose of describing an exemplary aspect of the invention, signals transmitted by mobile unit **120.1** may be received at multiple base station antenna arrays (e.g., at base stations **101.1**, **101.2**, and **101**.N). Adapting each base station antenna beam pattern (e.g., beam patterns **201.1**, **201.2**, and **201**.N) can enhance reception of signals transmitted by each mobile unit **120.1-120**.K. Transmissions to each mobile unit **120.1-120**.K can also be enhanced. For example, a transmission from base station **101.2** intended for mobile unit **120.2** may cause interference at mobile unit

120.1. However, this interference can be mitigated by including a cancellation signal in the transmission from base station 101.1 and/or base station 101.N. Since all of the base stations 101.1-101.N in this exemplary aspect are connected to the central processing facility 110, signal processing at this facility 110 can be performed to allow multiple base stations to work together and thereby enhance the radio coverage, bandwidth efficiency, and power efficiency.

With respect to each mobile unit 120.1-120.K, all of the interfering signals transmitted by the multiple base transceiver stations 101.1-101.N coherently combine to produce the exact waveform intended for that mobile unit with a high SNR (e.g., SINR). For example, first portions of waveforms transmitted by the multiple base transceiver stations 101.1-101.N combine coherently at a first mobile unit (e.g., 101.1) to produce a first set of data signals intended for the first mobile unit 101.1. Similarly, second portions of the transmitted waveforms combine coherently at a second mobile unit (e.g., 101.2) to produce a second set of data signals intended for the second mobile unit 101.2. However, the first portions combine destructively to cancel at the second mobile unit 101.2 and the second portions combine destructively to cancel at the first mobile unit 101.1. In some aspects of the invention, the high-SNR waveforms exist only in a small volume around the corresponding intended mobile unit. Since these highly localized regions of high SNR are synthesized interference zones, the diameter of these three-dimensional regions (such as may be indicated by a full-width half-maximum amplitude or power) can be less than a wavelength.

Propagation effects due to sparse antenna arrays are described in U.S. patent application Ser. No. 09/906,257, which is incorporated by reference in its entirety. When randomly spaced sources (or equivalently, sources transmitting random carrier frequencies) are employed, interference patterns (i.e., superpositions of the transmitted signals) away from the main lobe (i.e., where signals are configured to combine coherently, or in phase) tend to have little variation between minima and maxima, particularly when many sources (or frequencies) are employed.

In the spatial dimensions, a rich scattering environment can provide a large number of effective sources (i.e., each scatterer is an effective source). It is anticipated that some aspects of the invention may employ very large numbers of transmitters to generate signals that coherently combine in 3-dimensional space at a desired receiver(s). When very large numbers (e.g., hundreds or more) of transmitters and/or effective sources are employed, the signal amplitude (or power) can fall off dramatically at a short distance (even a fraction of a wavelength) from the superposition peak. The signal levels can remain at a consistently low SNR throughout 3-dimensional space except, perhaps, very close to the transmitters. With a sufficiently large number of transmitters, it may be possible to transmit signals from each transmitter that are so low in power that the signals intended for a particular user device are indistinguishable from background noise throughout almost all of the coverage area except in a small volume at the user device where they coherently combine. Thus, some aspects of the invention can provide a type of physical-layer low probability of interception/low probability of detection (LPI/LPD) benefit due to spatial processing that is analogous to LPI/LPD benefits of ultra-wideband signals. Such LPI/LPD benefits can enhance security in wireless networks.

Array processing can be performed at the central processor 110 to adapt transmission and reception beam patterns to improve one or more operating criteria, such as signal-to-noise, signal-to-noise plus interference, probability of error, bit error rate, etc. Various aspects include the use of known training sequences and pilot signals, as well as blind adaptive techniques. Open-loop and/or closed-loop feedback techniques can be used.

In one aspect, each UE may be assigned an orthogonal uplink pilot. However, the maximum number of orthogonal pilots is limited by the duration of the coherence interval divided by the channel delay spread. Thus, aspects of the invention may employ any of various channel estimation algorithms, such as blind techniques, that circumvent the use of pilots altogether. By way of example, the '163, '854, and '107 applications disclose blind techniques that jointly estimate the channels and the payload data.

Even though the propagation channel is reciprocal (between uplink and downlink in time-division duplex systems), the RF front-ends in the base transceivers and UEs may not be reciprocal between the uplink and downlink. Accordingly, calibration of the hardware to ensure reciprocity may be performed, such as disclosed in the '163 application.

The array-processing aspects of the invention can also be used in conjunction with control of other system operating parameters, including, but not limited to, power control, throughput, bandwidth, channel coding (e.g., convolutional, block, trellis, etc.), and frequency band scheduling. In one aspect, the system reduces the transmit power of a mobile unit when array processing enhances the signal-to-noise-plus-interference of that unit's radio link. In another aspect, the level of array processing is adjusted with respect to some quality factor associated with each unit. For example, array processing may be performed only for units that exceed a certain degree of signal degradation, require a certain amount of throughput, or have a predetermined quality-of-service level (QOS). Array processing can be used for data links in a system that provides data and voice services, since digital links require a higher QOS. Array processing can be used to compensate for signal-quality degradation for units assigned to interfering channels.

It should be appreciated that signal processing at the central processing facility 110 may be performed by multiple computer processors via distributed computing (e.g., cloud computing) such as disclosed in the '163 application. In some aspects, the base station signal processing at the central processing facility 110 can be implemented in a real-time SDR to provide for software-defined networks that enable more dynamic organization of resources, such as disclosed in the '163 application. The central processor 110 may comprise one or more servers in a data center configured to compute baseband waveforms using an SDR, such as described in the '163 application.

Since multiple base transceiver stations 101.1-101.N are employed to serve each UE 120.1-120.K via Cooperative-MIMO subspace processing, it is advantageous for the coverage areas of base transceiver stations 101.1-101.N employing the same spectral resources to overlap. This is contrary to how cellular base stations are positioned in a conventional cellular network. Prior-art base stations conform to a cellular layout that is carefully planned to minimize transmission overlap. However, aspects of the disclosure are not constrained to such cell plans because subspace processing can produce constructive and destructive interference zones throughout the radio access network's coverage area to enable spectral reuse, potentially for very large numbers of UEs, even UEs that are in close proximity to each other (e.g., on the order of a few wavelengths, or even less). This enables universal spectral reuse while facilitating

deployment of the radio access network infrastructure. In some aspects, the base transceiver stations **101.1-101**.N can be placed pseudo-randomly throughout the radio access network, such as to take advantage of locations that are convenient and/or less costly, and with less concern about coverage area and the presence of obstructions in the propagation environment.

In some aspects, since each UE **120.1-120**.K is concurrently served by multiple base transceiver stations **101.1-101**.N with overlapping coverage areas, a failure of a small number of base transceiver stations **101.1-101**.N is less likely to cause a service disruption. Rather, the spatial multiplexing/demultiplexing **114.1** can adapt to changes in the configuration of the base transceiver stations **101.1-101**.N, such as to ensure uninterrupted service.

The spatial multiplexing/demultiplexing **114.1** can perform various spatial processing techniques, including (but not limited to) ZF, MMSE, MRC, and/or successive interference cancellation. In some aspects, MRC can offer certain advantages due to the ease in which it can be implemented in a distributed manner and its computational simplicity (e.g., when used for demultiplexing, received uplink signals can be multiplied by the conjugate channel responses, and pre-coding downlink transmissions is similarly simplified). The combination of the MRC receiver (for the uplink) and its counterpart, maximum ratio pre-coding (for the downlink) comprise matched filtering, which is disclosed in the '163 and '854 applications. MRC can be advantageous when channel responses associated with different terminals are substantially uncorrelated.

As disclosed in the '163 application, the fronthaul network **105** can take various forms, including a mesh architecture. Since at least some of the fronthaul links **105** can be wireless (such as disclosed in the '850 application), and given that the base transceiver stations **101.1-101**.N can comprise remote radio heads (or other simple radio transceivers), as disclosed in the '850 application, the base transceiver station **101.1-101**.N hardware can be a fraction of the cost of prior-art base stations and can be deployed more quickly. Furthermore, as disclosed in the '163, '854, and '107 applications, UEs **120.1-120**.K and other devices (not shown) in the radio access network can function as base transceiver stations, such as to dynamically adapt to increased network loads and/or increased UE density, compensate for base station outages, and/or expand the coverage area.

FIG. **3**A is a flow diagram of a super-array processing method in accordance with an aspect of the invention. A plurality of base transceiver stations (e.g., transmission points, or access points) is configured to transmit reference signals **301**, which are measured by UEs to calculate channel state information **302**. For example, the '850 application discloses that reference signals, which include known training sequences and pilot signals, are transmitted, and a channel model is developed by a receiver upon receiving the transmitted reference signals. The channel state information can comprise channel information relative to multiple base station antennas residing on multiple geographically distributed base stations.

The UEs feedback the channel state information to the transmission points **304**, and the transmission points and/or the central processor calculate pre-coding weights **305** therefrom. The '850 application discloses that open-loop and/or closed-loop feedback may be employed. While channel state information can comprise quantized channel estimates, channel state information can comprise alternative indicators, such as codewords. In some aspects of the invention, such as disclosed in the '850 application, step **305** comprises selecting UE's for which array processing is to be performed, wherein only UE's having a predetermined quality-of-service level are selected. In some aspects disclosed in the '850 application, different levels of array processing may be performed, the level of array processing being selected with respect to a quality factor associated with each UE.

Multiple transmission points are coordinated by the central processor to transmit the pre-coded data **307** to each UE. In some aspects of the invention, such as in accordance with the disclosure of the '163 application, step **305** and/or **307** comprises selecting a portion of the network to serve a particular UE. For example, a predetermined set of transmission points is selected to process transmissions to a particular UE based on received pilot signal power. Upon receiving the transmissions, each UE demodulates the received signals **308**. Since UE's may comprise antenna arrays, such as disclosed in the '850 application, step **308** may comprise array processing, including MIMO processing.

In accordance with one aspect of the invention disclosed in the '163 application, network processing functions are computed by a plurality of spatially separated processors. For example, the central processor can be replaced by a distributed computing system. The distributed computing system can comprise a plurality of transmission points. In some aspects, the distributed computing system can comprise UE's, repeaters, and/or other network equipment.

In accordance with aspects disclosed in the '850 application, super-array processing comprises a coordinated multipoint technology which sends and receives signals from multiple sectors or cells to a given UE. By coordinating transmission among multiple cells, interference from other cells can be reduced and the power of the desired signal can be increased.

In one aspect of the invention, signaling over a fronthaul network can be used between base stations (e.g., eNodeB's) to coordinate among cells. In another aspect of the invention, multiple remote radio equipments (RREs) are connected via an optical fiber fronthaul carrying a baseband signal between cells and a central eNodeB, which performs the RAN baseband signal processing and control, so the radio resources between the cells can be controlled at the central eNodeB. Other aspects of the invention include combinations of distributed control based on independent eNodeB configurations and centralized control based on RRE configurations.

FIG. **3**B is a flow diagram of a super-array processing method in accordance with an aspect of the invention in which channel information is estimated from measurements of reference signals transmitted by the UEs. This exemplary method can be useful when time division duplexing (TDD) is employed, such as wherein the uplink and downlink channels assigned to each UE share the same frequency band. For estimation of channels at the transmitter in TDD networks, one can rely on the reciprocity of the uplink and downlink channels so that channel estimation on the uplink can be used for downlink transmission.

In one aspect of the invention, each UE transmits a known reference signal **311**, such as one or more known training sequences and/or pilot signals, which are described in the '850 application. The transmitted reference signals are received by antennas of multiple base transceivers, and the channel state information is measured **312** by the base transceiver stations and/or at least one central processor. As disclosed in the '850 application, the channel state information can comprise frequency-domain channel state informa-

tion. In one aspect, measured channel state information is coupled by the base transceiver stations to the central processor to be used for calculating pre-coding weights **314**. In accordance with another aspect, the central processor performs steps **312** and **314**. As disclosed in the '163 application, steps **312** and **314** can comprise reference-signal processing, blind adaptive techniques, directive, and/or retro-directive techniques. Communication between the base transceiver stations and the at least one central processor is provided by a high speed network backbone, or fronthaul, which may comprise optical fiber, wired connections, wireless connections, or any combination thereof. Pre-coded data is transmitted **316** by multiple transmission points under the control of the central processor. Each UE receives pre-coded transmissions from multiple transmission points and demodulates the received data **317**.

In one aspect of the invention, joint transmissions by multiple cells (i.e., base transceiver stations) to a given UE employ the same time and frequency radio resources. Dynamic cell selection provides for selecting a portion of the base station network to serve a particular UE. Furthermore, UE's can be selected for array processing, such as based on a UE's quality of service level. Pre-coding between the cells provides for coherent transmission, which results in in-phase combining at the receiver. With uplink multi-cell reception, the signal from a UE is received by multiple cells and combined. The UE does not need to be aware of whether multi-cell reception is occurring, so it should have little impact on the radio interface specifications.

As described in the '850 application, some aspects of the invention provide for sharing data and channel state information among groups of base stations to coordinate their transmissions in the downlink and jointly process the received signals in the uplink. These techniques can effectively turn otherwise harmful inter-cell interference into useful signals, enabling significant power gain, increased channel rank, and/or diversity advantages. While some systems disclosed herein describe cellular base stations by way of example, it should be appreciated that additional and/or alternative radio transceivers may be employed, including fixed relay stations, remote radio heads, mobile stations, peer-to-peer radio transceivers, access points, and combinations thereof.

FIGS. **4**A and **4**B are flow diagrams depicting spatial demultiplexing implemented via multi-cell MIMO cooperation in wireless networks. In dense networks where interference emerges as the key capacity-limiting factor, multi-cell cooperation can dramatically improve the system performance. Remarkably, such techniques can literally exploit inter-cell interference by allowing the user data to be jointly processed by several interfering base stations, thus mimicking the benefits of a large virtual MIMO array.

In FIG. **4**A, UE's transmit reference signals **401** and data signals **403**. Transmitted reference signals received by multiple base transceiver stations are measured to generate channel state information **402**, from which spatial demultiplexing weights are calculated **404**. In one aspect of the invention, a central processor measures the channel state information **402** and calculates demultiplexing weights **404** for a geographically distributed set of base transceiver stations. In another aspect of the invention, each base transceiver station measures the channel state information **402**, which is then forwarded to at least one central processor. In some aspects of the invention, distributed computing may be employed for calculating the spatial demultiplexing weights **404**. For example, computational parts of step **404** may be performed by multiple base transceiver stations. The central processor then demultiplexes the data transmissions **406** received from the UEs.

In FIG. **4**B, the transmission points and/or the central processor employ blind-adaptive processing, such as disclosed in the '163 application, to demultiplex received data transmissions. Data signals transmitted **411** by the UE are received and processed by multiple base transceiver stations and at least one central processor. Blind adaptive processing provides channel state information **412**, which is used to calculate spatial demultiplexing weights **414**, which are used to demultiplex **416** the data transmissions received from the UEs.

FIG. **5** is a flow diagram depicting a method in accordance with some aspects of the invention in which multiple transmission points and at least one central processor cooperate to produce subspace pre-coded downlink transmissions to multiple UEs. A base transceiver station (e.g., a transmission point) performs preliminary processing **501** of signals received from at least one UE and communicates channel state information corresponding to each UE to at least one central processor **503**. The channel state information can include channel measurements made by the UEs and/or the base transceiver stations. Thus, step **501** can comprise measuring the channel(s) of each UE. The central processor collects channel state information communicated by multiple base transceiver stations **504**, selects which base transceiver stations will serve each UE **506**, calculates the distributed-antenna pre-coding **508**, and coordinates the base transceiver stations to transmit pre-coded data signals to the UEs **510**. Each base transceiver station then transmits pre-coded data signals to the UEs **512**.

A base transceiver station (or transmission point), as used throughout the disclosure, can comprise a NodeB (such as employed in a UTRAN system) or an eNodeB (such as employed in an EUTRAN system). A central processor, as used throughout the disclosure, can include a radio network controller (RNC) in a UTRAN system or an eNodeB in an EUTRAN system. EUTRAN consists only of eNodeBs on the network side. The eNodeB performs tasks similar to those performed by the NodeBs and RNC together in UTRAN.

E-UTRA uses OFDM-MIMO antenna technology depending on the terminal category and can use subspace pre-coding for the downlink to support more users, higher data rates, and lower processing power. In the uplink, LTE uses both OFDMA and Carrier Interferometry (also called Single-Carrier Frequency-Division Multiple Access (SC-OFDMA)), such as disclosed throughout the '850 and '163 applications. This mitigates the very high peak-to-average power of conventional OFDM. For the uplink, in release 8 and 9, multi-user MIMO/Spatial division multiple access (SDMA) is supported.

LTE supports both Frequency-division duplex (FDD) and TDD modes. While FDD makes use of paired spectra for UL and DL transmission separated by a duplex frequency gap, TDD splits one frequency carrier into alternating time periods for transmission from the base station to the terminal and vice-versa. Both modes have their own frame structure within LTE, and these are aligned with each other. Thus, similar hardware can be used in the base stations and user terminals.

FIG. **6** is a flow diagram depicting a method in accordance with some aspects of the invention in which multiple transmission points and at least one central processor cooperate to perform distributed spatial demultiplexing of uplink transmissions received from multiple UEs. A base transceiver

station (e.g., a transmission point) performs preliminary processing **601** of uplink signals received from at least one UE and communicates channel state information corresponding to each UE to at least one central processor **603**. The channel state information can include channel measurements made by the UEs and/or the base transceiver stations. Thus, in some aspects, step **601** can comprise measuring the channel(s) of each UE. The central processor collects channel state information communicated by multiple base transceiver stations **604**, selects multiple base transceiver station antennas (including antennas on different base stations) from which signals will be combined for each UE **606**, calculates the distributed-antenna demultiplexing weights **608**, and performs spatial demultiplexing **610** to separate multiple same-band signals transmitted by the UEs and received by multiple base transceiver stations.

With respect to aspects of the disclosure, a multi-antenna wireless communication system, such as one employing Coordinated Multipoint transmission and/or reception, can mitigate inter-cell interference. In such a system, multiple antennas are deployed across a plurality of geographically contiguous cells (or sub-cells) and connected to a central processor, e.g., via a fast backhaul. This architecture enables the central processor to jointly process downlink signals transmitted from and/or uplink signals received at the multiple antennas, in order to mitigate inter-cell interference.

In accordance with some aspects of the disclosure, to jointly process downlink signals transmitted from the multiple antennas, in particular, the central processor is provided with information characterizing the associated downlink channel responses. If the system employs FDD, the served UEs measure these downlink channel responses and feed them back to the central processor. If the system instead employs TDD, the downlink channel responses can advantageously be estimated from uplink signals received at the multiple antennas based on the assumption that for TDD, the downlink channel can be inferred from the uplink channel (e.g., the uplink and downlink channels can be reciprocal).

This assumption of reciprocity between the downlink and uplink channel, however, may sometimes be inaccurate in a multi-antenna system. For instance, each of the multiple antennas is connected to a corresponding transceiver that comprises a transmit-receive radio frequency (RF) chain. These transmit-receive RF chains may have different frequency responses, due for example to differences in the transfer characteristics of the components (e.g., analog filters, power amplifiers, etc.) making up those RF chains. If the RF chains of the multiple antennas do not have identical frequency responses, the assumption of reciprocity no longer proves accurate, which in turn can prevent advantageous estimation of the downlink channel responses from uplink signals. Accordingly, the RF chains can be initially, and perhaps periodically, calibrated with one another to account for differences in their frequency responses, such as disclosed in U.S. Pat. No. 6,211,671, which is incorporated by reference in its entirety.

FIG. **7** is a flow diagram depicting messages passed between network devices corresponding to steps in a super-array processing method. Such flow diagrams can assist a software developer in designing software modules with instructions on non-transient computer-readable memory that program a computer processor to perform methods disclosed herein.

In one aspect of the invention, a reference signal is transmitted **751**, from which channel state information is calculated. For example, each antenna on each of a plurality of base stations **701** and **702** can transmit a reference signal (**711** and **712**, respectively), such as a known training signal or a pilot tone, which a UE **700** receives and processes to determine its channel state information.

In a feedback step **752**, the UE transmits its channel state information **713** and **714** back to its respective base station **701** and **702**. The base stations **701** and **702** relay the channel state information (e.g., messages **715** and **716**) received from their UEs to at least one central processor **710**.

As should be appreciated from the disclosure, an alternative step **751** can comprise the base stations **701** and **702** receiving transmitted reference signals from the UEs (such as UE **700**) and estimating the channels therefrom. Then the feedback step **752** comprises the base stations **701** and **702** relaying the channel state information **715** and **716** to the at least one central processor **710**.

In step **753**, the central processor **710** calculates distributed antenna system weights w_1 and w_2 **753** based on the channel state information **715** and **716**. In a cooperative-MIMO demultiplexing step (not shown), the weights can be used to demultiplex interfering data streams (not shown) in the uplink channels between the UEs **700** and base stations **701** and **702** routed to the central processor **710**.

Cooperative-MIMO multiplexing provides for employing the distributed antenna system weights for pre-coding data D to be transmitted to each UE **700**. For example, weight vectors w_1 and w_2 are used to pre-code a data matrix, and the pre-coded data signals **717** and **718** are routed to their respective base stations **701** and **702**. The base stations **701** and **702** transmit signals **719** and **720** comprising the pre-coded data to the UEs **700**.

As illustrated in FIG. **8**, software developed in accordance with aspects of the invention may comprise functionality that is separable into multiple independent and interchangeable modules. In some aspects, a module may comprise a software object. In some applications, a module may comprise a container that contains other objects. While the scale of a module may vary depending on the programming language and the application, modules are typically designed to perform logically discrete functions and interact via well-defined interfaces. It should be appreciated that in some aspects of the disclosure, modules can comprise data objects, and such data objects reside in physical memory of a computing device and can comprise executable instructions stored in memory that cause a processor to execute steps that give rise to the disclosed functionality as described below.

FIG. **8** comprises pseudo-code that depicts data structures and processing functions that can be implemented by a computer processor programmed to perform methods in accordance with aspects of the invention, including methods disclosed in the '850 application. An object, such as a virtual array object, V_array **840**, can comprise methods and data structures that package distributed-array assets (e.g., antenna systems of different base transceivers, radio signal processors associated with those antenna systems, baseband signal processing systems in the base transceivers and/or in the central processor(s), and front-haul networks) in a manner that conceals certain details. For example, the V_array object **840** may comprise a private section **850** in which a combination of data structures and functions can only be accessed within the object **840**. By way of example, objects Bts **851** and Fronthaul **852** are private members. Private data structures and functions can conceal implementation details of the object's **840** interface (e.g., how Public functions are implemented and how Public data structures are created).

The virtual antenna array object **840** includes an implementation, which is typically expressed by one or more

functions, such as functions **862-866**. The implementation contains the working code that corresponds to the elements declared in the interface, such as the Antenna object **861**. Functions **862-866** may call other functions which may be internal and/or external to the object **840**. By way of example, function f_select_ue(. . .) **862** selects UEs based on some predetermined quality factor, such as disclosed in the '850 application. Function f_select_antenna(. . .) **863** selects antennas in the array to serve a particular UE, such as disclosed in the '163 application. Function f_csi(. . .) measures channel state information for each antenna/UE combination, such as disclosed in the '850 application. Function f_mux(. . .) provides for spatial multiplexed transmission of pre-coded data across the array of antennas (which may reside on multiple geographically distributed base stations), such as disclosed in the '850 application. Function f_rx(. . .) receives data from a predetermined set of antennas residing on multiple geographically distributed base stations, such as disclosed in the '850 application.

In one aspect of the invention, each Antenna object **861** is associated with an antenna on a base transceiver station (indicated by the Bts object **851**), so the virtual antenna array can include antennas associated with different base stations, such as disclosed in the '850 application. The base transceiver stations can be connected to a central processor via a fronthaul network, such as disclosed in the '850 application. Thus, the virtual array object **840** can comprise one or more Fronthaul objects **852** associated with communications between the Antenna objects **861**.

In some aspects of the invention, the virtual antenna array object **840** conceals information related to its antenna elements being distributed across multiple base transceivers (and/or UEs). For example, in some aspects, the virtual antenna array object **840** conceals information about fronthaul networks communicatively coupling signals between the antenna elements and signal processors (such as baseband processors, including MIMO processors). Thus, each virtual antenna array object **840** can conceal network communications within an object-oriented interface.

In accordance with some aspects of the invention, the virtual antenna array object **840** is part of a distributed control environment that provides services, such as access, interaction, and control of base transceiver antennas in a network of geographically distributed base transceivers.

A module interface expresses the data and/or functional elements that are provided and required by the module. For example, the virtual antenna array object **840** could receive as its input an element indicating a particular UE. Thus, a virtual antenna array could be created for each UE. The elements defined in the interface are usually detectable by other modules. In one aspect of the invention, quality factors and signal strength are some of the parameter by which physical antennas distributed across multiple base transceivers can be selected for inclusion in the virtual antenna array object **840**. In some aspects, a quality factor or signal strength comprises a measurement of a known training signal. Elements may comprise various data structures, such as lists, arrays, queues, stacks, and other objects. Each data structure has associated operations that may be performed on it and pre-conditions and constraints on the effects of those operations.

Once a virtual array object **840** is created, it may be passed as an argument to another module, such as a multi-user MIMO object, Mu_mimo **810**. For example, function calls **801** and **802** access functional elements **822** and **821**, respectively, in the Mu_mimo object's **810** interface **820**. In some aspects, arguments in the function calls **801** and **802** can comprise function calls in the V_array object's **840** interface.

The f_precode(. . .) function **821** employs channel state information (csi) to generate a set of antenna array weights (such as via a private function, f_weight(. . .) **831**). The weights are used by function **821** to pre-code a data set (tx_data) to produce pre-coded data (precoded_data). The pre-coded data can then be transmitted by the f_mux(. . .) function **865** in the same virtual array object **840** used by the f_precode function **821**. Thus, in accordance with some aspects of the invention, the f_precode function **821** can perform multi-user MIMO pre-coding for an array of geographically distributed antennas. The f_demux(. . .) function **822** processes channel state information (csi) and received data (rx_data) from the virtual antenna array **840** to demultiplex the received data.

In the uplink, MIMO receiver processing techniques can be used to efficiently exploit the spatial dimensionalities of the MIMO channel to increase WWAN capacity. In aspects of the invention, from an algorithmic perspective, there is no discernible difference in processing a plurality of different transmissions from a single UE configured for MIMO versus processing one signal from each of a plurality of different UEs configured only for Single Input, Multiple Output (SIMO). Similarly, in some aspects of the invention in which fronthaul latency is either negligible or compensated for, there is no algorithmic difference in MIMO receiver processing whether the receiving array comprises antennas employed on multiple base transceiver stations or an antenna array on a single base transceiver station. In the downlink, in some aspects of the invention in which fronthaul latency is either negligible or compensated for, there is no algorithmic difference in MIMO transmitter processing whether the transmitting array comprises antennas employed on multiple base transceiver stations or an antenna array on a single base transceiver station. For these reasons, at least some implementation details of the virtual array object **840** can be concealed from the multi-user MIMO object **810**.

A MIMO system employs multiple (N_T) transmit antennas and multiple (N_R) receive antennas for data transmission. A MIMO channel formed by the N_T transmit and N_R receive antennas may be decomposed into N_C independent channels, wherein $N_C \leq \min\{N_T, N_R\}$. Each of the N_C independent channels is also referred to as a spatial subchannel (or subspace channel) and corresponds to a dimension. In one common MIMO system implementation, the N_T transmit antennas are located at and associated with a single transmitter system, and the N_R receive antennas are similarly located at and associated with a single receiver system. A Cooperative-MIMO system can be effectively formed for a multiple access communication system having a set of base transceiver stations communicatively coupled together and coordinated to concurrently communicate with a number of UEs. In this case, each base transceiver station and each terminal can be equipped with one or more antennas. A Cooperative-MIMO system can be effectively formed for a multiple access communication system having a multiple UEs communicatively coupled together and coordinated to concurrently communicate with at least one base transceiver station. In this case, the base transceiver station is typically equipped with multiple antennas and each terminal can be equipped with one or more antennas. However, if geographically distributed base transceiver stations are employed, each base transceiver station can be equipped with one or more antennas.

The wireless links between the distributed base transceiver station antennas and the UE antennas are modeled as a complex channel matrix H of dimensions $K \times N_T$, where K is the aggregate number of UE antennas and N_T is the number of distributed antennas. H_{DL} is the DL channel matrix and H_{UL} is the UL channel matrix. Channel reciprocity holds if DL and UL are set to the same carrier frequency:

$$H_{DL}=H_{UL}^{T}=H$$

where the superscript symbol, "^{T}", denotes the transpose matrix operation.

In one aspect of the invention, channel estimation is initiated with transmission of a training signal by each of the antennas of a plurality N of base stations. Assuming M antennas per base station, there are N·M training signal transmissions.

Each UE receives each training signal through each of its antenna(s) and frequency down-converts the training signal to baseband, where it is digitized and processed. Signal characterization logic, such as represented by function f_csi(. . .) **864** characterizes the channel from the received training signal (e.g., identifying phase and amplitude distortions, such as in the case of a flat fading channel, or calculating a channel impulse response) and stores the characterization in memory. Some aspects of this characterization process are similar to that of prior-art MIMO systems, with a notable difference being that the each UE only computes the characterization vector for its own antenna(s) rather than for all K antennas, and each UE is configured to perform channel characterization from training signals transmitted from multiple base transceiver stations. In other aspects of the invention, function f_csi(. . .) **864** characterizes the channel from training signals transmitted by the UEs. Thus, function f_csi(. . .) **864** may reside on the base transceiver stations and/or the central processor. In accordance with some aspects of the invention, software objects, and even components with software objects disclosed herein may reside on multiple devices, including UEs, base transceiver stations, and central processors.

In accordance with one aspect of the invention, each UE produces a sub-matrix of a full cooperative-MIMO channel matrix H. For example, if a UE has one antenna (or it has multiple antennas and a combining system that combines signals received by the multiple antennas), then a channel estimate corresponding to a training signal transmitted by one antenna of one of the base stations is an element of a $1 \times N_T$ vector, where N_T is the total number of base station antennas, expressed by $N_T=\Sigma_{n=1}^{N} M_n$, where N is the number of base stations, and M_n is the number of antennas corresponding to an nth base station. In some aspects, a channel estimate comprises a complex-valued flat-fading coefficient. In some aspects, a channel estimate comprises a matrix, such as an impulse response vector.

In accordance with an aspect of the invention, a first UE having a single antenna generates a $1 \times N_T$ vector of channel characterization data: $[H_{1,1}, H_{1,2}, \ldots, H_{1,N_T}]$. A second UE having a single antenna generates a $1 \times N_T$ vector of channel characterization data: $[H_{2,1}, H_{2,2}, \ldots, H_{2,N_T}]$. A kth UE having a single antenna generates a $1 \times N_T$ vector of channel characterization data: $[H_{k,1}, H_{k,2}, \ldots, H_{k,N_T}]$. This channel characterization data can be a data set (e.g., csi) within the V_array object **840**.

Based on channel conditions and/or proximity of a UE to each base station, a particular set of base stations may be selected to serve the UE. For example, this selection process may be performed by the f_select_antenna(. . .) function **863**. Thus, one or more UEs may be assigned to a subset of the total number of base stations. In such instances, values of the channel characterization data corresponding to a non-serving base station relative to a UE may equal zero. In some cases, certain values of the full cooperative-MIMO channel matrix H, such as matrix elements corresponding to indices of non-serving base station antennas relative for a particular UE, may be set to zero

In some aspects of the invention, a kth UE comprises multiple N_k antennas configured to perform MIMO. For each UE's antenna, a channel estimate corresponding to a training signal transmitted by one antenna of one of the base stations is an element of a $1 \times N_T$ vector. Thus, the kth UE can generate an $N_k \times N_T$ submatrix of the full cooperative-MIMO channel matrix H.

The UEs upload their channel characterization sub-matrices to the base stations via the WWAN, and the sub-matrices are communicated to the central processor via the fronthaul network. Thus, in some aspects, the f_csi(. . .) function **864** can comprise components distributed across UEs, base stations, and one or more central processors. As the central processor collects the channel characterization sub-matrices, they are stored as the full $K \times N_T$ cooperative-MIMO channel matrix H, where K is the total number of UE antennas and N_T is the total number of base station antennas.

Since each UE is an independent device, each UE often receives its own unique data stream. Thus, in some aspects of the invention, the central processor sources multiple data streams and routes them as separate data streams intended for each UE. In order to do this, the central processor comprises precoding logic for precoding the signals transmitted from each antenna of each of the base stations based on the signal characterization matrix H. In one aspect of the invention, the pre-coding logic is implemented via one or more software instructions, such as the f_precode(. . .) function **821** in the Mu_mimo object **810**. The central processor then routes the precoded_data (or the precoding weights and data symbols) to the plurality of base stations. Routing can be part of the f_precode(. . .) function **821**, or it can comprise a separate function call. Thus, each base station antenna is configured to transmit a subspace-coded data sequence which is a function of the data symbols and the channel matrix H.

In one aspect of the invention, cooperative MIMO improves the uplink communications (i.e., the link from the UEs to the Base Stations). In this aspect, the channel from each UE is continually analyzed and characterized by uplink channel characterization logic residing in each base transceiver station or central processor, which may be implemented by the f_csi(. . .) function **864**. For example, each UE may transmit a training signal, which the channel characterization logic analyzes (e.g., as in a typical MIMO system) to generate the channel characterization matrix H.

As described throughout the '163 application, the '854 application, and the '107 application, all of which are incorporated by reference in their entireties, various spatial processing techniques may be employed. Such processing techniques may be included within the f_precode **821** and f_demux **822** functions.

In one aspect of the invention, f_demux **822** performs linear spatial processing on the received signals (for a non-dispersive MIMO channel with flat fading) or space-time processing on the received signals (for a dispersive MIMO channel with frequency selective fading). The spatial processing may be achieved using linear spatial processing techniques such as a channel correlation matrix inversion technique, a minimum mean square error (MMSE) technique, and others. These techniques may be used to null out

the undesired signals and/or to maximize the received SNR of each of the constituent signals in the presence of noise and interference from the other signals. The space-time processing may be achieved using space-time processing techniques such as an MMSE linear equalizer, a decision feedback equalizer (DFE), a maximum-likelihood sequence estimator (MLSE), and others. In some aspects, iterative cancellation techniques, such as successive interference cancellation may be employed.

In some aspects of the invention, f_precode **821** performs directive and/or retro-directive techniques for calculating antenna array weights for transmission in a distributed antenna system. Such techniques are disclosed in the '163 application. In some aspects of the invention, as disclosed in the '187 application, eigenvalue-decomposition approaches, such as singular value decomposition, may be employed for transmitter spatial processing.

For example, a MIMO channel formed by the N_T transmit antennas comprising multiple transmission nodes (e.g., base stations) and N_R receive antennas comprising multiple UEs can be characterized by an $N_R \times N_T$ channel response matrix H for each OFDM subband, wherein each matrix element $h_{i,j}$ of H denotes coupling or complex channel gain between transmit antenna j and receive antenna i. For simplicity, the MIMO channel is assumed to be full rank with $S=N_T \leq N_R$.

For data transmission with eigensteering, eigenvalue decomposition can be performed on a correlation matrix of H to obtain S eigenmodes of H, as follows:

$$R=H^H \cdot H=E \cdot \Lambda \cdot E^H,$$

where R is a correlation matrix of H; E is a unitary matrix whose columns are eigenvectors of R; Λ is a diagonal matrix of eigenvalues of R; and "^{H}" denotes a conjugate transpose.

A unitary matrix U is characterized by the property $U^H U=I$, where I is the identity matrix. The columns of a unitary matrix are orthogonal to one another, and each column has unit power. The matrix E is also called an "eigenmode" matrix or a "transmit" matrix and may be used for spatial processing by the central processor to transmit data on the S eigenmodes of H. The eigenmodes may be viewed as orthogonal spatial channels obtained through decomposition. The diagonal entries of Λ are eigenvalues of R, which represent the power gains for the S eigenmodes. The eigenvalues in Λ may be ordered from largest to smallest, and the columns of E may be ordered correspondingly. Singular value decomposition may also be performed to obtain matrices of left and right eigenvectors, which may be used for eigensteering.

For data transmission with eigensteering, the transmitting entity may perform spatial processing for each subband as follows:

$$z=E \cdot s,$$

where s is a vector with up to S data symbols to be sent on a particular subband; and z is a vector with N_T spatially processed symbols for the subband. In general, D data symbols may be sent simultaneously on D (best) eigenmodes of H for each subband, where $1 \leq D \leq S$. The D data symbols in s are spatially processed with D columns of E corresponding to the D selected eigenmodes.

For data transmission with a spatial spreading matrix, such as a CI spatial spreading matrix, the transmitting entity may perform spatial processing for each subband as follows:

$$z_{ss}=V \cdot s$$

where V is a spatial spreading matrix for the subband; and z_{ss} is a vector with up to N_T spread symbols for the subband. Each data symbol in s is multiplied with a respective column of V to obtain up to N_T spread symbols.

In general, D data symbols may be sent simultaneously on each subband with matrix spreading, where $1 \leq D \leq S$. The D data symbols in s may be multiplied with a $N_T \times D$ spreading matrix V(k) to obtain N_T spatially processed symbols for z_{ss}. Each spatially processed symbol for each subband includes a component of each of the D data symbols being sent on the subband. The N_T spatially processed symbols for each subband are then transmitted on the S spatial channels of H.

As disclosed throughout the '187 application, any of various water-filling or water-pouring schemes may be employed to optimally distribute the total transmission power over the available transmission channels, such as to maximize spectral efficiency. For example, water-filling can be used to adapt individual UE transmission powers such that channels with higher SNRs are provided with correspondingly greater portions of the total transmit power. A transmission channel, as defined herein, may include a spatial (e.g., a sub-space) channel, a space-frequency channel, or some other channel defined by a set of orthogonalizing properties. Similarly, water filling may be used at a physically connected (i.e., wired) antenna array. The transmit power allocated to a particular transmission channel is typically determined by some predetermined channel-quality measurement, such as SNR, SINR, BER, packet error rate, frame error rate, probability of error, etc. However, different or additional criteria may be employed with respect to power allocation, including, but not limited to, UE battery life, load balancing, spatial reuse, power-control instructions, and near-far interference.

The modulation and channel coding for each transmission channel may be adapted with respect to the corresponding SNR. Alternatively, transmission channels may be grouped with respect to their data-carrying capability. Thus, groups of transmission channels may share common modulation/coding characteristics. Furthermore, transmission channels having particular SNRs may be used for particular communication needs. For example, voice communications may be allocated to channels having low SNRs, and thus, data-carrying capabilities. In some cases, transmission channels that fail to achieve a predetermined threshold SNR may be eliminated. In one embodiment of the invention, water filling is employed such that the total transmission power is distributed over selected transmission channels such that the received SNR is approximately equal for all of the selected channels.

In accordance with some aspects of the invention, hardware systems, such as UEs, base transceiver stations, and central processors, can include a processing element capable of executing processing threads or tasks.

As depicted in FIG. **9**, a UE can include a controller, such as at least one computer or data processor **910**, at least one non-transitory computer-readable memory medium embodied as a memory **920** that stores a program of computer instructions **921**, and at least one suitable radio frequency (RF) transmitter/receiver **901** for bidirectional wireless communications with multiple base transceiver stations via one or more antennas **905**.

As depicted in FIG. **10**, a base transceiver station includes a controller, such as at least one computer or a data processor **1012**, at least one computer-readable memory medium embodied as a memory **1014** that stores a program of computer instructions **1016**, and at least one suitable RF transceiver **1002** for communication with the UEs via one or more antennas **1001.1**-**1001.**N_M. The base transceiver station is coupled via a fronthaul transceiver **1020** to a data and

control path to the central processor, such as a network control element. In one aspect of the invention, the fronthaul may be implemented as an S1 interface. In another aspect, the fronthaul may comprise an X2 interface. In another aspect, the fronthaul can comprise a direct eNodeB internal interface (e.g., optical fiber connection) such as a connection between a radio remote head and an eNodeB.

Thus, there is some central unit where several base transceiver stations are connected as such, with the goal being that the base transceiver stations (e.g., transmission points, macro eNodeBs, etc.) are centrally controlled together. The control can be at the location of a macro eNodeB, but could also be at a different location.

As depicted in FIG. **11**A, a central processor, such as a network control element, comprises a controller, such as at least one computer or a data processor **1112**, at least one computer-readable memory medium embodied as a memory **1114** that stores a program of computer instructions **1116**, and at least one fronthaul transceiver **1120** coupled to a data and control path (i.e., a fronthaul network) between the central processor and multiple base transceiver stations.

At least one of the programs **921**, **1016**, and **1116** is assumed to include program instructions that, when executed by the associated computer processor(s), enable the corresponding device(s) to operate in accordance with the exemplary aspects of the invention.

The '163 application discloses SDR platforms that enable dynamic implementations of a full protocol stack, including Physical-layer processing. Some aspects are disclosed in the context of software-defined networks, such as to enable more dynamic organization of resources. Disclosed software radio implementations include instantiations of virtual base stations.

In some disclosed aspects, software radio provides associated control operations, such as identifying a particular transmission protocol used by a particular device, reserving channels for transmission, monitoring channel use (including channel reservation and channel release), requesting data transmissions and/or state information from remote devices, attaching tags to data streams for identification and/or access control, and providing instructions to remote transceivers to adjust or control processing, transmit status information, and/or identification.

By way of example, and with respect to implementing base transceiver station processing in a central processor or in a distributed computing system, a software-defined radio in accordance with one aspect of the invention can provide a base station instantiation for a UE. Specifically, the software-defined radio can perform base station processing functionality in combination with Cooperative-MIMO subspace processing to use a plurality of geographically distributed base transceiver stations that communicate with the UE via the radio access network. In an LTE network, this means that the software-defined radio implements a virtual eNodeB to support the LTE protocol stack for that user while providing for subspace coding to support spatial multiplexing.

In one aspect, when a UE joins the network, the SDR might provide for requesting identification, performing channel reservation, and requesting state information (e.g., channel state information) from the UE. The combination of software-defined radio and Cooperative-MIMO implemented with virtualized base station processing via the central processor or even distributed (e.g., cloud) computing enables each UE to be served independently of other UEs concurrently employing the same spectrum, and possibly using the same base transceiver station hardware. This is because Cooperative-MIMO subspace processing enables multiple non-interfering subspace channels in the same spectrum to be used by each UE, even closely spaced UEs, which can eliminate the need for other multiple access partitioning of the spectral resource (such as via TDMA, OFDMA, CDMA, etc.). When the UE ends its connection with the network, the SDR releases the channel and its instantiated virtual base station.

In accordance with some aspects, consolidation of processing from multiple base stations to a central processor (e.g., an offsite data center) constitutes a virtual base station that employs multiple antennas of different base transceiver stations and remote (and possibly software-defined) base station processing. Further aspects distribute the base station processing over multiple processing cores via distributed (e.g., cloud) computing. As disclosed in the '163 application, multiple different transmission protocols may be employed simultaneously. Thus, SDR instances (e.g., virtual base stations) employing different protocol stacks may coexist within the same software-defined radio and can be implemented concurrently within the same spectrum.

A CI-based software radio can extend adaptive link-layer techniques to the physical layer. This enables more efficient use of the spectrum by dynamically adjusting physical-layer characteristics to current channel conditions, network traffic, and application requirements. CI can significantly improve wireless network performance and functionality by adapting to different requirements for bandwidth, error rate, latency, link priority, and security.

Embodiments of a CI-based communication system may include interactive capabilities between the physical layer and higher layers such that a response to changing conditions and operational requirements can be directed to an appropriate physical-layer function. For example, a base station or central processor in a mobile wireless network can dynamically create channels (e.g., spatial multiplexing channels) depending on the number of mobile units in its coverage area and their service requirements. When additional units enter the area, the system can be reconfigured accordingly.

In ad-hoc networks, base station functions (e.g., routing, power control, synchronization, geo-location services, etc.) may be distributed among various devices. Aspects of the disclosure can also include adapting base-station and access-point functions to maintain link quality and perform load balancing (including managing power budgets for devices acting as routers and relays, managing system spectrum allocations, and/or adjusting cell boundaries to adapt to changing user demands, power budgets, and spectrum use). Thus, in some aspects, the super-array processing system **112** may include a power control **114.3**.

Bandwidth can be dynamically allocated to uplink and downlink channels depending on network traffic characteristics. Units requiring real-time or broadband services may be assigned to dedicated channels, whereas units having bursty data requirements may be assigned to a shared channel. Aspects of the invention can provide for combinations of time-domain and frequency-domain processing to produce signals having desired physical-layer characteristics.

SDRs disclosed in the '163 application are configured to provide for various signal processing objectives for implementing multiple-access protocols (e.g., DS-CDMA, TDMA, OFDM, MC-CDMA), channel coding, modulation (e.g., phase modulation, frequency modulation, amplitude modulation, time-offset modulation, etc., including different constellations (e.g., binary, M-ary), multiplexing (e.g.,

TDM, FDM, CDM), formatting (e.g., frame length, headers, payload length, etc.), source coding, providing for frequency agility (e.g., frequency hopping, variable aggregate bandwidth, frequency selectability, etc.), encryption, and/or sub-channel coding.

FIG. **11**B is a block diagram that depicts a cloud-based software-defined radio, such as disclosed in the '163 application. A plurality of hardware components (such as servers **1101** and **1102**) are communicatively coupled together via a network **1190**. Server **1101** comprises at least one processor (e.g., CPU **1161**) and at least one memory **1141**. Similarly, server **1102** comprises at least one processor (e.g., CPU **1162**) and at least one memory **1142**. A software-defined radio platform can comprise a plurality of signal-processing software components residing in one or more of the memories **1141** and **1142** of the hardware components, **1101** and **1102**, respectively. By way of example, SDRs **1151.1-1151**.*i* are stored in memory **1141**, and SDRs **1152.1-1152**.*j* are stored in memory **1142**. By way of example, the hardware components **1101** and **1102** may include a computer main frame or a workstation.

Although not shown, interfaces can couple the hardware components **1101** and **1102** together, such as via the network **1190**. Such interfaces disclosed in the '163 application include radio interfaces for a radio network. The network **1190** may comprise various types of networks, including a bus. Also disclosed in the '163 application is the concept of interfaces for the software components (e.g., **1151.1-1151**.*i* and **1152.1-1152**.*j*) as it relates to software design, such as object oriented design. Interaction and inter-connectivity between software and hardware interfaces is also contemplated for coupling together hardware and/or software components.

The SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j* may include local and/or remote computer programs configured to process signals, such as for various physical-layer signal processing, including baseband processing. For example, the SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j* may include one or more programs for performing digital signal processing. One or more of the SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j* may provide control signals to one or more hardware components such as to select, adapt, or otherwise reconfigure signal processing.

The memory can comprise various types of storage mediums (e.g., disk drive, tape drive, CR Rom, DVD, flash memory, or any other storage device) for storing application programs (e.g., the SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j*) and data. Hardware and/or the software may perform A/D conversion, as necessary. In some applications, modulation and/or demodulation may be performed digitally with any combination of software and hardware.

In one set of aspects of the invention, a software component (such as at least one of the SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j*) residing at a remote receiver location (e.g., a base transceiver station) receives signals transmitted in the radio access network, processes the received signals, and conveys some control information in the data stream (e.g., in a header or pilot channel) to hardware components residing in another location (e.g., at a central processor or another base transceiver station). Signal-processing operations may be distributed throughout a network in a way that balances processing loads and/or communication-resource (e.g., spectrum use) loads. Alternatively, in a Cooperative-MIMO network wherein UEs cooperate with a base transceiver station to perform joint processing for spatial multiplexing and/or demultiplexing signals, most of the signal processing may be performed by the base transceiver station (and/or the central processor) to reduce the cost and complexity (and power usage) of the UEs. As described with respect to centralized processing of base transceiver operations, RF processing is performed at each base transceiver station, and most or all of the baseband signal processing may be performed at a central processing facility.

In one set of aspects of the disclosure, software can be uploaded to a remote transceiver (e.g., base transceiver station) via one or more communication channels. This simplifies software updates and enhances signal-processing versatility of the network. In another set of aspects, software updates can be uploaded to a central processor (e.g., a cloud network organized by a central processor) where most or all of the baseband processing is performed.

Software-based radios can provide adaptability to different communication standards. The '163 application discloses various systems and techniques that can migrate many different transmission protocols to a common high-performance SDR platform that is suitable for all applications. In some aspects of the disclosure, the SDR platform can be configured to enable coexistence of different standard systems within the same spectrum. For example, the power emission, frequency band, or other configuration parameters of a legacy radio access network can be adjusted to accommodate the adoption of new transmission protocols while avoiding harmful interference with the legacy protocol.

As new wireless standards are developed to enhance data rate and coverage in the radio access network, the base transceiver stations and/or central processors can be updated to support those standards. In some aspects, only the central processor(s) needs to be updated. By way of example, the central processor may comprise distributed computing resources, such as multiple servers residing in one or more data centers. The servers may comprise hardware components of an SDR platform.

In one aspect, the base transceiver stations and/or central processors are SDRs equipped with programmable computational capability, such as FPGA, DSP, CPU, GPU, and/or GPGPU, configured to run algorithms for baseband signal processing in the radio access network. If the standard is upgraded, new baseband algorithms can be uploaded to the central processors and/or from the central processors to the base transceiver stations to reflect the new standard. This SDR feature allows for continuous upgrades to the radio access network, such as when new technologies are developed to improve overall system performance.

In one aspect of the disclosure, a cloud SDR network comprises a multi-user MIMO system implemented with cooperative-MIMO over a plurality of geographically distributed base transceiver stations communicatively coupled to a central processor. The central processor is configured to perform at least some of the baseband processing in the radio access network. In some aspects, the central processor and the base transceiver stations are configured to exchange information to reconfigure system parameters, such as to dynamically adapt to changing conditions of the radio access network, including the network architecture (such as described in the '187 application).

As disclosed with respect to coordinated multipoint systems with a central processor configured to perform cooperative MIMO, the base transceiver stations in a cloud SDR network can be configured to generate simultaneous non-interfering wireless links to serve different UEs with different multiple access techniques (e.g., TDMA, FDMA, CDMA, OFDMA, etc.) and/or different modulation/coding schemes. For example, if the base transceiver stations perform RF processing and the central processor performs just

baseband processing, the SDRs can be configured to perform baseband processing. Based on the active UEs in the radio access network and the standard(s) they use for their wireless links, the SDRs implemented by the central processor (such as SDRs in a distributed computing environment) can instantiate virtual base station processes in software, each process configured to perform the baseband processing that supports the standard(s) of its associated UE(s) while utilizing a set of the base transceiver stations within range of the UE(s).

In accordance with one aspect of the invention, baseband waveforms from multiple ones of the SDRs **1151.1-1151.***i* and **1152.1-1152.***j* are coupled into the Super-Array Processing System **112** depicted in FIG. **2**. The baseband waveforms are combined in the Spatial Multiplexing/Demultiplexing module **114.1** using Cooperative-MIMO subspace processing to produce multiple pre-coded waveforms. The routing module **114.2** sends the pre-coded waveforms over the fronthaul **105** to multiple ones of the base transceiver stations' **101.1-101**.N antennas **102.1-102**.M_1, **106.1-106**.M_2, and **104.1-104**.M_N. The base transceiver stations **101.1-101**.N can be coordinated to concurrently transmit the pre-coded waveforms such that the transmitted waveforms propagate through the environment and constructively interfere with each other at the exact location of each UE **120.1-120**.K. The coherent combining of these waveforms at the location of each UE **120.1-120**.K results in the synthesis of the baseband waveform that had been output by the SDR instance **1151.1-1151.***i* and **1152.1-1152.***j* associated with that UE **120.1-120**.K. Thus, all of the UEs **120.1-120**.K receive their own respective waveforms within their own synthesized coherence zone concurrently and in the same spectrum.

In accordance with one aspect of the invention, each UE's corresponding synthesized coherence zone comprises a volume that is approximately a carrier wavelength or less in width and centered at or near each antenna on the UE. This can enable frequency reuse between nearby—even co-located—UEs. As disclosed in the '107 application, the Spatial Multiplexing/Demultiplexing module **114.1** can be configured to perform maximum ratio combining. Any of various algorithms for MIMO processing disclosed in the '107 application may be employed by methods and apparatus aspects disclosed herein. In some aspects, the module **114.1** can perform zero forcing, such as to produce one or more interference nulls, such as to reduce interference from transmissions at a UE that is not an intended recipient of the transmission. By way of example, but without limitation, zero forcing may be performed when there are a small number of actual transmitters (e.g., base transceiver station antennas) and/or effective transmitter sources (e.g., scatterers in the propagation environment).

By way of example, FIG. **12** is a block diagram that depicts a central processor **1100** communicatively coupled via a fronthaul network **1240** to multiple base transceiver stations, such as base transceiver stations **1271** and **1272**. Each base transceiver station **1271** and **1272** comprises a WWAN transceiver **1202** and **1203**, respectively, and baseband processor **1212** and **1213**, respectively. WWAN transceiver **1202** comprises a number N_1 of WWAN transceiver antennas **1204.1-1204**.N_1, and WWAN transceiver **1204** comprises a number N_M of WWAN transceiver antennas **1205.1-1205**.N_M. The baseband processor **1212** comprises a computer processor **1214** and a memory **1216**. The baseband processor **1213** comprises a computer processor **1215** and a memory **1217**. In accordance with some aspects of the disclosure, the baseband processors **1212** and **121** comprise Channel State Information processing logic **1218** and **1219**, respectively, and Channel State Information routing logic **1220** and **1221**, respectively. Each base transceiver station **1271** and **1272** comprises a fronthaul transceiver **1230** and **1231**, respectively, communicatively coupled via the fronthaul network to the central processor **1100**.

In accordance with some aspects of the disclosure, Channel State Information processing logic **1218** and **1219** can collect channel information uploaded by the UEs (not shown) and/or determine channel state information from measurements of training signals transmitted by the UEs (not shown). Channel State Information routing logic **1220** and **1221** can route channel state information to at least one central processor, such as the central processor **1100**.

In some aspects of the disclosure, the central processor **1100** comprises Channel State Information processing logic **1126**, Pre-coding logic **1136**, and Base Station Routing logic **1146**. In one aspect, computer software, such as logic **1126**, **1136**, and **1146**, comprises instructions stored on a non-transitory computer-readable medium (e.g., memory **1114**), that when executed on the processor **1112**, perform the steps of storing the WWAN channel state information received from the base transceiver stations (e.g., base transceiver stations **1271** and **1272**) based on the WWAN channel state information and/or at least one quality metric that characterizes each communication link between a base transceiver station and a UE; and selecting a plurality of antennas residing on multiple base transceiver stations to provide a set of distributed antennas. For example, a set of distributed antennas can be selected to serve each UE. Next, the processor **1112** calculates subspace processing weights from each UE's channel state information for the each UE's corresponding set of distributed antennas. The corresponding instructions can be in the Pre-coding logic **1136** and/or in subspace demultiplexing logic (not shown). The processor **1112** coordinates each UE's corresponding set of distributed antennas to communicate in the WWAN via the fronthaul network. For example, the corresponding instructions for coordinating the distributed antennas can be in the Base Station Routing logic **1146**. The central processor **1100** provides for performing at least one of subspace multiplexing of WWAN signals transmitted by each set of distributed antennas and subspace demultiplexing signals received by each set of distributed antennas.

The exemplary aspects of the disclosure may be implemented, at least in part, by computer software executable by the data processor **910** of the UEs (such as the UE shown in FIG. **9**), the data processor **1012** of the base transceiver stations (such as the base transceiver station shown in FIG. **10**), by the data processor **1112** of the central processor (such as the central processor shown in FIG. **11**A), by multiple data processors in a distributed computing system (not shown), and/or by hardware, or by a combination of software, hardware, and firmware.

In accordance with one aspect of the invention, subspace multiplexing is provided by the Pre-coding logic **1136** configured to produce pre-coded subspace (i.e., spatial multiplexing) weights and to encode data with the weights, and the Base Station Routing logic **1146** configured to route the encoded data to the base transceiver stations for transmission to the UEs. In accordance with another aspect of the invention, subspace demultiplexing is provided by the Base Station Routing logic **1146** configured to route UE uplink signals received by the base transceiver stations to the central processor **1100** and the subspace demultiplexing logic (not shown) configured to produce subspace demultiplexing weights based on the channel state information and

to de-multiplex (i.e., decode) the received signals. Thus, performing at least one of subspace multiplexing of WWAN signals transmitted by each set of distributed antennas and subspace demultiplexing signals received by each set of distributed antennas enables multiple UEs to employ simultaneous interference-free same-band communications.

In accordance with some aspects of the invention, certain features, such as pre-coding logic and subspace demultiplexing logic, can comprise an Application Programming Interface (API) or library that defines functionalities that are independent of their respective implementations, which allows definitions and implementations to vary without compromising each other. By way of example, and without limitation, APIs provided for base station network control can enable MIMO processing applications to operate on an abstraction of the network, such as by exploiting distributed antenna array systems and coordinated base station operations and capabilities, without being tied to the details of their implementation.

In accordance with some aspects of the disclosure, the steps of selecting antennas on multiple base transceiver stations for MIMO processing and coordinating the multiple base transceiver stations for cooperative-MIMO communications (which includes routing communication signals to and/or from the multiple base transceiver stations as part of a cooperative subspace processing operation) tie the mathematical operation (i.e., multi-user MIMO subspace processing) to specific and measurable operational benefits (i.e., based on measurable physical phenomena), such as the ability to improve WWAN performance (e.g., spectral efficiency, number of subspace channels, data rate per user, number of users supported, SNR, BER, etc.).

These steps add significantly more to MIMO processing than mere computer implementation. By employing steps, such as selecting multiple base transceiver stations to simultaneously serve each UE in a MIMO subspace processing operation, coordinating the selected multiple base transceiver stations to perform in a subspace multiplexing and/or demultiplexing process, and provisioning at least one central processor to perform subspace multiplexing and/or demultiplexing of signals transmitted by and/or received from the selected multiple base transceiver stations, the corresponding aspects of the invention go beyond the mere concept of simply retrieving and combining data using a computer.

In accordance with the disclosure, the various data processors, memories, programs, transceivers, and interfaces, such as depicted in FIGS. **9**, **10**, **11**, and **12**, can all be considered to represent means for performing operations and functions that implement the disclosed non-limiting aspects and embodiments.

The computer-readable memories (e.g., memories **920**, **1014**, **1114**, **1216**, and **1217**) may be of any type suitable to the local technical environment and may be implemented using any suitable data storage technology, such as semiconductor based memory devices, random access memory, read only memory, programmable read only memory, flash memory, magnetic memory devices and systems, optical memory devices and systems, fixed memory and removable memory. The computer processors (e.g., computer processors **910**, **1012**, **1112**, **1214**, and **1215**) may be of any type suitable to the local technical environment, and may include one or more of general purpose computers, special purpose computers, microprocessors, digital signal processors (DSPs) and processors based on multi-core processor architectures, as non-limiting examples.

In accordance with aspects of the invention depicted and described in the '163 application, FIG. **13**A illustrates a subspace processing method configured in accordance with some aspects of the invention. A data-sequence vector u having length N is provided to a transmit filter **1301** before being coupled into a communication channel **99**. The channel **99** acts on a transmitted data vector x via an N×N non-singular matrix H and an additive noise vector n having a variance of $N_o/2$. A signal vector y received from the channel **99** is expressed by:

$$y=Hx+n$$

The received signal vector y is processed by a matched filter **1302** to generate an output signal vector z, which is expressed by:

$$z=R_f x+n'$$

where $R_f=H^*H$ and $n'=H^*n$. An estimate of x given z is expressed by:

$$\tilde{x}=R_b z+e$$

where $R_b^{-1}=R_f+(N_o/2)R_{xx}^{-1}$, R_{xx} is the covariance of x, and e is the MMSE error. Additional processing, such as any of various adaptive feedback techniques, may be incorporated at the receiver end.

Although sub-space processing is commonly associated with array processing, the '163 application also discloses coding and decoding based on sub-space processing techniques. For example, as a signal is routed from one node to at least one other node in a network, algebraically unique linear codes are applied to the data for each "hop." In one set of embodiments, sub-space processing and CI methods can be combined. Sub-space processing can include frequency-diversity interferometry and/or interferometry between one or more sets of diversity-parameter values including, but not limited to, polarizations, codes, modes, phases, and delays.

As disclosed in the '163 application, FIG. **13**B illustrates a subspace processing method that employs decision feedback. In this case, Cholesky factorization provides:

$$R_f=G^*S_oG$$

where S_o is a diagonal matrix and G is a monic, upper-diagonal matrix. A decision feedback equalizer includes a feed-forward filter **1303**, a decision system **1304**, and a feedback filter **1305**. An exemplary decision feedback equalization algorithm is represented by:

$$\tilde{z} := S_o^{-1}G^{-*}H^*y$$

for $k = 0, N-1$

$$\hat{x}_{N-k} := \text{decision}\left(\tilde{z}_{N-k} - \sum_{i=1}^{k} g_{N-k,N-k+i}\hat{x}_{N-k+i}\right)$$

end

where g_{ij} are elements of G, and $\hat{x}_i$ and $\hat{z}_i$ are elements of $\hat{x}$ and $\hat{z}$ respectively.

A decision feedback equalizer may reorder the received substreams by rearranging the rows and columns of H. For example, a layered processing approach may be employed. Symbols are detected sequentially and interference from previously detected symbols is subtracted. Received vector elements are weighted to null (or reduce) interference from undetected symbols.

Method and apparatus implementations of radio transceivers in accordance with aspects of the disclosure, such as radio transmission techniques and radio transmitters employed by UEs and/or base transceiver stations, are

depicted in the block diagram of FIG. **14**A. The blocks disclosed herein can be steps of a method, functional blocks of a transmitter and/or transmitter system, and/or components of a transmitter and/or transmitter system. In some aspects of the disclosure, such as disclosed in the '850 and '163 applications, a transmitter's components can reside on different devices, such as on different network devices communicatively coupled together via a network.

An exemplary aspect of the disclosure provides for OFDM signaling. An information signal s(t) is encoded and/or interleaved in block **1401**. Various types of coding that are known in the art can be employed. For example, in the uplink, it can be desirable to produce a transmission signal with low dynamic range (i.e., peak to average power). Thus, the UEs can employ CI coding on OFDM subcarriers to produce CI-OFDM (also known as a single-carrier OFDM) signals.

The coding/interleaving block **1401** can provide for generating or otherwise acquiring symbol values to be impressed onto the subcarriers. The information signal can be provided with predetermined training symbols in a training symbol injection block **1402**. Training symbols can be used for various purposes, including, but not limited to, channel estimation, signal-quality estimation, and synchronization.

An IFFT **1403** (or equivalent process) impresses the coded data symbols onto the subcarriers and adds a cyclic prefix. FIR filtering and interpolation **1404** is performed prior to preparing the resulting signal for transmission into a communication channel, typically via an RF front end (not shown).

Various methods and systems adapted to perform the blocks shown in FIG. **14**A can be provided by transmission systems and methods pertaining to the aspects and embodiments of the disclosure. Furthermore, various other signal-processing steps that are typically performed in radio transmitters may be included herein. For example, pre-equalization steps and/or systems may be included in the transmission methods and transmitters disclosed herein.

As described throughout the disclosure, array processing may be performed in transmitters and in transmission methods. Array processing (e.g., subspace multiplexing) can be performed after FIR filtering and interpolation **1404**. In some aspects, array processing can be integrated into the coding **1401**, IFFT **1403**, and/or FIR filtering **1404** blocks.

As used herein, RAN baseband processing is the Physical Layer processing of baseband signals, such as digital baseband signals that will be transmitted in the RAN (after DAC and up-conversion), and digitized baseband signals produced from received radio signals in the RAN. RAN baseband processing is distinguished from IP processing in that RAN baseband processing is particular to the RAN. By way of example, FIR filtering **1404**, modulation (e.g., IFFT **1403**), and training signal injection **1402** are RAN baseband processes. Coding **1401** can include Physical Layer and/or higher layers. For example, forward-error correction (FEC) is often employed by the data link layer or higher. It should be appreciated that RAN baseband processing includes RAN multiple access and RAN spread spectrum coding, but not transcoding. Interleaving **1401**, as it pertains to distributing data symbols over a physical resource (e.g., multiplexing data symbols on selected bins of a discrete Fourier transform) constitutes RAN baseband processing, whereas interleaving data bits in a data stream does not. Many base station network coordination processes, such as scheduling, handover, routing, power control, and control signaling, are not RAN baseband processing operations. While channel estimation is a RAN baseband processing operation, conveying channel estimates, SNRs, or BERs between base stations is not. While multiple access and multiplexing (i.e., generating the physical signals wherein data is partitioned by time interval, frequency, code space, etc.) constitutes RAN baseband processing, assigning network resources to UEs does not.

Method and apparatus implementations of radio transceivers in accordance with aspects of the disclosure, such as radio reception techniques and radio receivers employed by UEs and/or base transceiver stations, are depicted in the block diagram of FIG. **14**B. The blocks disclosed herein can be steps of a method, functional blocks of a receiver and/or receiver system, and/or components of a receiver and/or receiver system. In some aspects of the disclosure, such as disclosed in the '850 and '163 applications, a receiver's components can reside on different devices, such as on different network devices communicatively coupled together via a network.

Signals received from a communication channel are input to an FIR filtering and decimation block **1405**. Filtered signals may be processed in a synchronization step **1411** to control the timing of various reception processes, such as, but not limited to, a cyclic prefix removal and fast Fourier transform (FFT) step **1406** and array processing **1407**. Complex-amplitude measurements associated with individual subcarriers, such as estimates obtained via known training symbols and/or unknown data symbols, may be used in a channel-estimation step **1413**.

The channel estimation step **1433** can facilitate the generation of weights (e.g., array-processing and/or CI combining weights).

Array processing **1407** is performed to achieve some preferred combination of system capacity (e.g., subspace demultiplexing) and signal quality (e.g., diversity combining). For example, array processing **1407** may include spatial interferometry multiplexing and/or any other form of array processing. In some aspects, array processing **1407** may be assisted by an interference-estimation step **1416**. CI combining **1418** may be performed in conjunction with the array-processing **1407** and/or a decoding and de-interleaving **1408**. Alternatively, either or both the array-processing **1407** and the decoding and de-interleaving **1408** may perform CI combining **1418**. The decoding and de-interleaving step **1408** performs any necessary de-interleaving of data symbols received from the array-processing **1407** prior to, or following decoding **1408**. Decoding **1408** can include channel, multiple access, spread spectrum, encryption, and/or other decoding processes.

FIG. **15** is a block diagram of a transceiver in accordance with some aspects of the disclosure. A receiver system **1501** is configured to couple a received signal from a communication channel. One or more typical receiver-side signal processing techniques (such as filtering, mixing, down conversion, amplification, A/D conversion, etc.) may be performed on the received signal. A filter bank, such as an FFT **1502**, separates the received signal into a plurality of frequency components. If the received signal is an OFDM signal, the FFT **1502** retrieves a symbol measurement for each OFDM subcarrier. The components are provided with weights in a receiver weighting system **1503**. The weights may include one or more types of weights, such as channel-compensation weights, decoding weights, spatial de-multiplexing weights, multi-user detection weights, array-processing weights, wavelet-processing weights, etc. The weighted components are combined in a combiner **1504**. The combined signals may be processed in a data processor

1505. In some aspects, the data processor 1505 may be part of a blind-adaptive processor 1506 that is adapted to generate and/or adapt weights relative to one or more performance parameters, such as channel estimates, confidence measures, data estimates, signal power, probability of error, BER, SNR, SNIR, etc.

In one aspect, the blind-adaptive processor 1506 processes information-bearing CI symbol measurements produced by the FFT 1502. The processor 1506 may work in conjunction with the combiner 1504 to combine the measurements and estimate transmitted data. In some aspects, the combining process may include wavelet processing. The processor 1506 may work in conjunction with the data processor 1505 to provide a channel estimate based on data estimates. In some aspects, the processor 1506 can employ a time-varying channel-estimation filter. In some aspects, the processor 1506 provides channel compensation, which may be based on a statistical characterization of interference, such as a covariance matrix.

In some applications, the processor 1506 provides predistortion (i.e., pre-coding) weights to transmitted signals. A data stream is optionally processed by a transmit data processor 1507. A transmitter weighting system 1508 is configured to weight data symbols provided to frequency bins of a frequency-domain-to-time-domain converter, such as an IFFT 1509. Time-domain signals generated by the IFFT 1509 are provided to a transmission system configured to prepare the time-domain signals for transmission into a communication channel.

In accordance with aspects of the disclosure, transceiver operating characteristics can be adaptable, such as indicated in the block diagram depicted in FIG. 16. In one aspect, a control circuit 1601 is configured to receive one or more system requirements 1611 and, optionally, one or more channel characteristics 1612. The control circuit 1601 can adapt one or more signal parameters 1602 employed by a radio transceiver 1603, such as radio transceivers employed by UEs, base transceiver stations, and/or central processors. Signal parameter adaptation and/or selection affect one or more transceiver operating parameters 1621.

In one aspect, the control circuitry 1601 may scale a transmitted bit rate by scaling the symbol duration, the number of subcarriers, the subcarrier spacing, and/or the number of bits per symbol per subcarrier. This permits the transceiver 1603 to operate in different communications environments, which may require varying operating parameters and/or characteristics. By adapting the operating parameters and/or characteristics of the transceiver 1603, the control circuitry 1601 can dynamically change the radio signals, thereby providing for compatibility or improving performance. For example, dynamically scaling the bit rate enables widely varying signal bandwidths, adjustment of delay-spread tolerances, and adaptability to different SNR requirements. An adaptable transceiver system can be particularly useful for mobile wireless communications, as well as other applications that support a variety of services in a variety of environments.

In accordance with some aspects of the disclosure, an OFDM system may be configured to select the number of subcarriers and a variable symbol duration. The control circuitry can dynamically select the number of subcarriers to decrease the signal bandwidth and the transmission rate while delay-spread tolerance remains the same. The control circuitry 1601 can also dynamically increase the symbol duration to decrease the transmission rate and the signal bandwidth and provide an increase in delay-spread tolerance. In some aspects, the control circuitry 1601 can be adapted to adjust the transmission rate by changing the type of modulation. In accordance with other aspects, variable transmission rates can be achieved by using adaptive coding wherein different coding schemes are selected to improve the link reliability and/or to decrease the peak-to-average power ratio.

In accordance with yet other aspects of the disclosure, adaptable transmission rates permit asymmetric data rates throughout the network. For example, individual UEs can be allocated varying sets of subcarriers depending on their data bandwidth needs. Additionally, during data downloading, for example, a mobile unit could have a larger downlink data rate than uplink data rate.

In accordance with some aspects of the disclosure, base transceiver stations employ adaptive antenna processing wherein UEs feedback their channel estimates via the uplink when uplink and downlink channel characteristics are not identical. In some aspects, power control can be performed on individual subcarriers or on groups of subcarriers. Alternatively, or in addition to power control, certain subcarriers may be selected to optimize one or more operational parameters, such as throughput, probability of error, received signal power, transmitter power efficiency, SNR, QOS, etc.

Sets of subcarriers may be selected with respect to the types of services being provided. For example, different qualities of service corresponding to different-priority links and/or different link services may be criteria for selecting subcarriers. In one case, subcarriers having little distortion and interference may be selected for services (such as data links) that do not tolerate high BER. In another case, a transmission may be divided into sections and sent on two or more groups of subcarriers (or channels). In some aspects, a more important section, such as addressing information, may be sent on higher-quality subchannels than subchannels on which payload data is sent. Addressing and other control information is typically less tolerant to errors than payload data. Thus, important parts of a transmission may be transmitted on higher-quality subspaces and/or on subcarriers having little distortion and fading.

In some aspects of the disclosure, various demand-assigned protocols govern the utilization of the bus medium. As used herein, the term bus medium, or bus, refers to a communication system or communication resources employed to communicatively couple together distributed transceiver components in a manner that resembles the functions of a computer bus. This expression covers all related hardware components (wire, optical fiber, etc.) and software, including communication protocols. By way of example, a bus can comprise a fronthaul network, a backhaul network, a local area network, and/or a wide area network. In one aspect, a bus communicatively couples together internal components residing in different networked devices, wherein the internal components are configured (such as by a central processor or via some distributed processing means) to function together as a single transceiver or transceiver system. In such aspects, a bus can comprise communication pathways, internal networks, etc. inside the networked devices.

As disclosed herein, software instructions configured to perform methods in accordance with aspects of the disclosure can provide various combinations of object-oriented design features. For example, a radio transceiver system comprising multiple components distributed across multiple networked devices may be provided with an abstraction interface wherein the multiple different constituent components are mapped to a single abstract device. Thus, the details of how the radio transceiver system is implemented

(for example, whether the radio transceiver is a single discrete device or comprised of multiple constituent components communicatively coupled together via a bus) can be hidden from systems and operations configured to employ the radio transceiver system. In one example, MIMO processing algorithms can be employed across the multiple constituent components in substantially the same manner as would be employed in a single device comprising multiple antennas. As described herein, MIMO processing algorithms can include various types of algorithms, including, but not limited to, MRC, MMSE, ZF, and/or successive interference cancellation. In some aspects, certain details of the radio transceiver system implementation are provided to the abstract device. For example, certain implementation details (or at least the effects of the implementation) can help a MIMO processor compensate for latencies in the bus communications between cooperating devices in a Cooperative-MIMO configuration.

In accordance with one aspect of the disclosure, each data communication device (DCD) of a set of DCDs in a network communicates with a central access point (AP). Multiple DCDs may request access from the AP in the same request access (RA) burst. In one aspect, each of the multiple DCDs transmits its access request to the AP within a frequency-domain subchannel in the RA burst that is orthogonal to the frequency domain subchannels used by the other DCDs requesting access. In another aspect, each of the multiple DCDs transmits its access request to the AP within a subspace channel in the RA burst that is orthogonal to the subspace channels used by the other DCDs requesting access. Alternatively, other orthogonal diversity-parameter values may be employed. In some aspects, each DCD provides channel training information in the RA burst to allow the AP and/or DCD to adapt to variations in channel characteristics.

FIG. **17** is a block diagram depicting a plurality K of UEs **120.1-120**.K (e.g., mobile or fixed subscriber units) in a wireless network comprising a plurality N of base transceiver stations (e.g., access points) **101.1-101**.N. At least one of the UEs **120.1-120**.K is configured to transmit a pilot signal or known training signal that is received at the base transceiver stations **101.1-101**.N. The propagation environment ensures that the set of pilot signals received by the base transceiver stations **101.1-101**.N is unique for each UE's **120.1-120**.K location. In some aspects of the disclosure, the uniqueness of the propagation environment can be exploited to provide or enhance coding. The base transceiver stations **101.1-101**.N are adapted to process the received pilot signals. Processing operations may depend on various characteristics of the received pilot signals, including absolute and/or relative signal power levels. For example, a predetermined set of the base transceiver stations **101.1-101**.N may be selected to process signals for a given UE based on the received pilot signal power.

In one aspect, at least one of the base transceiver stations **101.1-101**.N is configured to perform channel analysis to characterize the propagation environment of the transmissions between each UE **120.1-120**.K and the base transceiver station(s) **101.1-101**.N. Channel analysis may include delay-profile and/or flat-fading characterizations. In some aspects of the disclosure, the propagation environment is employed as a unique identifier for each UE **120.1-120**.K. In some aspects, weights calculated from channel estimates may be utilized in multiple-access codes, encryption codes, and/or authentication and verification procedures.

In some aspects of the disclosure, channel analysis is used to generate filter weights and/or array-processing weights at the base transceiver stations **101.1-101**.N to process received and/or transmitted signals. Such weights may be generated using various algorithms, such as MRC, MMSE, ZF, and/or successive interference cancellation, as well as others. The base transceiver stations **101.1-101**.N may comprise single-antenna systems or multi-antenna systems, such as antenna arrays. Received signals may be compared to some local or global timing reference, such as to analyze phase offsets and/or signal timing.

In another aspect of the disclosure, the base transceiver stations **101.1-101**.N are configured to transmit pre-coded signals to the UEs **120.1-120**.K. For example, the transmissions can be pre-coded to exploit the multipath environment between the access points **10011** to **10015** and the UEs **120.1-120**.K to constructively combine at the UEs **120.1-120**.K.

In one set of aspects, transmission (i.e., pre-coding) weights are generated from the reciprocal of a channel matrix that characterizes the propagation environment between a plurality of the base transceiver stations **101.1-101**.N and at least one of the UEs **120.1-120**.K. Channel (i.e., pre-coding) weights may be generated via any combination of deterministic (i.e., training) and blind-adaptive processing. Channel weights may be selected and/or adapted to optimize coherent combining of the base transceiver stations' **101.1-101**.N transmissions at one or more of the UEs **120.1-120**.K. Similarly, the channel weights may be selected and/or adapted to optimize coherent combining of signals received by the base transceiver stations' **101.1-101**.N from one or more of the UEs **120.1-120**.K. Any of various combining techniques may be employed.

In some aspects, channel weights are adapted to generate beam-pattern nulls at one or more of the UEs **120.1-120**.K or other transceivers. Channel weights may be adapted to provide time-varying channel compensation. Thus, beam steering, null steering, or any other time-dependent adaptive array processing may be performed. Appropriate combinations of carrier selection and carrier weighting may be provided to achieve simultaneous directionality (e.g., spatial multiplexing) and diversity benefits. In some applications, any of the base transceiver stations **101.1-101**.N may be replaced by UEs configured to function as routers, relays, and/or array elements of an adaptive transceiver array.

FIG. **18** is a block diagram of a RAN comprising base transceiver stations **101.1-101**.N configured in accordance with an aspect of the invention. The fronthaul network **105** can comprise a wireless, fiber optic, and/or wireline network that communicatively couples the base transceiver stations **101.1-101**.N to a central processor **110**. The central processor **110** is configured to process signals received from and transmitted by the base transceiver stations **101.1-101**.N.

In accordance with one aspect of the disclosure in the '163 application, the central processor **110** comprises a distributed computing system **111**. In accordance with another aspect of the disclosure in the '163 application, the central processor **110** is replaced by the distributed computing system **111**. In one aspect, the distributed computing system **111** comprises a plurality of processors, which may be geographically distributed. As used herein, the term "processor" can refer to a computer processor, a computer, a server, a central processing unit (CPU), a core, a microprocessor, and/or other terminology that indicates electronic circuitry configurable for carrying out instructions of a computer program.

The processors are communicatively coupled together via at least one network, such as a backhaul network **115**. The backhaul network **115** can comprise an optical fiber net-

work, a wireline network (e.g., Ethernet or other cable links), a wireless network, or any combination thereof. In one aspect, the processors are programmed to function as a plurality N of virtual base stations **111.1-111**.N. By way of example, each virtual base stations **111.1-111**.N may comprise one or more of the processors and perform base station processing operations that would ordinarily be performed by one or more of the corresponding base stations **101.1-101**.N. Specifically, virtual base stations can be implemented via software that programs general-purpose processors. For example, an SDR platform virtualizes baseband processing equipment, such as modulators, demodulators, multiplexers, demultiplexers, coders, decoders, etc., by replacing such electronic devices with one or more virtual devices, wherein computing tasks perform the functions of each electronic device. In computing, virtualization refers to the act of creating a virtual (rather than actual) version of something, including (but not limited to) a virtual computer hardware platform, operating system (OS), storage device, or computer network resources.

In accordance with the art of distributed computing, a virtual base station's functions can be implemented across multiple ones of the plurality of processors. For example, workloads may be distributed across multiple processor cores. In some aspects, functions for more than one base station are performed by one of the processors.

As used herein, distributed computing refers to the use of distributed systems to solve computational problems. In distributed computing, a problem is divided into multiple tasks, and the tasks are solved by multiple computers which communicate with each other via message passing. A computer program that runs in a distributed system is referred to as a distributed program. An algorithm that is processed by multiple constituent components of a distributed system is referred to as a distributed algorithm. In a distributed computing system, there are several autonomous computational entities, each of which has its own local memory.

In accordance with aspects of the disclosure, the computational entities (which are typically referred to as computers, processors, cores, CPUs, nodes, etc.) can be geographically distributed and communicate with each other via message passing. In some aspects, message passing is performed on a fronthaul or backhaul network. The distributed computing system can consist of different types of computers and network links, and the system (e.g., network topology, network latency, number of computers, etc.) may change during the execution of a distributed program. In one aspect, a distributed computing system is configured to solve a computational problem. In another aspect, a distributed computing system is configured to coordinate and schedule the use of shared communication resources between network devices.

A distributed computing system can comprise a grid computing system (e.g., a collection of computer resources from multiple locations configured to reach a common goal, which may be referred to as a super virtual computer). In some aspects, a distributed computing system comprises a computer cluster which relies on centralized management that makes the nodes available as orchestrated shared servers. In some aspects, a distributed computing system comprises a peer-to-peer computing system wherein computing and/or networking comprises a distributed application architecture that partitions tasks and/or workloads between peers. Such distributed peer-to-peer computing systems are disclosed in the '107 application. In some aspects, peers are equally privileged, equipotent participants in the application. They are said to form a peer-to-peer network of nodes. Peers make a portion of their resources, such as processing power, disk storage, network bandwidth, etc., available to other network participants without the need for central coordination by servers or stable hosts. Peers can be either or both suppliers and consumers of resources.

As disclosed in the patents and patent applications incorporated by reference herein, and particularly with respect to aspects of Cooperative-MIMO systems and methods, network nodes can function as either or both clients and servers. Furthermore, when wireless network nodes cooperate in subspace processing, they create network resources, such as subspace (i.e., spatial multiplexing) channels, performance gains, RAN coverage area, etc. Even when UEs cooperate as a client array (e.g., a UE cluster) in a Cooperative-MIMO implementation, each UE can improve the data bandwidth, quality of service, range, and power efficiency of the other UEs in the array, or cluster. Thus, in some aspects of a Cooperative-MIMO system, UEs can extend the network infrastructure, such as to increase per-client data bandwidth, the number of clients served, coverage area, and/or quality of service without requiring substantial capital outlays from network operator to upgrade the base station network.

In Cooperative-MIMO systems, mobile UEs can opportunistically join together via a peer-to-peer overlay network for client-side MIMO processing. In some aspects, UEs can join base transceiver arrays via an overlay network to assist in server-side MIMO processing. Due to random movement of UEs, aspects of the invention do not impose a particular structure on the overlay network. Because there is no structure globally imposed upon them, unstructured networks are easy to build and allow for localized optimizations to different regions of the overlay. Also, in some aspects, because the role of all peers in the network is the same, unstructured networks are highly robust in the face of high rates of churn (i.e., when peers are frequently joining and leaving the network).

In accordance with some aspects of the disclosure, the base transceiver stations **101.1-101**.N are "dumb terminals," wherein base station signal processing (for example, the baseband processing) is performed by the central processor **110** (which may include the distributed computing system **111**). Thus, in some aspects, the base transceiver stations **101.1-101**.N are simply radio remote units. For example, the base transceiver stations **101.1-101**.N might perform only basic signal-processing functions, such as RF processing (i.e., radio front-end processing), which can include frequency conversion and (optionally) ADC/DAC functions, while the central processor **110** (which may include the distributed computing system **111**) performs baseband processing, including channel analysis and generating base transceiver MIMO weights.

In one aspect, the central processor **110** coordinates or performs baseband signal processing corresponding to base station operations, whereas the base transceivers **101.1-101**.N provide only RF front end signal processing, including frequency conversion, and optionally, ADC/DAC. The central processor can perform waveform shaping, error detection, error correction, power control, channel selection, multiple access control, multiplexing, modulation, formatting, synchronization, coding, etc. for the plurality of base transceivers (i.e., access points) communicatively coupled to the central processor via the fronthaul network. In some aspects of the disclosure, the central processor **110** provides for base-station functionality, such as power control, code assignments, and synchronization. The central processor **110** may perform network load balancing, including providing for balancing transmission power, bandwidth, and/or pro-

cessing requirements across the radio network. Centralizing the processing resources (i.e., pooling those resources) facilitates management of the system, and implementing the processing by employing multiple processors configured to work together (such as disclosed in the '163 application) enables a scalable system of multiple independent computing devices, wherein idle computing resources can be allocated and used more efficiently.

Some aspects allow base station processing resources (e.g., the processors in the distributed computing system **111**) and the remote RF units (e.g., the base transceiver stations **101.1-101**.N) to be deployed separately. For example, RAN coverage, capacity, and/or data bandwidth per UE can be improved by adding base transceiver stations, and then the SDR platform dynamically adapts to the new RAN base station configuration. Similarly, the SDR platform can adapt to the loss of one or more of the base transceiver stations **101.1-101**.N. The distributed computing system (e.g., cloud network) **111** can adapt to varying processing loads by allocating computing resources as needed. Furthermore, system upgrades, such as new transmission protocols, can be easily implemented via software upgrades to the SDR platform.

In some aspects, base-station functionality is controlled by individual base transceiver stations and/or UEs assigned to act as base stations. Array processing may be performed in a distributed sense wherein channel estimation, weight calculation, and optionally, other network processing functions (such as load balancing) are computed by a plurality of spatially separated processors. In some aspects, access points and/or subscriber units are configured to work together to perform computational processing. A central processor (such as central processor **110**) may optionally control data flow and processing assignments throughout the network.

As disclosed in the '850 application, the system depicted in FIG. **18** provides system performance benefits by centralizing (e.g., pooling) much of the equipment (and/or signal processing) typically employed at the cell sites. Cost reduction is another motivation for centralizing the radio access network, as most of a cellular network's ownership costs comprise operating costs, including site rental, power, and support and maintenance expenses. Thus, instead of distributing baseband processing equipment at the edge of the network as in conventional cellular networks, centralizing the radio access network at the central processor **110** can greatly reduce capital expenditures to build out and upgrade the radio access network, as well as reduce operating expenditures.

As disclosed in the '163 application, providing for distributed computing at the central processor **110** provides network function virtualization to the radio access network. Benefits that can be realized with some aspects of the disclosure include cost reduction from pooling and virtualizing baseband processing. This can eliminate the need to provision for peak capacity on a per-site basis, thus reducing processing requirements. Furthermore, instead of requiring dedicated base station hardware, some of the disclosed aspects provide for the use of commercial (e.g., general-purpose) servers running software.

As disclosed in the patents and applications incorporated by reference herein, other types of networks, including wireless networks, can connect the base transceiver stations **101.1-101**.N. One of the advantages of employing the optical fiber fronthaul **105** is that optical fiber can provide the high capacity and low latency required by many aspects of the invention. For example, when a large number of baseband processors are co-located at the central processor **110**, the amount of data bandwidth in the fronthaul and the synchronization requirements between base transceiver stations **101.1-101**.N can increase substantially when high RF bandwidth and MIMO are employed. Different aspects of the invention can provide for different functional splits between centralized and distributed functions.

Some aspects of the invention can reduce fronthaul requirements by implementing at least some of the Physical Layer processing at the base transceiver stations **101.1-101**.N while implementing other processing (e.g., higher layer processing, or the higher layer processing plus some of the Physical layer processing) at the central processor **110**. Thus, in some aspects of the invention, one or more of the base transceiver stations **101.1-101**.N depicted in the figures may be replaced by UEs adapted to perform as routers, repeaters, and/or elements of an antenna array.

In one aspect of the disclosure, the base station network comprising base transceiver stations **101.1-101**.N is adapted to operate as an antenna array. In such aspects, a portion of the network may be adapted to serve each particular UE. The central processor **110** and/or the base transceiver stations **101.1-101**.N may be configured to perform other signal-processing operations, such as, but not limited to, waveform shaping, error detection, error correction, power control, channel selection, multiple access control, multiplexing, modulation, formatting, synchronization, coding, etc. In some aspects of the disclosure, the central processor **110** is replaced by a distributed computing system. In some aspects, the distributed computing system may comprise a plurality of the UEs **120.1-120**.K, repeaters (not shown), and/or the base transceiver stations **101.1-101**.N.

FIG. **19** is a block diagram that depicts apparatus and method aspects of the disclosure. Access points (e.g., access point **1901**) and at least one access controller (e.g., central processor **1902**) are connected via a fronthaul network **1905**, which may comprise an optical fiber, wireless, and/or wireline network. In some aspects, the fronthaul network **1905** may comprise standard interfaces, such as Common Public Radio Interface (CPRI) or Open Base Station Architecture Initiative (OBSAI). The access point **1901** comprises radio processing equipment **1910**, and the central processor **1902** comprises baseband processing equipment **1920**.

In accordance with some aspects of the disclosure, the entire baseband processing is carried out in the central processor **1902** while there may be no baseband processing performed at the access points **1901**. For example, the radio processing equipment **1910** may comprise analog front end circuitry and digital front end circuitry, and the baseband processing equipment **1920** comprises circuitry for the layers L1 (i.e., the Physical Layer) and higher layers. In one aspect of the invention, the radio processing equipment **1910** may perform basic signal-processing tasks, such as amplification, RF filtering, frequency conversion, as well as other RF signal-processing functions. The baseband processing equipment **1920** may perform baseband processing, including modulation/demodulation, combining, channel characterization, power control, other system control functions, quality factor analysis, coding, array processing etc.

It should also be appreciated that in some aspects, such as supported by the disclosures of the patents and patent applications that are incorporated by reference, that either or both radio processing equipment **1910** and the baseband processing equipment **1920** may each be implemented with one or more processors and one or more memories including computer program code, the computer program code com-

prising instruction configured to cause the processor(s) to perform the corresponding radio processing and/or baseband processing functions.

In accordance with some aspects of the disclosure, physical-layer baseband processing is performed on an SDR platform, which can be implemented on a distributed (e.g., cloud) computing system. Physical-layer baseband processing can include multiplexing, de-multiplexing, modulation, de-modulation, and/or equalization.

In one aspect of the invention, the access point **1901** is a device that serves as the air interface to the user equipment and implements analog radio frequency functions of an eNodeB. The access point **1901** may include one or more antennas for communicating with one or more UEs, and may include support for a variety of antenna types and configurations including, but not limited to, single omni-directional antennas and MIMO arrays of directional antennas. Exemplary functions that may be performed by the access point **1901** include digital-to-analog (D/A) conversion, analog-to-digital (A/D) conversion, carrier multiplexing, power amplification, and RF filtering. The central processor **1902** may be an LTE network device configured to implement radio functions of the digital baseband domain. These functions may include, but are not limited to, radio base station control and management, MIMO processing, and channel coding and de-coding.

FIG. **20**A is a flow chart depicting methods in accordance with aspects of the disclosure. Each of a plurality of geographically distributed access points performs RF processing of signals received from UEs in a radio access network **2001**, such as a WWAN. The resulting RF-processed signals are communicated to a central processor via a fronthaul network **2002**, such as an optical fiber network. The central processor collects RF-processed signals from the plurality of geographically distributed access points **2003** and performs baseband processing of the collected signals **2004**. In one aspect of the disclosure, the baseband processing **2004** comprises distributed computing performed by a distributed computing system. For example, the central processor may configure a plurality of processors to perform baseband processing.

FIG. **20**B is a flow chart depicting methods in accordance with aspects of the disclosure. A central processor performs baseband processing of UE signals **2011** to be transmitted by a plurality of geographically distributed access points to UEs served by a radio access network. In one aspect of the disclosure, the baseband processing **2011** comprises distributed computing performed by a distributed computing system (e.g., a cloud). For example, the central processor may configure a plurality of processors to perform baseband processing.

The resulting baseband-processed signals are communicated to the plurality of geographically distributed access points via a fronthaul network **2012**. The central processor may coordinate the plurality of geographically distributed access points to transmit signals in the radio access network to the UEs **2013**. Each of the access points performs RF processing of the baseband-processed signals **2014** prior to transmitting the signals to the UEs.

In some aspects of the disclosure, the access point antennas are connected to the central processor via optical fiber. Various types of fronthaul networks may be employed, including optical fiber, wireline (e.g., cable), wireless (e.g., radio), and any combination thereof. In wireless backhaul networks, such as those disclosed in the '163 application, digitized RF signals from various nodes can be aggregated, which allows the building of networks in chain, tree, and ring topologies.

In some aspects, the access point antennas can be considered as radio remote units, and the central processor can be considered as a central hub unit. The baseband signals from multiple access points can be gathered and processed together in the central processor to provide distributed antenna system MIMO benefits, such as spatial multiplexing gain. Similar types of distributed antenna system MIMO processing (e.g., pre-coding) can be performed at the central processor for signals to be transmitted by the access points.

In one aspect of the disclosure, downlink data is transmitted via MRC spatial multiplexing with power control. It should be appreciated that different aspects can effect various types of combining via pre-coding configured with respect to signal propagation measurements in the RAN channel. Pre-coding may comprise MRC, ZF, MMSE, and/or any of a variety of adaptive techniques, including blind adaptive techniques disclosed in the '163 and '107 applications. Coding and power control can comprise open-loop and closed-loop methods. In some aspects, UEs may be selected by the central processor and scheduled for array processing based on quality metrics (e.g., channel conditions, power measurements, SNR, etc.).

In accordance with some aspects of the disclosure, a network topology is depicted in FIG. **21** comprising a source node **2100**, a destination node **2105**, and a plurality of intervening nodes **2102**.**1**-**2102**.P. The network nodes **2100**, **2105**, and **2102**.**1**-**2102**.P may comprise UEs and/or base transceiver stations. The network nodes **2102**.**1**-**2102**.P and any intervening nodes (not shown here, but depicted in the drawings of the '163 application) may be configured to function as routers and/or relays.

In accordance with some aspects of the disclosure, as the network evolves, the nodes adapt their routing tables. As network loads change, the nodes can perform load balancing, such as to ensure a predetermined range of bandwidth and transmit-power loads across the network. One or more paths to the destination node **2105** can be selected or modified to optimize loads across the network, minimize transmission power, and/or ensure received signal quality. In one aspect of the disclosure, multiple transmission paths to the destination node **2105** are employed to achieve one or more objectives, such as reducing the effects of fading, reducing transmission power in some of the relays, and/or distributing transmission power across the network.

Information intended for the destination node **2105** can be passed through the network along one or more intervening nodes **2102**.**1**-**2102**.P. One or more of the intervening nodes (e.g., nodes **2102**.**1**-**2102**.P) can provide a final radio link to the destination node **2105**. For the sake of simplicity, FIG. **21** depicts a plurality P of transmission paths **2101**.**1**-**2101**.P from the source node **2100** to the intervening nodes **2102**.**1**-**2102**.P. It should be appreciated that each transmission path can comprise multipath components. It should be appreciated that in some aspects, one or more intervening nodes (not shown) may be utilized between the source node **2100** and nodes **2102**.**1**-**2102**.P.

The source node **2100** comprises an antenna system **2110**, which may include one or more antennas. Similarly, each of the intervening nodes **2102**.**1**-**2102**.P comprises an antenna system (**2120**.**1**-**2120**.P, respectively) which may include one or more antennas. When multiple antennas are employed by a node (e.g., nodes **2100**, **2105**, and/or **2102**.**1**-

2102.P), the node may perform any combination of diversity processing and spatial multiplexing with respect to its antenna system.

In accordance with one aspect of the invention, the source node **2100** selects a plurality P of the intervening nodes **2102.1-2102**.P to provide cooperative subspace processing, such as to increase the rank of the subspace pre-coding matrix and increase the number of linearly independent coded transmissions. In a first aspect of the disclosure, the transmission paths **2101.1-2101**.P comprise the radio access network. In a second aspect of the disclosure, the transmission paths **2101.1-2101**.P comprise a fronthaul network. In both the first and second aspects, the intervening nodes **2102.1-2102**.P comprise antennas of a Cooperative-MIMO antenna array.

As depicted in FIG. **21**, a plurality P of the intervening nodes **2102.1-2102**.P can be selected to provide a final RF link (e.g., transmission paths **2103.1-2103**.P) to the destination node **2105**. It should be appreciated that each transmission path can comprise multipath components. It should be appreciated that in some aspects, one or more intervening nodes (not shown) may be utilized between the source node **2100** and nodes **2102.1-2102**.P.

In one aspect, the destination node **2105** selects the plurality P of the intervening nodes **2102.1-2102**.P to increase the number of linearly independent coded transmissions it receives, effectively increasing the rank of the matrix that encodes the transmitted data. In one aspect of the disclosure, the transmission paths **2103.1-2103**.P comprise the radio access network, and the antenna system **2115** comprises a spatial multiplexing system configured to perform subspace processing. In another aspect of the disclosure, the transmission paths **2103.1-2103**.P comprise a fronthaul network, and the intervening nodes **2102.1-2102**.P comprise antennas of a Cooperative-MIMO antenna array.

In one aspect, the transmitted signals comprise multiple addresses corresponding to at least one path from the source node **2100** to the destination node **2105**. The transmission may include multiple addresses corresponding to a plurality P of devices (e.g., nodes **2102.1-2102**.P) that provide the final RF link to the destination node **2105**. Alternatively, the transmission may include only the destination address of the destination node **2105**. More than one destination address may be included for a particular transmission. A transmission may be duplicated when paths diverge. For example, a message with addresses to nodes **2102.1-2102**.P can be duplicated by node **2100**. In some aspects, a broadcast message includes a plurality of addresses, and the network is configured to propagate a single version of the message to all of the addresses.

In accordance with one aspect disclosed in the '163 application, a data message is provided that includes a plurality of destination addresses. Processing instructions, such as transmission weight values (e.g., a pre-coding matrix), are included with the data message. A single copy of the message is routed through nodes that form a path that is common to all of the destination addresses. The message is duplicated where the paths to the destination addresses diverge, but different linear coding is applied to the message for each of the paths. As disclosed in the '163 application, each router or relay can provide its own unique linear codes to the messages that pass through it.

The codes may include any combination of polyphase CI codes, CI-based codes, and channel-specific spatial interferometry codes (e.g., linear codes based on the random channel). For example, the channel characteristics for each transmission path (**2101.1-2101**.P and/or **2103.1-2103**.P) can be exploited to provide addressing and/or multiple-access coding. Coding may include space-time coding, space-frequency coding, polarization coding, etc.

Some aspects of the disclosure provide for CI codes that can be implemented across one or more diversity-parameter spaces. Similar to random linear codes, all CI codes of a given set of CI code words can be constructed from a combination of linearly independent code vectors that form the CI code generation matrix. A CI coder is configured to generate a plurality of algebraically unique linear combinations of a plurality of information signals.

FIG. **22**A depicts an aspect of the disclosure wherein at least the source node **2100** transmits a plurality P of transmit messages $t_1, t_2, \ldots, t_P$ on the plurality P of network paths **2101.1**, **2101.2**, . . . , **2101**.P, respectively to the plurality P of intervening nodes (e.g., nodes **2102.1**, **2102.2**, . . . , **2102**.P). In one aspect, each of the transmit messages $t_1, t_2, \ldots, t_P$ comprises a unique linear combination of P information messages (or symbols) $x_1, x_2, \ldots, x_P$. For example, a pth transmit message t_p may employ a vector of coefficients $[\alpha_{p,1}, \alpha_{p,2}, \ldots, \alpha_{p,P}]$ that is a row or column of a code matrix having rank P. In one aspect disclosed in the '163 application, the code matrix (e.g., channel-specific coding) comprises space-time or space frequency codes (e.g., pre-coding), such as derived from channel measurements. The characteristic randomness of the P terrestrial wireless transmission paths (e.g., **2101.1-2101**.P) can provide a code matrix of random values with rank P if the transmission paths **2101.1-2101**.P are sufficiently uncorrelated.

In one aspect, the source node **2100** selects the transmission paths **2101.1-2101**.P to build up the rank of the code matrix. For example, the source node **2100** selects a sufficient number of the intervening nodes **2102.1-2102**.P to ensure that the code matrix has sufficient rank to permit the destination node **2105** to decode the received data. The source node **2100** transmits the codes along with the encoded messages through the network via the intervening nodes **2102.1-2102**.P.

FIG. **22**B depicts an aspect of the disclosure wherein the intervening nodes **2102.1-2102**.P provide a plurality P of received messages $r_1, r_2, \ldots, r_P$ on the plurality P of network paths **2103.1**, **2103.2**, . . . , **2103**.P, respectively to the destination node **2105**. In one aspect, each of the received messages $r_1, r_2, \ldots, r_P$ comprises a unique linear combination of P information messages (or symbols) $x_1, x_2, \ldots, x_P$. For example, a pth received message r_p may comprise a vector of coefficients $[\beta_{p,1}, \beta_{p,2}, \ldots, \beta_{p,P}]$ that is a row or column of a code matrix having rank P. In one aspect disclosed in the '163 application, the code matrix (e.g., channel-specific coding) comprises space-time or space frequency codes (e.g., pre-coding), such as derived from channel measurements. The characteristic randomness terrestrial wireless transmission paths (e.g., paths **2101.1-2101**.P and/or paths **2103.1-2103**.P) can provide a code matrix of random values with rank P if the transmission paths (**2101.1-2101**.P and/or paths **2103.1-2103**.P) are sufficiently uncorrelated.

In one aspect of the disclosure, the destination node **2105** selects the intervening nodes **2102.1-2102**.P to build up the rank of the received coding matrix. For example, the destination node **2105** can select a sufficient number of the intervening nodes **2102.1-2102**.P to ensure that the code matrix has sufficient rank to permit the destination node **2105** to decode the received data.

In some aspects of the disclosure, the intervening nodes **2102.1-2102**.P function as a cooperative-MIMO antenna

array, which enables the destination node **2105** to receive a sufficient number of linearly independent combinations of transmitted signals to permit demultiplexing of the received signals. In one aspect, signals received by each of the intervening nodes **2102**.1-**2102**.P comprises a linear combination of transmitted data signals, and the linear combinations and corresponding code vectors received by the nodes **2102**.1-**2102**.P are communicatively coupled to the destination node **2105** via a fronthaul network comprising the paths **2103**.1-**2103**.P. In another aspect of the disclosure, the destination node **2105** comprises an antenna array (e.g., antenna system **2115**), and the transmission paths **2103**.1-**2103**.P comprise the radio access network. The nodes **2102**.1-**2102**.P transmit the codes along with the encoded messages to the destination node **2105**. In this aspect, the nodes **2102**.1-**2102**.P and/or the transmission paths **2103**.1-**2103**.P can provide additional coding to the signals received at the destination node **2105**. In some aspects, the code matrix may be determined by the destination node **2105** by deriving channel measurements from training (e.g., pilot) signals in the received signals. In other aspects, control signals (such as known training signals) can be encoded such that a receiver, upon correcting for channel distortions, can determine the code(s).

FIG. **23**A is a flow diagram that illustrates aspects of the disclosure pertaining to cooperative subspace multiplexing. In one aspect, a plurality of cooperating nodes is selected to build the dimension of a subspace spanned by coded transmissions **2301**. The plurality of cooperating nodes may comprise a source node. In some aspects, the source node communicates with cooperating transmitter nodes via a fronthaul network.

Linear codes are generated **2302**, for example, from channel estimates of a scattering-rich propagation environment. The natural randomness of terrestrial multipath channels can provide statistically random codes. In some aspects, linear coding is provided to transmissions via pre-coding based on channel measurements. In some aspects, linear coding may be provided to transmissions by multipath in the propagation environment. In such aspects, linear codes corresponding to different transmission channels will be algebraically unique if the channels from which the codes are derived are uncorrelated. This occurs when there is sufficient scattering. Thus, employing multipath scattering for encoding transmissions can be achieved by ensuring that transmitting antennas are sufficiently spatially separated to ensure uncorrelated subspace channels.

In some aspects of the invention, linear codes are generated **2302** and then the cooperating transmit nodes are selected **2301** to at least match the dimension of the set of linear codes (e.g., the rank of a resulting code matrix). In other aspects, the linear codes are generated **2302** to match the dimension of the subspace enabled by a pre-selected set of cooperating transmit nodes.

The cooperating transmit nodes transmit the coded messages and code matrix **2303**. In one aspect, the code vectors are transmitted along with the data payload. In some aspects, the code vectors may be included in control signals. For example, the code matrix may be conveyed by encoding known values, such as training signals. In some aspects, the natural randomness of the channel encodes transmitted messages and training signals. Thus, transmitting the coded messages and code matrix **2303** can comprise transmitting signals from cooperating transmit nodes that are sufficiently spatially separated to provide uncorrelated transmission channels.

FIG. **23**B is a flow diagram that illustrates aspects of the disclosure pertaining to cooperative subspace demultiplexing. In one aspect, a plurality of cooperating nodes is selected to build the dimension of a subspace spanned by received coded messages **2311**. The plurality of cooperating nodes may comprise a destination node.

A matrix of linear codes is determined from the received signals **2312**. For example, cooperating receiver nodes can communicatively couple their received messages to the destination node (or some other node(s) configured to perform MIMO subspace demultiplexing) via a fronthaul network. In some aspects, the code matrix accompanies the received messages in the data payload and/or as separate control information. In some aspects, the code matrix is determined from measurements of known training signals in the received messages.

In one aspect of the disclosure, determining the code matrix **2312** can indicate a required dimension that permits decoding. Thus, selecting cooperating nodes **2311** may be performed following step **2312**, such as to ensure that a sufficient number of linearly independent combinations of the original messages are collected to enable decoding. Once the destination node (or at least one other node configured to perform MIMO subspace demultiplexing) receives a sufficient number of linearly independent combinations, the received messages are decoded **2313**.

FIG. **24**A is a block diagram depicting a transceiver and transceiver method configured to perform routing in accordance with some aspects of the invention. In one aspect, each block comprises a step or set of steps, which can be performed by one or more circuits or machine components, such as a specialized computing device programmed with instructions to perform specific functions. In one aspect, each block comprises a circuit or a portion of a circuit in a transceiver apparatus. In another aspect, each block comprises a set of instructions that programs a specialized computing device to perform one or more steps disclosed herein. In another aspect, each block and/or a plurality of the blocks comprises at least one specialized computing device programmed with instructions to perform specific functions.

Transmitted signals are received by a receiver system **2401** that outputs a baseband signal. In a wireless network, the receiver system **2401** performs RF and, optionally, baseband processes typically performed to convert an RF signal to a baseband or intermediate frequency signal. For example, the receiver system **2401** may perform channel selection, filtering, amplification, frequency conversion, and A/D conversion.

In one aspect, each transmitted signal comprises a coded data payload and a preamble (or header) that comprises the code. The codes may comprise channel-specific coding. A decoder **2402** can be configured to decode the baseband signal relative to one or more codes in the header. A signal processor **2403** may process the decoded signals prior to producing an output data stream. Signal processing may include one or more signal-processing operations, including, but not limited to, quantization, channel decoding, multiple access decoding, demultiplexing, formatting, demodulation, channel estimation, channel compensation, synchronization, filtering, error detection, error correction, signal-quality analysis, multi-user detection, phase-jitter compensation, frequency-offset correction, time-offset correction, etc.

A control system **2404** is configured to select, adapt, or otherwise control the operation of one or more transceiver components. For example, channel estimates and/or signal-quality analysis performed by the signal processor **2403** may be processed in the control system **2404**, such as to adapt

decoding performed by the decoder **2402**. The control system **2404** may provide power control to a transmission system (e.g., transmission system **2406**) and/or otherwise provide network control. Similarly, coding may be adapted by the control system **2404**.

A pre-coder **2405** is configured to process input data bits to produce a coded signal that is coupled to the transmission system **2406**. The transmission system **2406** performs signal-processing operations typically performed to prepare a baseband signal for transmission into a communication channel. In a wireless network, the transmission system **2406** may perform one or more processes, including, but not limited to, D/A conversion, modulation, filtering, amplification, frequency conversion, beam forming, etc.

Signals from the receiver system **2401** can also be coupled through a routing system **2410**. In one aspect, signals from the receiver system **2401** are coupled to a decoder **2412**, which may include a bank of decoders. In one aspect of the disclosure, the decoder **2412** decodes received signals that are to be retransmitted. The decoded signals are processed in a signal processor **2413**, which may perform similar signal-processing operations as signal processor **2403**. Furthermore, the signal processor **2413** may perform pre-processing operations prior to coding in a pre-coder **2415**. The pre-coder **2415** may include a bank of pre-coders. A control system **2414** may be configured to select, adapt, or otherwise control the operation of one or more of the transceiver components **2412**, **2413**, and **2415**.

In one aspect, the control system **2414** and the coder **2415** may provide channel-compensation and/or beam-forming weights to the coded symbols. Such weights may be regarded as part of the routing process (e.g., the pre-coding). In some aspects, since routing decodes some signals that are not intended for the transceiver, the router components **2412**, **2413**, **2414**, and **2415** can be isolated from the rest of the transceiver by a fire wall **2410**.

In one aspect, the set of router components **2412**, **2413**, **2414**, and **2415** receives signals to be routed, decodes the signals **2412**, cleans up the decoded signals **2413**, and re-encodes the cleaned-up signals **2415** for retransmission **2406**. Additional pre-coded signals (e.g., from the pre-coder **2405**) can be combined with the pre-coded signals from the pre-coder **2415** prior to retransmission **2406**. As indicated by the junction that joins the pre-coder **2405** and the pre-coder **2415** prior to the transmitter **2406**, pre-coded signals to be routed may be summed with pre-coded "Data Input," which produces linear combinations of pre-coded signals.

As disclosed in the '850 and '163 applications, in some aspects, the decoder **2412** does not decode some or all of the input coded signals. Rather, the decoder **2412** maps the input coded signals to different code spaces. For example, when basic linear CI codes are employed, the code coefficients resemble Fourier Transform coefficients which are distributed uniformly on the unit circle in the complex plane. One advantage to using basic linear CI codes is that such codes are orthogonal, and some implementation do not require transmitting the decode vector(s) with the coded transmission. Orthogonal codes comprise different integer numbers of "rotations" on the unit circle in the complex plane. For non-zero rotations, a vector sum of the code coefficients produces a zero result. For a zero rotation, all the code values are mapped to the same point on the unit circle, so the code values sum coherently. Decoding **2412** can map an input code having a first number of rotations to an output code having a second number of rotations. If the second number of rotations is zero, then summing the result yields a solution for a code space in the set of linearly independent coded data values whose coefficients are basic linear CI code values. Thus decoding **2412** can solve for one or more unknowns (i.e., information signals) in the set of linear combinations and/or map at least one code space to at least another code space.

In one aspect of the disclosure, communication signals comprise coded sets of low-bandwidth subchannels. Thus, interference resulting from multipath and effective multipath resulting from retransmissions through the network can be reduced to flat fades. Sub-carrier bandwidths may be adapted to the multipath channel in one or more parts of the network. Coding may be adapted with respect to one or more parameters, including geographical distributions of subscriber units and access points, channel conditions, link priority, security, subscriber services, number of subscribers, etc.

In some aspects of the disclosure, each network node has access to the community's transmissions. The system can allow each node to dynamically select for reception only those transmissions that are relevant to that node. Individual transceivers may be equipped with adaptable or programmable decoders designed to select and decode one or more transmissions. The transceivers may be provided with a bank of decoders to decode and process multiple received signals simultaneously.

FIG. **24**B is a block diagram of a transceiver configured to perform routing in accordance with aspects of the invention. It should be appreciated that FIG. **24**B, as well as the other block diagrams of the disclosure, can indicate both apparatus and method implementations. For example, the blocks can indicate circuits, devices, systems, or other physical components of an apparatus or system. In some aspects, the blocks indicate functional components. The grouping of the functional components can take different physical forms. In some aspects, more than one block may be embodied by one particular physical component. In some aspects, a plurality of physical components can be employed as one of the blocks. In some aspects disclosed in the '850 and '163 applications, at least some of the disclosed signal processing operations can be performed by a computer processor and a computer-readable memory comprising processing instructions that instruct the processor to physically change input signals.

In the transceiver depicted in FIG. **24**B, signals from the receiver **2401** are coupled through a routing system **2420** and then retransmitted by the transmitter **2406**. The routing system **2420** can comprise a processor **2419** configured to process received signals to be routed, and then outputting processed signals to the transmitter **2406**. The received signals to be routed may comprise baseband and/or intermediate-frequency (IF) signals. The processor **2419** can be configured to perform one or more baseband or IF processes, including, but not limited to, signal shaping, filtering, re-quantization, error detection, error correction, interference mitigation, multi-user detection, amplification, up sampling, down sampling, frequency conversion, D/A conversion, AGC, symbol remapping, etc.

It should be appreciated that in some aspects, retransmitting (e.g., relaying, routing, and/or repeating) the received signal can effectively increase the rank of the channel matrix H from the perspective of the destination receiver(s), particularly if propagation channel is a scattering-rich environment. The rank of H is the sum of non-zero singular values λ_i in which each λ_i corresponds to an eigenmode of the channel (i.e., an eigen-channel, or subspace channel). Each non-zero eigenmode can support a data stream, thus the

MIMO channel can support k spatial sub-space channels, where k is the number of non-zero eigenvalues λ_i.

In accordance with some aspects of the disclosure, base-station responsibilities are assigned to (or assumed by) individual UEs. For example, base-station operations can be coordinated with simultaneous coded transmissions of a traffic channel and a control channel. Codes may include CI codes, CI-based coding, channel-specific coding, or any combination thereof. A time division duplexing method may be employed for transmit and receive operations to implement the necessary control functions for operation without a base station. At least one of the UEs can be assigned to be a network control station. By using time division duplexing for transmit and receive operations, the same frequency band(s) can be used for uplink and downlink, which can simplify channel estimation and MIMO processing.

A UE acting as a network control station can maintain power control and time synchronization normally performed by a base station. For example, power control can be maintained within predetermined time intervals by a feedback control loop using proportional integration and differentiation to smooth control such that power oscillations are maintained within desired limits. The network control functions may automatically be transferred if the connection with the transceiver is terminated or there is a predetermined degree of signal-quality degradation. The network control station can have channel control capabilities to assure transmission security. For example, the network control station may assign codes to other UEs to change the security or priority of individual communication links.

FIG. **25**A is a block diagram illustrating a network configuration that employs channel reuse between a plurality of networks. A signal **2500** having channel allocation C_1 in a first network is received by a transceiver **2510** (with antenna system **2520**). For example, the first network may comprise a WWAN, or "macro-cell." The channel C_1 is reused for communication in a second network (e.g., a micro-cell network) **2550** comprising transceivers **2510-2513**. For example, transmissions **2501-2503** employ the channel allocation C_1. As disclosed in the '163 application, the transmissions **2501-2503** can comprise array-processing pre-coding, which can permit reuse of the channel allocation C_1 by the second network via interference mitigation.

In one aspect of the disclosure, antenna systems **2520**, **2521**, **2522**, and **2523** may comprise multiple antennas, and each transceiver **2510**, **2511**, **2512**, and **2513** may be configured to perform array processing with its own antenna system. In another aspect of the invention, the transceivers **2510**, **2511**, **2512**, and **2513** can be configured to perform cooperative array processing, wherein array processing (such as subspace processing) operations are jointly processed by multiple ones of the transceivers **2510**, **2511**, **2512**, and **2513**. Combinations of local array processing (i.e., array processing on individual transceivers) and cooperative array processing (e.g., Cooperative MIMO) may be performed.

FIG. **25**B is a block diagram illustrating a network configuration that employs cooperative array processing and reuses channel C_1 allocated to a first link **2500**. In one aspect, a plurality of the transceivers (**2511**, **2512**, and **2513**) employs channel C_1 to communicate with transceiver **2520**. For example, the transceivers **2511**, **2512**, and **2513** transmit signals **2504**, **2505**, and **2506**, respectively, to transceiver **2510**. Pre-coding operations on the transmitted signals **2504**, **2505**, and **2506** can provide for beam forming (or equivalent array processing) operations. Various combining operations may be provided to produce any combination of interference rejection, diversity enhancement, and sub-space processing (i.e., capacity enhancement). The aforementioned operations can permit a micro-cell network (e.g., network **2550**) to employ the same macro-cell channels (e.g., channel C_1) without interfering with the macro-cell network.

Methods described with respect to FIGS. **25**A and **25**B and the related disclosures in the '163 application, the transceivers **2510**, **2511**, **2512**, and **2513** can be implemented, by way of example and without limitation, with apparatus embodiments depicted in and described with respect to FIGS. **24**A and/or **24**B.

FIG. **26** is a block diagram depicting systems and methods according to some aspects of the disclosure. In one aspect, a cooperative-MIMO network **2660** comprises multiple groups of separate geographically distributed transceivers, wherein at least a first group **2651** employs cooperative subspace processing (e.g., cooperative-MIMO) to communicate with at least a second group **2652**, such as disclosed in the '107 and '163 applications. In one aspect of the disclosure, the first transceiver group **2651** comprising transceivers **2610-2613** is configured to communicate subspace signals **2601-2603** employing a common channel C_1 to the second transceiver group **2652**, which comprises transceivers **2614-2616**. Since the transceivers **2610-2616** can be configured to operate in multiple networks (e.g., macro-cell and micro-cell networks), in one aspect, network **2660** can be a micro-cell network configured to reuse channel C_1, which is used for communication in the macro-cell.

The subspace signals **2601-2603** comprise a plurality of spatial subchannels that occupy a common frequency spectrum, time interval, and code space denoted by the common channel C_1, wherein subspace processing provides for non-interfering parallel subchannels. As disclosed herein, subspace processing can comprise any combination of transmitter-side and receiver side subspace processing. For example, subspace processing can comprise pre-coding (i.e., spatial multiplexing). In some aspects, subspace processing comprises subspace decoding (i.e., spatial demultiplexing).

The transceivers **2610-2616** each comprises an antenna system (e.g., antenna systems **2620-2626**, respectively), that includes one or more antennas. Thus, in some aspects, more than one antenna per transceiver can be available for cooperative-MIMO processing. In some aspects, one or more of the transceivers **2610-2616** can perform local antenna array processing (e.g., diversity combining and/or spatial multiplexing) in addition to participating in cooperative-subspace processing. As used herein, "spatial multiplexing" can denote the general practice of subspace processing, which can comprise pre-coding (also referred to as subspace coding or spatial multiplexing) and/or decoding (also referred to as subspace decoding or spatial demultiplexing). In some cases, "spatial multiplexing" specifically denotes subspace processing on the transmitter side of a communication link (which is distinguished from spatial demultiplexing performed on the receiver side of the link), and, thus, comprises subspace coding (also referred to as pre-coding). The intended scope of the terminology used in the disclosure is indicated by the context in which it is used.

With reference to FIGS. **25**A, **25**B, and **26**, and related disclosures in the '163 application, FIG. **27** is a flow diagram that depicts methods according to some aspects of the invention. In one aspect, a client transceiver (i.e., a client node) receives a channel allocation (e.g., channel C_1) for communicating in a first communication link **2701**. For example, the client transceiver may receive a signal in channel C_1. Alternatively, the client transceiver may be allocated channel C_1 for transmitting signals. The channel

allocation C_1 typically comprises a specified frequency band, time interval, and code space. When no multiple access codes are employed, the code space is simply a vector of ones (e.g., [1, 1, 1, . . . , 1]). By way of example, the channel C_1 may be allocated for communication between the client transceiver and at least one other transceiver in the first network, the channel C_1 being allocated so as not to interfere with other communication links in the first network.

A "client transceiver," as used herein, indicates a transceiver that is served by a first network via the first communication link. In some aspects of the disclosure, the client transceiver may perform additional network functions, and as such, may function as any of various network devices, such as a router, a relay, a repeater, or a gateway.

A transceiver group comprising multiple transceivers, including the client transceiver, is selected to communicate in a second communication link **2702**. In one aspect, selecting **2702** comprises provisioning a plurality of the transceivers to cooperatively transmit signals in the second link. In another aspect, selecting **2702** comprises provisioning a plurality of the transceivers to cooperatively receive signals in the second link. Pluralities of both transmitting and receiving transceivers may be selected, such as depicted in FIG. **26**.

In some aspects, the client transceiver functions as a router or relay, such as to forward communications it receives via the first link to a destination node or another intermediate node via at least a second link. The client may select **2702** the transceivers to which it forwards communications. In one aspect, communications forwarded by the client transceiver to a plurality of cooperating transceivers constitute the second link. In another aspect, transmissions from cooperating transceivers (which may or may not include the client transceiver) comprise the second link. In one aspect, the first link is part of a first network and the second link is part of a second network.

The channel C_1 is reused for communicating in the second link **2703**. Specifically, the second link simultaneously employs the same frequency band and code space as in the first link. Thus, some aspects of the invention are configured to mitigate co-channel interference between signals in the first and second links. Some aspects employ cooperative subspace processing **2704** between at least two transceivers communicating in the second link to mitigate interference between signals in the first and second links. For example, spatial multiplexing (i.e., pre-coding) performed by a plurality of cooperating transmitters can cancel transmissions in the second link that would otherwise interfere with the reception of transmissions in the first link. Spatial demultiplexing (i.e., subspace decoding) performed by cooperating transmitters can separate interfering first-link and second-link signals, such as to permit reception of either or both first-link and second-link signals by transceivers operating in the second link.

By way of example, if the first link channel C_1 is a downlink channel, then cooperative subspace multiplexing and/or demultiplexing can separate received second-link signals from received first-link signals within the transceiver group. By way of example, if the first-link channel C_1 is an uplink channel, then cooperative subspace multiplexing (e.g., pre-coding) can cancel co-channel interference due to second-link signals received by receivers communicating in the first link. Also, cooperative subspace multiplexing and/or demultiplexing can separate received second-link signals from received first-link signals within the transceiver group.

As will be appreciated to those skilled in the art, disclosures of the '850 and '163 applications can be employed in various types of communication networks, including LTE networks, which comprise a flat network architecture as opposed to hierarchical architectures of other cellular standards.

Thus, in accordance with some aspects of the disclosure, the UEs disclosed herein comprise LTE UEs. By way of example, a UE may comprise an RF transceiver for fixed and/or mobile clients receiving data streams over a downlink channel(s) in the radio access network and transmitting data via the uplink channel(s) in the radio access network.

A base transceiver station may comprise an eNodeB, which may handle radio resource management, user mobility, and scheduling. The base transceiver stations interface the fronthaul network with the radio access network. A base transceiver station of one aspect of the disclosure is an access point comprising an RF front-end configured to convert baseband signals to RF and RF signals to baseband. The base transceiver station may comprise a Digital-to-Analog Converter (DAC)/Analog-to-Digital Converter (ADC). In some aspects, the base transceiver station is a simple RF transceiver equipped with power amplifier/antenna(s), and RF signals are communicatively coupled between the base transceiver station and the central processor via the fronthaul network, which can include RF-over-fiber technology, such as described in related patents and applications that are incorporated by reference.

A controller employed in an LTE network may comprise a base transceiver station configured to perform certain specialized functions, such as transmitting training signals, receiving/transmitting control information from/to the UEs, receiving channel state information (CSI) or channel quality information from the UEs, etc. Coordinated multipoint systems disclosed herein may comprise multiple controllers. In an LTE network, the controller may comprise a mobility management entity.

A fronthaul network configured in an LTE system may comprise a combination of S1 and X2 interfaces. By way of example, but without limitation, the fronthaul may comprise S1-MME links between the mobility management entity and eNodeBs, S1-U links between the serving gateway and eNodeBs, and X2 links between multiple eNodeBs. In some aspects, the fronthaul network comprises the S1 interface. In other aspects, the fronthaul network comprises the X2 interface.

The LTE network typically comprises a gateway, which comprises a serving gateway (S-GW) that terminates the E-UTRAN interface, and a PDN gateway (P-GW), which interfaces with external networks. In accordance with aspects of the disclosure, the central processor can be implemented by the gateway, such as the S-GW component. In other aspects, one or more of the eNodeBs can be configured to operate as the central processor.

While aspects of the disclosure describe Cooperative-MIMO processing in which high channel selectivity (wherein selectivity refers to statistical variations of spatial gains of propagating signals) is achieved via rich multipath environments and/or geographically distributed transmitters (and/or receivers), alternative aspects may employ other diversity parameters (such as signal polarization) and/or various techniques (e.g., coherence multiplexing, frequency diversity interferometry, etc.), such as described in Applicant's patents and other applications, to achieve channel selectivity. By way of example, in U.S. Pat. No. 6,331,837, which is hereby incorporated by reference in its entirety, Applicant discloses that different antenna beam patterns can

provide for different spatial gains, thereby providing the selectivity necessary to achieve spatial multiplexing and/or de-multiplexing. Specifically, subspace processing can be achieved in the beamspace domain of a transmitting and/or receiving array, thus transferring the MIMO operation from the antenna elements to the beamspace. Data streams are mapped onto specific transmitted beam patterns, and beamspace multiplexed data streams are sent simultaneously. Similarly, specific radiation patterns are used to receive transmissions. Since beamspace multiplexing exploits aerial degrees of freedom, such techniques can be advantageous for arrays with closely spaced elements. In some aspects of the disclosure, one or more antenna elements in an array are parasitic elements.

One aspect of the '837 patent discloses outputs from multiple beamforming processes being input to a spatial de-multiplexing process. In the case wherein the number of active receiving antennas is less than the number of transmitting antennas, if the beamforming processes produce a number of linearly independent combinations of received transmissions at least equal to the number of transmit sources, then there is sufficient rank in the resulting channel matrix to separate the received signals. In one sense, the beamforming process can be implemented as a multiple-access coding process that maps M logical channels onto N physical subspace channels, where M>N. Although the total theoretical capacity of the channel (such as expressed by the corresponding Shannon-Hartley theorem for the corresponding MIMO implementation employed) does not increase, the capacity is partitioned across more subchannels. In one aspect, the M subchannels each have a lower SNR (and thus smaller capacity) than the corresponding N subchannels. This could be a result of more correlation between the elements of the channel matrix as its dimension increases. The reciprocal of any such process can be applied to spatial multiplexing. Various techniques, including coherence multiplexing, polarization subspace multiplexing, and frequency diversity interferometry are described, and these and the other disclosed techniques can be employed within the spatial multiplexing and de-multiplexing methods and systems disclosed herein.

The following references, which are part of the disclosure of the '850 application, are incorporated by reference in their entireties: U.S. patent application Ser. Nos. 09/718,851; 60/219,482; 60/194,633; 09/703,202 (now U.S. Pat. No. 7,076,168); Ser. No. 09/381,588 (now U.S. Pat. No. 7,010,048); Ser. No. 09/393,431 (now U.S. Pat. No. 6,888,887); Ser. Nos. 09/347,182; 09/324,206 (now U.S. Pat. No. 6,331,837);

B. Natarajan, C. R. Nassar and S. Shattil, "Exploiting Frequency Diversity in TDMA through Carrier Interferometry," Proceedings of Wireless 2000, 12th International Conference on Wireless Communications, Jul. 10-12, 2000, pp. 469-476;

B. Natarajan, C. R. Nassar and S. Shattil, "Throughput Enhancement in TDMA through Carrier Interference Pulse Shaping," IEEE Vehicular technology Conference Proceedings, vol. 4, pp. 1799-1803, Fall 2000, Boston;

C. R. Nassar, B. Natarajan and S. Shattil, "Introduction of Carrier Interference to Spread Spectrum Multiple Access," Proceedings of the IEEE Emerging Technologies Symposium on Wireless Communications and Systems, Dallas, Apr. 12-13, 1999;

S. Shattil, C. R. Nassar, "Array control systems for multicarrier protocols using a frequency-shifted feedback cavity," Radio and Wireless Conference, 1999. RAWCON 99. 1999 IEEE 1-4 Aug. 1999 pp. 215-218;

Z. Wu and C. R. Nassar, "MMSE frequency combining for CI/DS-CDMA," IEEE Radio and Wireless Conference, Denver, Colo., Sep. 10-13, 2000, pp. 103-106;

S. A. Zekavat, C. R. Nassar and S. Shattil, "Smart antenna spatial sweeping for combined directionality and transmit diversity," *Journal of Communications and Networks (JCN), Special Issue on Adaptive Antennas for Wireless Communications*, vol. 2, no. 4, December 2000, pp. 325-330.

Some aspects of the disclosure can employ CI coding for spread-OFDM, spreading across subspaces, and/or other applications, such as described throughout the patents, applications, and non-patent literature cited herein, each of which is incorporated by reference in its entirety. In the following description, some of the variables used in the previous description are reused. However, the definition of each of those variables is intended to be interpreted with respect to the context in which they are currently defined, which takes precedence over any previous definition for the purpose of the following discussion only.

In OFDM, the transmission bandwidth is partitioned into a plurality N (which typically equals 2 raised to some integer power) of orthogonal subcarrier frequencies. Multicarrier spread-spectrum employs spreading across the subcarriers to produce a transmit signal expressed by $x=F^{-1}Sb$, where F^{-1} is an inverse discrete Fourier transform (IDFT), S is a spread-OFDM code matrix, and b is the transmitted symbol vector. The inverse DFT typically employs an over-sampling factor. In such instances, inverse DFT's dimension is M×N (where M>N is the number of time-domain samples per OFDM symbol block), whereas the dimension of the spread-OFDM code matrix is N×N.

At the receiver, the received spread-OFDM signal is expressed by $r=HF^{-1}Sb$, where H is a channel matrix for the transmission channel. A cyclic prefix in OFDM changes the Toeplitz-like channel matrix into a circulant matrix. The circulant channel matrix H is expressed by

$$H=F^{-1}\Lambda_H F,$$

wherein Λ_H is a diagonal matrix whose diagonal elements can correspond to the first column of the circulant channel matrix H.

Thus, neglecting noise for simplicity, the received signal is represented by

$$r=F^{-1}\Lambda_H FF^{-1}Sb,$$

which is

$$r=F^{-1}\Lambda_H Sb.$$

The OFDM receiver processes r with a DFT to produce

$$y=\Lambda_H Sb.$$

In one aspect, in order to facilitate the estimation of b, it can be advantageous to employ a spreading code matrix S that commutes with Λ_H. For example, the matrix $S=\Lambda_C F$ may be employed, wherein Λ_C is the diagonal matrix of the circulant matrix C, which is defined by $C=F^{-1}\Lambda_C F$.

In this case, the received signal, r, is expressed as

$$r=F^{-1}\Lambda_H FF^{-1}(\Lambda_C F)b,$$

which can be written as

$$r = F^{-1}\Lambda_H \Lambda_C Fb$$
$$= F^{-1}\Lambda_C \Lambda_H Fb.$$

In the case of basic CI spreading, the spreading matrix $S=\Lambda_C F$ can be implemented with $\Lambda_C=I$, such that the spreading matrix S is just an N×N DFT matrix (e.g., an N×N matrix comprising DFT coefficients wherein N is an integer greater than two). While the use of fast Fourier transform techniques for DFT processing are well known, in the examples disclosed herein, a DFT matrix used for CI spreading (and a corresponding IDFT employed for CI de-spreading) can have matrix dimension N>2, but need not be constrained to powers of two.

In one aspect, the OFDM receiver performs DFT processing on the received signal, r, followed by equalization (e.g., Λ_H^{-1}, although other types of equalization can be performed, such as to compensate for noise and interference), and then CI despreading (e.g., F^{-1}) is performed. In some aspects, equalization and despreading can be performed as a combined and/or iterative process. Equalization (or equalization and despreading) can include multi-user detection techniques, such as successive interference cancellation, as well as other techniques.

In some aspects, the data symbols b can comprise symbols of a reference signal. Reference signals can comprise known training symbols, which can be used for channel estimation and/or channel quality determination. By way of example, demodulation reference signals transmitted in the uplink channel can be used for channel estimation, which can be part of a coherent demodulation process, such as may be performed at a base transceiver station and/or central processor. The channel estimates may be used to provide for spatial demultiplexing of signal transmissions from multiple UE antennas and/or multiple UEs. The channel estimates can be used to derive precoding weights (such as spatial precoding weights) for precoding transmissions in the downlink. In some aspects, sounding reference signals are used to determine channel quality, which may be employed to provide frequency-dependent scheduling on the uplink. In some aspects, the reference signals are time-multiplexed with user-data signals. In some aspects, the reference signals are frequency-multiplexed with user-data signals. In some aspects, the reference signals are code-division multiplexed with user-data signals.

By way of example, CI spreading (such as DFT spreading) can be performed to spread demodulation reference signals on LTE uplink channels, such as demodulation reference signals associated with transmissions of uplink data on the Physical Uplink Shared CHannel (PUSCH) and/or control signaling on the Physical Uplink Control CHannel (PUCCH). Similarly, CI spreading can be used to spread LTE's Sounding Reference Signal (SRS), which is used for channel quality determination to enable frequency-selective scheduling on the uplink. For example, the SRS may be transmitted on the last CI superposition pulse (i.e., SC-OFDMA symbol) in a sub frame. UEs transmitting their SRS in the same sub frame can be multiplexed via frequency or code division multiplexing.

If training signals (such as signals comprising known symbols) are employed, channel estimates can be derived from the received signal r, such as to provide channel state information used for precoding and/or decoding. In some aspects, the CI spreading matrix can comprise channel precoding. For example, the spreading matrix can be $S=\Lambda_H^{-1}F$, where Λ_H^{-1} is an estimated inverse channel matrix. The precoding can take various alternative forms and can employ any of the precoding techniques that are known in the art. For example, precoding can be configured to minimize bit error rates and/or improve any other link performance metric, such as may be measured by the receiver and/or determined by the transmitter. In accordance with aspects of the disclosure, precoding can comprise subspace MIMO precoding.

Since OFDM's over-sampled DFT is K×N, the basic CI spreading matrix S can resemble a sin c pulse-shaping filter, except that it maps each data symbol to a cyclically shifted (and orthogonally positioned) superposition of OFDM subcarriers in an OFDM symbol interval T_s. In some aspects, the CI spreading comprises pulse shaping, such as to produce raised-cosine, Gaussian, or other shaped pulses. For example, CI spreading can comprise a windowing function. Frequency-domain windowing can shape the frequency-domain signal such as to provide a predetermined time-domain pulse shape, as well as other time-domain features. Alternatively, other forms of pulse shaping can be performed.

In some aspects, CI spreading comprises a block transform wherein each superposition pulse is a cyclic shift of a pulse waveform within a fixed time interval, such as OFDM symbol interval T_s. In other aspects, CI spreading is implemented via a sliding window transform. While the pulse waveform is constrained within a given time interval, the time intervals of successive pulse waveforms can be shifted (e.g., incrementally shifted) in time, and the time intervals can overlap.

Since each CI-spread symbol comprises a linear combination of the data vector's b values, if a spread symbol is lost during transmission, that loss is mitigated due to the spreading. Thus, CI spreading can permit accurate estimation of a received signal despite substantial losses (such as due to flat fading, interference, etc.), even before error-correction processing is performed by the receiver. CI spreading can permit a receiver to accurately decode a transmission without requiring all of the spread symbols. For example, a receiver may accurately estimate N data values b by employing fewer than N spread symbols.

Since the CI-spread symbols employ predetermined linear relationships between the data symbols of b, techniques typically employed in multi-user detection (such as, but not limited to, successive interference cancellation and mixed-decision symbol estimation) can be used to enhance performance at the receiver. Thus, in some aspects of the invention, orthogonality of the spreading codes is not required if the spreading coefficients are known at the receiver. Rather, the code spaces processed by the receiver may simply need to be sufficiently de-correlated from each other to estimate the data symbols b. In this respect, despreading can be considered to comprise equalization. In other aspects, spatial precoding based on channel state information can be regarded as part of CI spreading, wherein the transmission channel effectively orthogonalizes the CI-spread transmissions received by the receiver(s). Thus, precoding is sometimes referred to as pre-equalization. In some aspects of the invention, the above-mentioned spreading matrix S comprises an invertible transform, which produce a sequence of coded data symbols x from an input data vector b: x=Sb. The inverse of the transform is then performed at the receiver to decode the received signals.

FIG. **28**A illustrates a method for providing CI-coded transmissions of information and control signals. In some aspects of the disclosure, such methods are performed by a UE. By way of example, a UE can comprise a processor and a memory coupled to the processor, the memory including a set of instructions stored therein and executable by the processor to perform the method depicted in FIG. **28**A. In some aspects, the UE can comprise circuits configured to perform one or more steps of the methods disclosed herein.

By way of example, a CI code generation process **2801** provides CI codes and/or CI-based codes for spreading at least one information signal and at least one control signal. A control signal can include one or more control-function signals, such as, but not limited to, power control signals, synchronization signals, code assignment signals, priority assignment signals, link assignment signals, channel assignment signals, duplexing control signals, training signals, signals indicating notice of transfer of control responsibilities, and request acknowledgement signals. Coding processes **2802** and **2803** can encode the information signal(s) and control signal(s), respectively. A transmission process **2804** provides for transmission of the coded signals, such as via any of the transmission protocols disclosed in the '163 application, the '850 application, and the other references mentioned in their disclosures.

In some aspects, one or more of the processes disclosed herein, such as processes **2801-2804**, can comprise a processor, a circuit, an apparatus component, and/or a functional block of a transmitter apparatus. In some aspects, a processor, circuit, and/or apparatus component can be configured to perform a plurality of the processes **2801-2804**. In some aspects, one or more of the processes **2801-2804** comprises a step in a method.

FIG. **28**B is a flow diagram depicting a method for managing network control in a CI network by one or more subscriber units according to some aspects of the disclosure. A CI transceiver can be configured to transmit CI-coded information and control signals **2810**. In a network identification and communication restriction step **2811**, CI spreading codes can be used, at least in part, to spread the communication and control channels. CI codes can be allocated to restrict communications between transceivers permitted to operate in the network, such as by providing for scheduling RAN resources in accordance with any of the multiple access protocols disclosed herein. CI codes can also be used to identify a radio network and each of the radio devices, as well as the type of communications being transmitted.

Duplexing **2812** provides for management of transmission and reception. Various types of duplexing can be employed, such as time-division duplexing, frequency-division duplexing, code-division duplexing, polarization-division duplexing, etc. A CI transceiver may include a plurality of CI decoders in parallel to enable simultaneous reception of more than one signal. Similarly, transmission of coded signals can be performed simultaneously with reception when the transmitted CI codes differ from the code of the received signal. Furthermore, different CI codes can be used to encode transmissions to differentiate types of transmitted signals. The use of CI spreading for multiplexing and multiple access are disclosed throughout the papers, patent applications, and patents incorporated by reference herein.

A network-control step **2813** can indicate that at least one of the subscriber units performs as a network control station. A network control station can initiate communications and maintain power control and time synchronization of the network. This can be an important function in a Cooperative-MIMO system, such as wherein a plurality of subscriber units cooperatively process RAN signals for uplink and/or downlink operations. Some aspects provide for transfer **2814** of network control from at least one subscriber to at least one other subscriber. The network control station can voluntarily transfer, or be commanded to transfer, power control and time synchronization of the network to any other radio in the network.

FIG. **28**C illustrates a network-control method that can be implemented in accordance with certain aspects of the disclosure. A CI coding step **2821** provides different CI codes (such as may be used to spread a signal) to information and control signals. In some aspects, a network control station can provide time-division duplexing **2822** to regulate transmission and reception. A network-control step **2823** can provide for network control by the network control station. Network control **2823** can include various operations, including, but not limited to, synchronization, power control, code assignment, channel assignments (i.e., scheduling), channel coding, transmission-path selection, load balancing, and spectrum management.

FIG. **28**D is a flow diagram that depicts a routing method in accordance with certain aspects of the disclosure. Coding **2831** can comprise providing a multi-address, CI-coded signal for transmission **2832**. The addresses may be provided via any combination of precoding and header addressing. Transmitted signals may be routed via one or more paths through a network. Duplication **2833** can be provided when transmission paths through a node diverge. Duplicated signals are transmitted along their respective paths.

FIG. **29**A is a flow diagram that depicts a CI signal generation method in accordance with some aspects of the disclosure. In some aspects, a UE can be configured to perform methods disclosed herein, such as the method in FIG. **29**A. By way of example, a UE can comprise a processor and a memory coupled to the processor, the memory including a set of instructions stored therein and executable by the processor to perform the method depicted in FIG. **29**A.

In one aspect, a DFT-spreader spreads a plurality of reference-signal symbols with Fourier coefficients to generate a DFT-spread reference signal **2901**. A symbol-to-subcarrier mapper maps DFT-spread symbols of the DFT-spread reference signal to a plurality of OFDM subcarriers **2902**. For example, mapping **2902** can be performed according to an OFDMA scheme, some other multiple-access scheme, and/or any other multiplexing scheme, such as disclosed herein. An OFDM modulator (such as an IFFT) modulates the DFT-spread reference symbols onto the plurality of OFDM subcarriers **2903** (according to their mapping **2902**) to produce a baseband OFDM transmission signal. In some aspects, the baseband OFDM transmission signal is processed **2904** prior to RF processing (not shown). For example, baseband processing **2904** may comprise appending a cyclic prefix, pulse shaping, digital-to-analog conversion, filtering, and/or other baseband processing.

In accordance with aspects disclosed herein, methods and functionality, such as depicted in the figures and described throughout the specification, can be implemented via one or more circuits, by a system of devices, by a digital processor programmed with instructions to perform the associated method(s) or function(s), and/or by any other apparatus. In accordance with some aspects of the disclosure, the aforementioned methods and/or functions are performed by a UE. In some aspects, at least one non-transitory computer-readable medium may comprise machine-readable instructions configured to program a general-purpose processor to perform one or more of the methods and functionalities disclosed herein.

In accordance with some aspects of the disclosure, the DFT spreader comprises an N-point DFT, and the OFDM modulator comprises an M-point inverse Fast Fourier Transform. In one aspect, the value of M is greater than N. The '163 application discloses that an N-point transform, such as a DFT, can be used to spread the information symbols to

produce coded symbols that are complex-weighted sums of the information symbols. Other transforms are also disclosed. CI can comprise a wide variety of complex spreading codes that are orthogonal (and/or nearly orthogonal), the variety employing DFT coefficients being among the simplest.

While in some aspects, the OFDM subcarriers are contiguous and within a single band, in other aspects, the OFDM subcarriers can comprise non-contiguous subcarriers. The non-contiguous subcarriers may be incrementally (i.e., equally) spaced and/or non-incrementally (i.e., unequally) spaced. Thus, the subcarriers can be distributed over noncontiguous bands. Different users may be assigned to different sets of subcarriers to provide for OFDMA. For example, the '163 application discloses that the OFDM subcarriers can be selected as a block of contiguous subcarriers, or the OFDM subcarriers can be non-contiguous. Interleaved spreading can comprise selecting non-contiguous OFDM subcarriers that are incrementally (i.e., equally) spaced throughout a given band. In some aspects, spreading can comprise selecting non-incremental (i.e., unequally) spaced OFDM subcarriers. In interleaved spreading, the IFFT can comprise a mapping function to provide the respective CI-OFDM symbols to their corresponding non-contiguous frequency bins of an IFFT.

In CI-OFDM, each information symbol can be spread over a set of subcarriers by using orthogonal CI spreading codes. In one aspect, the spreading code S(k) for a kth OFDM symbol is expressed as:

$$S(k)=\{e^{i0\cdot 2\pi k/N}, e^{i1\cdot 2\pi k/N}, \ldots, e^{i(N-1)\cdot 2\pi k/N}\}, \quad k=0,1,\ldots,N-1$$

where N is the spreading-code length (e.g., the number of subcarriers over which the information symbol is spread). In one aspect, a block of up to N information symbols can be spread into a block of N spread-OFDM symbols **2901**.

In one aspect, a jth OFDM symbol x(j) that is input to the IFFT in an OFDM transmitter can be expressed as:

$$x(j)=\Sigma_{k=0}^{N-1} b(k)\cdot e^{i2\pi jk/N}, j,k=0,1,\ldots, N-1.$$

where b(k) denotes the kth information symbol.

Blocks of CI-coded information symbols can be serial-to-parallel converted and input into an IFFT operation. The output of the IFFT is parallel-to-serial converted to produce a CI-OFDM signal having N frequency components. For a subcarrier separation $f_s=1/T_S$, where T_S is the OFDM symbol duration, the baseband CI-OFDM signal x(t) is:

$$x(t) = \sum_{k=0}^{N-1}\sum_{j=0}^{N-1} b(k)\cdot e^{i2\pi f_s t}\cdot e^{i2\pi kj/N}$$

For $N=2^m$ (i.e., m is an integer, so N is a power of 2), the spreading can be performed using an FFT, and de-spreading can comprise an IFFT.

At a receiver, time-domain samples of a received OFDM signal are serial-to-parallel converted and operated upon with an FFT before being de-spread by a corresponding CI despreading operation (such as an IFFT). The '163 application discloses some aspects in which equalization is performed by the receiver before de-spreading, and some aspects in which pre-coding performed at the transmitter provides for pre-equalization.

The '163 application discloses that reference signals (e.g., control signals, such as training signals, synchronization signals, etc.) are spread via CI spreading. This is different than in other spread-OFDM systems (such as MC-CDMA), which do not spread reference signals. In MC-CDMA, the receiver must perform channel equalization (and thus channel estimation) prior to despreading. Thus, in the case of pilot-based channel estimation, the transmitted pilots cannot benefit from the spreading sequence orthogonality properties and must be transmitted at different times or frequencies in order for a receiver to estimate the channel coefficients.

In some aspects of the disclosure, CI spreading of the reference signals can provide certain advantages, such as producing a signal with low PAPR, providing a superposition signal that facilitates synchronization, facilitating time-domain channel measurements, producing a signal that can facilitates both time-domain and frequency-domain channel measurements, as well as other advantages. For example, in one aspect, CI spreading can produce a superposition signal having predetermined amplitude characteristics in the time domain which facilitates time-domain channel analysis (and subsequent equalization) when advantageous. Since the superposition signal comprises OFDM as its basis, frequency-domain channel analysis (and subsequent equalization) can be performed when advantageous. Time-domain equalization typically has poorer performance than frequency-domain equalization, but frequency-domain equalization can be more computationally complex and consume more power. In one aspect, computational processing and power consumption can be reduced with little or no performance sacrifice in a poor scattering environment, such as may be characterized by a small delay spread, whereas frequency-domain equalization may be performed when the delay spread is above a predetermined threshold.

The '163 application discloses that in some aspects, CI spreading **2901** can comprise precoding, such as MIMO subspace precoding. The '163 application also discloses that selection (i.e., scheduling) of OFDM subcarriers (e.g., mapping **2902**) can be based on some quality metric associated with the channel quality of each subcarrier.

The method depicted in FIG. **29**A can be referred to as CI signal synthesis. FIG. **29**B is a flow diagram that depicts a CI signal analysis method in accordance with some aspects of the disclosure. After RF processing (not shown), a baseband signal derived from a received transmission can be processed **2911**, which can include analog-to-digital conversion (ADC), removal of any cyclic prefix (or guard interval), filtering (such as pulse-shape matched filtering), and/or other baseband signal processing. The resulting digital baseband signal is demodulated **2912** via a process (such as an IFFT) that provides time-domain to frequency-domain conversion of the baseband OFDM signal to provide data symbols that are received on each subcarrier. The data symbols can include DFT-spread reference symbols. Demapping **2913** can be performed to select a particular set (or sets) of the data symbols with respect to an OFDMA scheme and/or some other multiple access and/or multiplexing scheme, such as disclosed herein.

FIG. **30**A is a block diagram of a transmitter according to an aspect of the disclosure. Reference signals and, optionally, user data signals are processed by a CI coder **3021**, such as an N-point DFT, which provides DFT spreading to the reference signals. In some aspects, the N-point DFT **3021** can spread both the reference symbols and the user data symbols. The coding performed by the CI coder **3021** can be referred to as linear precoded OFDMA.

In one aspect, a UE comprises the transmitter shown in the diagram. In another aspect, a base transceiver terminal comprises the transmitter. In other aspects, such as described throughout the '163 application, any type of network node

(such as a node in a network mesh) can comprise the transmitter. By way of example, each node can represent an interconnect router and may comprise a computer processor. The node can comprise a network controller, which can be configured to perform network control functions. In some aspects, the network controller can be distributed among the nodes of the mesh network.

As disclosed in the '163 application, TDD can be performed. For example, TDD enables channel reciprocity which can permit uplink reference signals, such as training signals (e.g., pilot tones) to be used to estimate the downlink channel. The '163 application also discloses that frequency-division duplexing (FDD) can be employed. In one aspect, the UE measures its downlink channel and then provides feedback of the channel measurements on the uplink. In other aspects of FDD, a base transceiver station may calculate downlink channel state information from uplink training signals. The '163 application discloses other types of duplexing that can be employed, including code division duplexing, cancellation division duplexing, polarization division duplexing, and spatial division duplexing.

Various techniques for multiplexing are disclosed in the '163 application. For example, in orthogonal frequency division multiplexing, different subcarrier sets can be assigned to different devices. The assignment of a device's subcarriers can be performed by a mapping module **3022**. For example, a subcarrier interleaver **3022** can assign non-contiguous equally spaced subcarriers across a given frequency range to a UE as part of a scheduling process in OFDMA. In some aspects, the DFT spreader's **3021** outputs are mapped **3022** to a contiguous block of subcarriers. In such aspects, since a subset of the total number of subcarriers is assigned to each device, an M-point IFFT **3023** performs the OFDM modulation wherein M>N. The '163 application also discloses time-division multiplexing, code-division multiplexing, and space-division multiplexing.

In one aspect, a set of reference symbols can be transmitted across all the assigned subcarriers of a set. Multiple devices can be assigned to the same subcarrier set. Thus, in one aspect, each of multiple devices assigned to the same subcarriers can transmit its reference symbols in a different time slot. In some aspects, each device can be assigned different DFT spreading codes. In some aspects, DFT spreading codes can be employed to separate reference signals from user data signals. By way of example, U.S. patent application Ser. No. 09/324,206 (now, U.S. Pat. No. 6,331,837), which is incorporated by reference in its entirety, discloses encoding a reference signal using CI spreading. In some aspects of the disclosure, the DFT spreader **3021** can implement spatial precoding. In some aspects, the reference symbols can be interleaved between user data symbols.

OFDM modulation **3023** can comprise providing for pulse shaping. Pulse-shape selection can be based on various parameters, including spectral characteristics, time-domain signal features, feasibility of synchronization, interference and noise immunity, and implementation costs and complexities. Various pulse shapes can be provided by appropriately weighting the subcarriers, such as via a windowing function. Roll-off factors can be controlled by selecting and/or adjusting subcarrier weights. Various filtering techniques may be used to generate subcarrier superposition signals having predetermined time-domain characteristics. In one aspect, cyclic prefix insertion **3024** can include pulse shape filtering (not shown). The resulting digital baseband signal is processed by a radio front-end transmitter **3025**, which can provide for various radio front-end processing operations, such as digital-to-analog conversion, frequency up-conversion, amplification, filtering, and coupling into the radio channel.

FIG. **30**B is a block diagram of a CI-OFDM receiver configured in accordance with some aspects of the disclosure. The CI-OFDM receiver provides for a signal processing path that includes an RF radio and analog-to-digital converter **3026**, a cyclic prefix remover **3027**, an M-point FFT (time-domain to frequency-domain converter) **3028**, a subcarrier de-mapper/equalizer (de-interleaver) **3029**, and an N-point IDFT (De-spreader) **3030**.

The CI-OFDM receiver receives transmitted signals comprising DFT-spread reference symbols (and optionally, user data symbols) via at least one receive antenna (not shown), down-converts the received signals and converts them from analog to digital with the RF/ADC **3026**, and removes the cyclic prefix via the cyclic prefix remover **3027**. The FFT **3028** performs an M-point DFT once the CP has been removed, and the frequency-domain components produced therefrom are de-mapped (and in some cases equalized) by the subcarrier de-mapper **3029**. An N-point IDFT **3030** de-spreads the de-mapped frequency-domain components to produce a complex time-domain signal, which is processed by subsequent baseband processing (not shown).

In some cases, the cyclic prefix is a copy of the last part of the block, which provides a guard time between successive blocks and converts a discrete time linear convolution into a discrete me circular convolution. Thus, transmitted data propagating through the channel can be modeled as a circular convolution between the channel impulse response and the transmitted data block, which in the frequency domain is a pointwise multiplication of the DFT frequency samples. Then, to remove the channel distortion, the DFT of the received signal can simply be divided by the DFT of the channel impulse response point-wise, or frequency domain equalization may be used.

Some aspects of the disclosure provide for an apparatus comprising a processor and a memory coupled to the processor, wherein the memory includes a set of instructions stored therein and executable by the processor to perform methods disclosed herein. In one aspect, for a group of N data symbols of a reference signal, the processor performs N-point DFT spreading on the N data symbols to generate a set of N DFT-spread components of the N data symbols. The processor then maps the N DFT-spread components of the N data symbols to N subcarriers of a set of M subcarriers (M>N) to generate a set of complex subcarrier amplitudes. The processor performs an M-point inverse discrete Fourier transform, such as an inverse fast Fourier transform (IFFT), on the set of complex subcarrier amplitudes to generate a reference-signal sequence comprising M discrete time-domain values.

In accordance with certain aspects of the disclosure, CI-OFDM can be configured as a DFT pre-coded OFDMA scheme. CI-OFDM is distinctly different from prior-art OFDMA, for example, because of the DFT pre-coding (e.g., spreading) of the symbols in the transmitter, and the corresponding IDFT of the demodulated symbols in the receiver. Because of this pre-coding, the CI-OFDM subcarriers are not independently modulated, as in the case of the OFDMA subcarriers. CI-OFDM distinguishes itself from other spread-OFDM techniques in that its PAPR is lower than the PAPR of a conventional OFDMA signal. The use of CI-OFDM transmission techniques by UEs is described herein because lower PAPR greatly benefits mobile terminals in terms of transmit power efficiency. Thus, such CI-OFDM coding can be employed for UE uplink transmissions.

FIG. **31** is a block diagram that depicts a non-transient computer-readable memory **3100** comprising a set of instructions stored therein and executable by a processor to perform methods in accordance with aspects of the disclosure. In some aspects, the computer-readable memory **3100** can reside on at least one UE and be configured for processing uplink transmissions.

In one aspect, the instructions can comprise a software interface such as to provide for access to resources (e.g., functions, variables, etc.) inside a program or source code segment. Interfaces between software components can provide constants, data types, types of procedures, exception specifications, and/or method signatures. Sometimes public variables are defined as part of an interface. A software interface may provide access to computer resources, such as memory, CPU, storage, etc.). In some aspects, a software module comprises an interface and an implementation, wherein the implementation can contain code configured to perform procedures and methods described in the interface, as well as comprising private variable, procedures, and/or other structures and/or capabilities.

In one aspect, data bits corresponding to a reference signal (and, optionally, user data) is input to a baseband modulator source-code segment **3101** configured to transform the binary input to a multi-level sequence of complex numbers b in one of several possible modulation formats, including binary phase shift keying (BPSK), quaternary PSK (QPSK), 16 level quadrature amplitude modulation (16-QAM), 64-QAM, as well as others. The system may adapt the modulation format, and thus the transmission bit rate, to match the current channel conditions the terminal. In some aspects, source-code segment **3101** is referred to as a bit-to-symbol mapper that converts each set of bits to a symbol in a modulation constellation.

The input of a Spread-DFT source code segment **3102** comprises the data symbols b, which the source code segment **3102** groups into blocks, each containing N symbols. Serial-to-parallel conversion may be performed. The Spread-DFT source code segment **3102** can be configured to perform an N-point DFT to produce frequency-domain symbols which are the DFT-spread input symbols b. In one aspect of the invention, the above-mentioned spreading matrix S is employed as an invertible transform to produce a sequence of coded data symbols x from an input data vector b: x=Sb.

By way of example, FIG. **32** illustrates an invertible transform matrix S that may be employed in some aspects of the invention. In one aspect, the invertible transform matrix S is an N×N DFT matrix. Each row (e.g., row **3201**) of the matrix S multiplies original data vector b (which comprises N values) to produce a coded data symbol x_i. Specifically, each coded data symbol x_i comprises a linear combination of the original data symbols b, wherein the coefficients of the linear combination are values of the invertible transform matrix S, which is the DFT matrix.

In some aspects, such as described in the references disclosed herein, the Spread-DFT source code segment **3102** can be called a CI coder, a time-domain-to-frequency-domain converter, or an OFDMA precoder. In some aspects, source-code segment **3102** comprises a filter (which may include various filter types, including windowing filters), such as may be used for pulse shaping, shaping the spectrum of the transmitted signal, imparting predetermined time-domain features to the transmitted signal, and/or other filter functions. As described in the incorporated references and disclosed herein, source-code segment **3102** can further comprise spatial precoding functionality and/or other types of precoding.

A symbol-to-subcarrier mapping source code segment **3103** maps each of the N DFT outputs of x to one of M (M>N) orthogonal subcarriers. As in conventional OFDMA, a typical value of M might be 256 subcarriers and N=M/Q is an integer submultiple of M. Q is a bandwidth expansion factor of the symbol sequence. If all terminals (e.g., UEs) transmit N symbols per block, the system can potentially handle Q simultaneous transmissions without co-channel interference. When spatial multiplexing (e.g., spatial multiplexing or spatial demultiplexing) is employed, the number of concurrent non-interfering channels can be substantially higher. The result of the subcarrier mapping is a set of complex subcarrier amplitudes, where N of the amplitudes are non-zero.

As in conventional OFDMA, an M-point inverse DFT source code segment **3104** transforms the subcarrier amplitudes to a complex time-domain signal. In some aspects, this is referred to as frequency-domain-to-time-domain conversion. In accordance with certain aspects of the invention, such as disclosed in the incorporated references, the spread data symbols can be distributed over other diversity parameters. For example, each of a plurality of subcarrier sets can be transmitted by a different antenna. Thus, the source-code segment **3104** and/or circuitry coupled to the processor can be configured to distribute each set of OFDM subcarriers to a different set of antennas for transmission. For example, such aspects are disclosed in U.S. Pat. No. 7,839,941, which is a national stage of PCT/US99/02838, which are incorporated by reference in their entireties.

A cyclic-prefix appending source code segment **3105** appends a set of symbols (e.g., a cyclic prefix, a postfix, and/or a guard interval) to the sequence of complex time-domain symbols in order to prevent inter-block interference (IBI) due to multipath delay.

The time-domain signal may be provided with additional baseband processing **3106**, which can include pulse shaping and/or other baseband processing, to produce a digital baseband transmission signal. The digital baseband transmission signal is typically provided to radio front-end circuitry (not shown), where processing circuitry can provide for DAC, filtering, frequency up-conversion, amplification, and/or other RF front-end processing prior to transmission. However, other types of radio front-end processing may be performed. By way of example, and without limitation, direct conversion of the baseband signal to RF may be performed via digital processing.

FIG. **33** is a block diagram that depicts a non-transient computer-readable memory **3300** comprising a set of instructions stored therein and executable by a processor to perform methods in accordance with aspects of the disclosure. In some aspects, the computer-readable memory **3300** can reside on at least one base transceiver station, at least one central processor, or a combination thereof, and be configured for processing received uplink transmissions.

Received signals are processed by a radio front-end (not shown), which can provide for amplification, filtering, frequency down-conversion, ADC, and/or other radio front-end processes typically performed in the art. In some aspects, a radio front-end can perform direct digital down-conversion of the received radio signal to a digital baseband signal.

An optional front-end digital processing source-code segment **3301** can be provided for direct down-conversion, ADC, filtering, synchronization, and/or other digital pro-

cessing of a received radio signal, an intermediate signal, an analog baseband signal, and/or a digital baseband signal.

An optional cyclic prefix removal source-code segment **3302** can be provided for removing a cyclic prefix, a postfix, a guard interval, or any combination thereof from a baseband digital signal.

An M-point DFT source-code segment **3303**, which may be configured to perform an M-point FFT, converts the baseband digital signal, which comprises a time-domain sequence of symbols, into a set of frequency-domain components, which represent complex amplitudes of the OFDM subcarriers. These complex-valued subcarrier symbols include DFT-spread signals, which comprise DFT-spread reference symbols.

A demapping source-code segment **3304** separates the subcarrier symbols by subcarrier sets, which can correspond to multiplexing and/or multiple-access schemes employed in the OFDM system.

The de-mapped symbols, which include spread reference symbols, are processed by an N-point IDFT source-code segment **3305**, which may be configured to perform an N-point IFFT, to despread the spread reference symbols. The de-spread reference symbols may undergo additional baseband processing **3006**, which may include channel estimation, equalization, spatial demultiplexing, decoding, filtering, error correction, data-symbol estimation, multi-user detection, and/or other baseband processing operations. In some aspects of the disclosure, channel estimation, equalization, spatial demultiplexing, multi-user detection, and/or other baseband processing can be performed prior to IDFT processing, such as directly following the DFT **3303** and/or the de-mapping **3304**.

Cyclic delay diversity (CDD) has been contemplated as a transmit diversity technique for OFDMA, such as presented in S. A. Zekevat, C. R. Nassar, and S. Shattil, "Smart antenna spatial sweeping for combined directionality and transmit diversity," *Journal of Communications and Networks* (*JCN*), *Special Issue on Adaptive Antennas for Wireless Communications*, vol. 2, no. 4, pp. 325-330, December 2000; S. A. Zekevat, C. R. Nassar, and S. Shattil, "Combined directionality and transmit diversity via smart antenna spatial sweeping," 38th Annual Allerton Conference on Communications, Control, and Computing, Champaign-Urbana, Ill., Oct. 4-6, 2000; and in S. Shattil and C. R. Nassar, "Array Control Systems For Multicarrier Protocols Using a Frequency-Shifted Feedback Cavity," IEEE Radio and Wireless Conference, Denver, Colo., Aug. 1-4, 1999, all of which are incorporated by reference in their entireties.

In CDD, a phase angle change in the frequency domain (such as may be provided as a cyclic shift delay in the time domain) can be applied to a signal prior to transmission. In OFDMA systems, CDD can be implemented after OFDM modulation. For example, after the IDFT, the transmit signal is split into N_T antenna branches. The cyclic shift of the first antenna is set to zero, while in the other branches, the signal is cyclically shifted by an antenna-specific cyclic shift δ_n, $n=1, \ldots, N_T-1$. The equivalent representation in the frequency domain is provides phase diversity.

In accordance with the disclosure of PCT/US99/02838, such as claimed in U.S. Pat. No. 7,839,941, a method and apparatus for enhancing transmit diversity provides for modulating each of at least one data symbol onto a plurality of subcarriers to be transmitted from a plurality of antennas, thereby producing a transmitted signal; and periodically changing the relative phase between the subcarriers. CI coding, such as DFT spreading disclosed herein provides for modulating each reference data symbol onto a plurality of OFDM subcarriers. Aspects disclosed therein provide for producing a periodically scanning beam pattern, which can be achieved via any of a variety of mechanisms that cause a phase shift in the transmitted signals.

Also disclosed in PCT/US99/02838, a type of CDD diversity scheme is referred to herein as subband based transmit diversity (SBTD). In SBTD, the contiguous bandwidth of a device (which may be a UE) having N_T transmit antennas ($N_T \geq 2$) is divided into N_T sub-bands, with each of the N_T transmit antennas being assigned to a respective one of the N_T sub-bands, wherein each transmit antenna transmits $1/N_T$ of data symbols for the device in its respective sub-band. A method and apparatus for enhancing transmit diversity provides for modulating each of at least one data symbol onto a plurality of subcarriers to be transmitted from a plurality of antennas, thereby producing a transmitted signal; and providing for a frequency offset between subcarriers transmitted from different antennas.

Because CI-OFDM signals are still being transmitted within contiguous sub-bands of contiguous sub-carriers in SBTD, SBTD preserves the low PAPR property of CI-OFDM and does not introduce frequency selectivity into CI-OFDM processing. Furthermore, dividing the transmitted data between separate sub-bands and on separate antennas can potentially reduce the complexity of the transmitter circuitry, as the size of the DFT (per antenna) may be reduced compared to the DFT required in non-SBTD diversity schemes. These aspects may be employed in the apparatus and method implementations disclosed herein. By way of example, such CDD techniques can be employed across distributed terminals in a Cooperative-MIMO system.

The various blocks shown in the figures may be viewed as method steps, and/or as operations that result from operation of computer program code, and/or as a plurality of coupled logic circuit elements constructed to carry out the associated function(s).

In general, the various exemplary aspects may be implemented in hardware or special purpose circuits, software, logic or any combination thereof. For example, some aspects may be implemented in hardware, while other aspects may be implemented in firmware or software which may be executed by a controller, microprocessor or other computing device, although the invention is not limited thereto. While various aspects of the exemplary embodiments of this invention may be illustrated and described as block diagrams, flow charts, or using some other pictorial representation, it is well understood that these blocks, apparatus, systems, techniques or methods described herein may be implemented in, as non-limiting examples, hardware, software, firmware, special purpose circuits or logic, general purpose hardware or controller or other computing devices, or some combination thereof.

It should thus be appreciated that at least some aspects of the exemplary aspects of the invention may be practiced in various components such as integrated circuit chips and modules, and that the exemplary aspects of this invention may be realized in an apparatus that is embodied as an integrated circuit. The integrated circuit, or circuits, may comprise circuitry (as well as possibly firmware) for embodying at least one or more of a data processor or data processors, a digital signal processor or processors, baseband circuitry and radio frequency circuitry that are configurable so as to operate in accordance with the exemplary aspects of this invention.

Various modifications and adaptations to the foregoing exemplary aspects of this invention may become apparent to those skilled in the relevant arts in view of the foregoing

description, when read in conjunction with the accompanying drawings. However, any and all modifications will still fall within the scope of the non-limiting and exemplary aspects of this invention.

The invention claimed is:

1. An OFDM transmitter, comprising:

an OFDM spreader configured to spread a plurality of data symbols with Fourier coefficients to generate a discrete Fourier Transform (DFT)-spread data signal;

a mapper configured to map the DFT-spread data signal to a plurality of OFDM subcarriers; and

an OFDM modulator configured to modulate the DFT-spread data signal onto the plurality of OFDM subcarriers to produce an OFDM transmission signal comprising a superposition of the OFDM subcarriers, wherein the OFDM spreader is configured to provide the superposition with a reduced peak-to-average power ratio.

2. The OFDM transmitter recited in claim **1**, wherein the OFDM spreader comprises an N-point DFT and the OFDM modulator comprises an M-point inverse discrete Fourier Transform, wherein M>N.

3. The OFDM transmitter recited in claim **1**, wherein the OFDM modulator comprises an inverse fast Fourier transform.

4. The OFDM transmitter recited in claim **1**, wherein the data symbols comprise reference-signal symbols, which comprise at least one of known training symbols and synchronization symbols.

5. The OFDM transmitter recited in claim **1**, wherein the plurality of OFDM subcarriers comprise at least one of contiguous OFDM subcarriers and equally spaced non-contiguous OFDM subcarriers.

6. The OFDM transmitter recited in claim **1**, further comprising a pulse-shaping module configured to provide the OFDM transmission signal with a predetermined pulse shape.

7. The OFDM transmitter recited in claim **1**, further comprising a cyclic prefix appender configured to append at least one of a cyclic prefix, a postfix, and a guard interval to the OFDM transmission signal.

8. The OFDM transmitter recited in claim **1**, wherein the OFDM spreader is configured to provide channel precoding.

9. The OFDM transmitter recited in claim **1**, wherein the plurality of data symbols are at least one of time-multiplexed with reference-signal symbols, frequency-multiplexed with reference-signal symbols, and code-multiplexed with reference-signal symbols.

10. The OFDM transmitter recited in claim **1**, further comprising a Cyclic Delay Diversity (CDD) module configured to provide CDD to the OFDM transmission signal.

11. A method, comprising:

multiplying a plurality of data symbols by a discrete Fourier Transform (DFT) spreading matrix to produce a plurality of DFT-spread symbols;

mapping the plurality of DFT-spread symbols to a plurality of OFDM subcarriers; and

modulating the plurality of DFT-spread symbols onto a plurality of OFDM subcarriers to produce a DFT-spread OFDM signal to be transmitted into a wireless channel, wherein the DFT-spread OFDM signal comprises a superposition of the OFDM subcarriers, and wherein the DFT spreading matrix is configured to provide the superposition with a reduced peak-to-average power ratio (PAPR).

12. The method recited in claim **11**, wherein the plurality of OFDM subcarriers is a subset of subcarriers, the subset comprising at least one of a block of contiguous subcarriers, and a set of non-contiguous subcarriers.

13. The method recited in claim **11**, wherein the plurality of OFDM subcarriers is selected based on measured channel quality of the subcarriers.

14. The method recited in claim **11**, wherein the mapping is configured to provide the DFT-spread OFDM signal with reduced PAPR.

15. The method recited in claim **11**, wherein at least one of the DFT spreading matrix and the mapping is configured to provide a DFT-spread reference signal comprising a coherent superposition of reference symbol components on different subcarriers.

16. The method recited in claim **11**, wherein the plurality of data symbols comprises at least one reference-signal symbol employed for at least one of synchronization and channel estimation.

17. The method recited in claim **11**, further comprising appending at least one of a cyclic prefix, a postfix, and a guard interval onto the DFT-spread OFDM signal.

18. The method recited in claim **11**, wherein the DFT spreading matrix comprises an N-point DFT, and the modulating comprises employing an M-point inverse-DFT, and wherein N<M.

19. The method recited in claim **11**, further comprising providing Cyclic Delay Diversity to the DFT-spread OFDM signal.

20. The method recited in claim **11**, further comprising pulse shaping to provide the OFDM transmission signal with a predetermined pulse shape.

21. A User Equipment configured to perform the method recited in claim **11**.

22. An apparatus comprising:

a processor; and

a non-transitory memory coupled to the processor, the non-transitory memory including a set of instructions stored therein and executable by the processor to:

for a set of data symbols, perform an N-point discrete Fourier transform (DFT) spreading on the set of data symbols to generate a plurality N of DFT-spread data symbols;

map the N DFT-spread data symbols to at least N subcarriers of a plurality M of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers to generate a set of complex subcarrier amplitudes; and

perform an M-point inverse discrete Fourier transform (IDFT) on the set of complex subcarrier amplitudes to generate a time-domain sequence to be transmitted into a wireless channel, the time-domain sequence comprising a superposition of the OFDM subcarriers, wherein the N-point DFT spreading is configured to provide the superposition with a reduced peak-to-average power ratio.

23. The apparatus recited in claim **22**, wherein the N subcarriers comprise at least one of contiguous OFDM subcarriers and non-contiguous OFDM subcarriers.

24. The apparatus recited in claim **22**, configured to reside on a User Equipment.

25. The apparatus recited in claim **22**, wherein M>N.

26. The apparatus recited in claim **22**, wherein the IDFT comprises an inverse fast Fourier transform.

27. The apparatus recited in claim **22**, wherein the non-transitory memory further comprises instructions to perform pulse-shaping on at least one of a set of signals, the set comprising the plurality of DFT-spread data symbols and the time-domain sequence, in order to provide the superposition with a predetermined pulse shape.

28. The apparatus recited in claim **22**, wherein the non-transitory memory further comprises instructions to append at least one of a cyclic prefix, a postfix, and a guard interval to the time-domain sequence.

29. The apparatus recited in claim **22**, wherein the at least N subcarriers is selected based on a measured channel quality.

* * * * *

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(54) **PRE-CODING IN MULTI-USER MIMO**

(71) Applicant: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

(72) Inventor: **Steve Shattil**, Cheyenne, WY (US)

(73) Assignee: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

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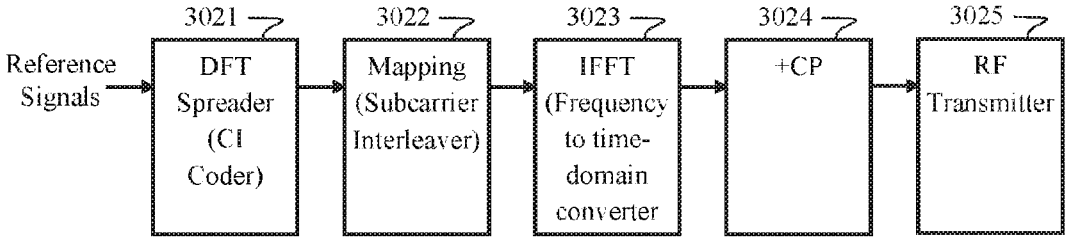
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Primary Examiner — Yee F Lam
(74) *Attorney, Agent, or Firm* — Steven J Shattil

(57) **ABSTRACT**

In a multi-user communication system, a pre-coder in a transmitter comprises a Discrete Fourier Transform (DFT) spreader provides data symbols spread with Fourier coefficients to generate DFT-spread data symbols. An OFDM modulator, such as an inverse-DFT, modulates the DFT-spread data symbols onto OFDM subcarriers to produce a pre-coded OFDM transmission signal. The Fourier coefficients reduce the transmission signal's peak to average power.

29 Claims, 33 Drawing Sheets



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LTE: Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding (3GPP TS 36.212 version 8.8.0 Release 8), Jan. 2010.

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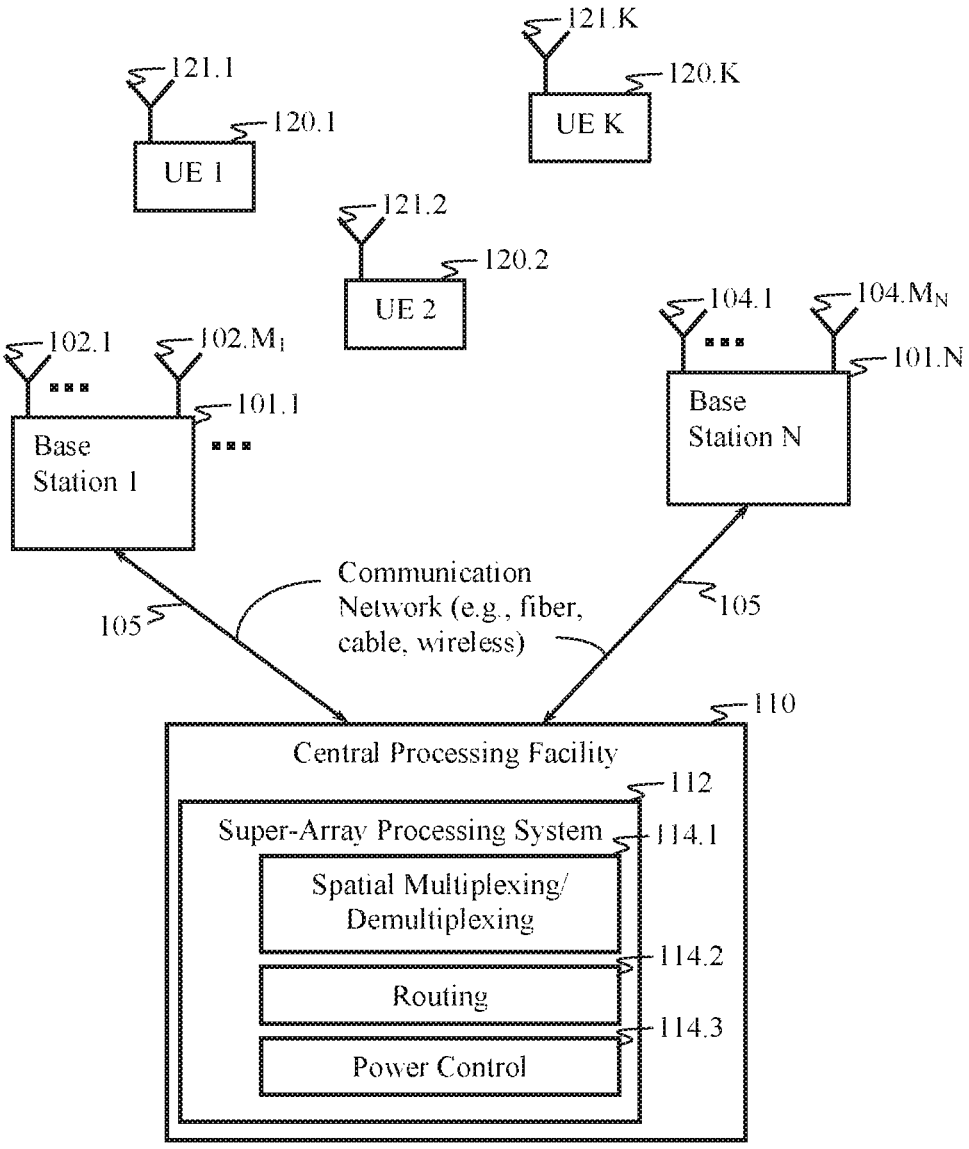

121.K
120.K
UE K
121.1
120.1
UE 1
121.2
120.2
UE 2
104.1
$104.M_N$
101.N
Base Station N
102.1
$102.M_1$
101.1
Base Station 1
105
Communication Network (e.g., fiber, cable, wireless)
105
110
Central Processing Facility
112
Super-Array Processing System
114.1
Spatial Multiplexing/ Demultiplexing
114.2
Routing
114.3
Power Control

Figure 1

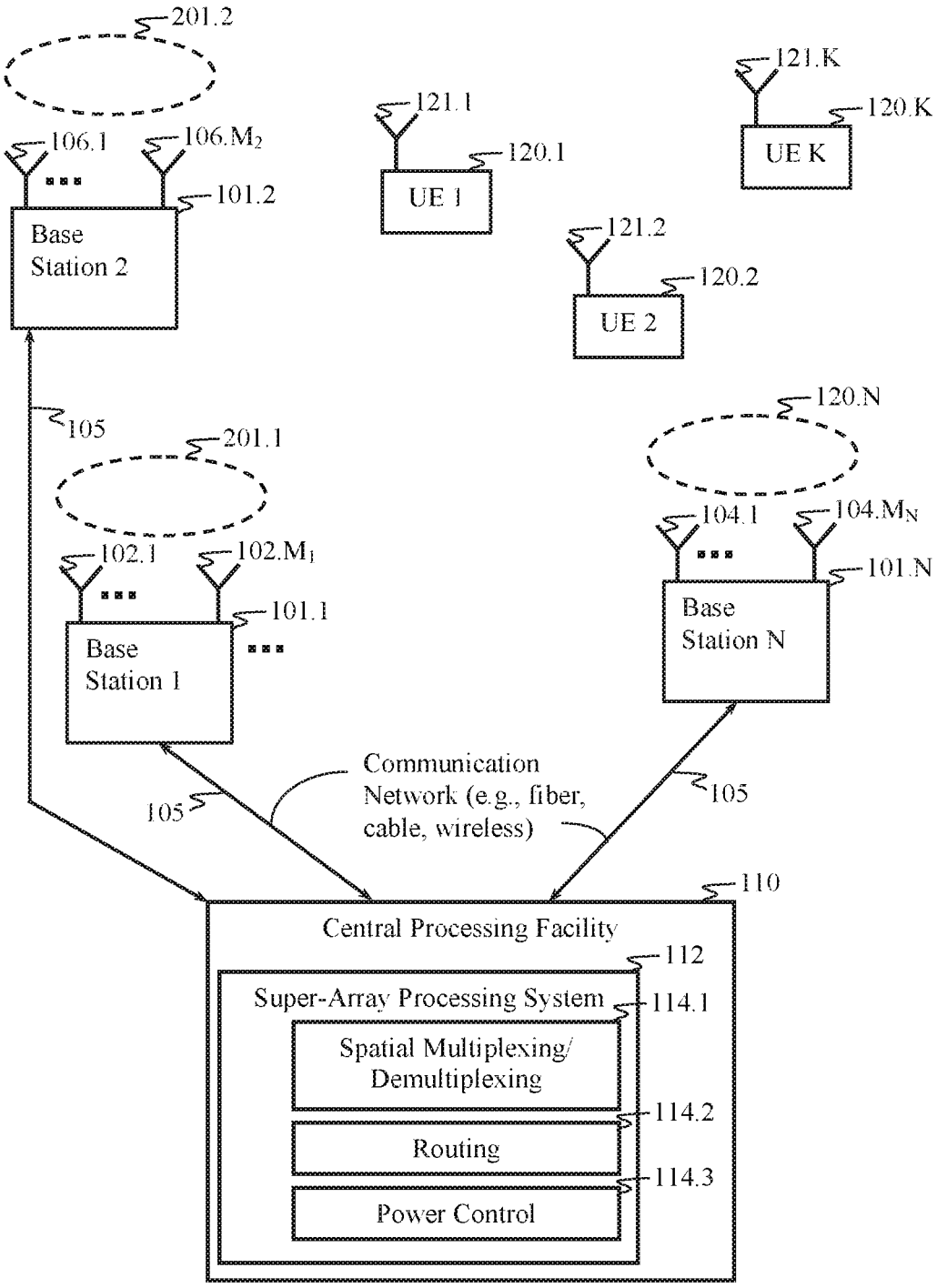

201.2
106.1
106.M2
101.2
Base Station 2
121.1
120.1
UE 1
121.K
120.K
UE K
121.2
120.2
UE 2
105
201.1
102.1
102.M1
101.1
Base Station 1
120.N
104.1
104.MN
101.N
Base Station N
Communication Network (e.g., fiber, cable, wireless)
105
105
110
Central Processing Facility
112
Super-Array Processing System
114.1
Spatial Multiplexing/ Demultiplexing
114.2
Routing
114.3
Power Control

Figure 2

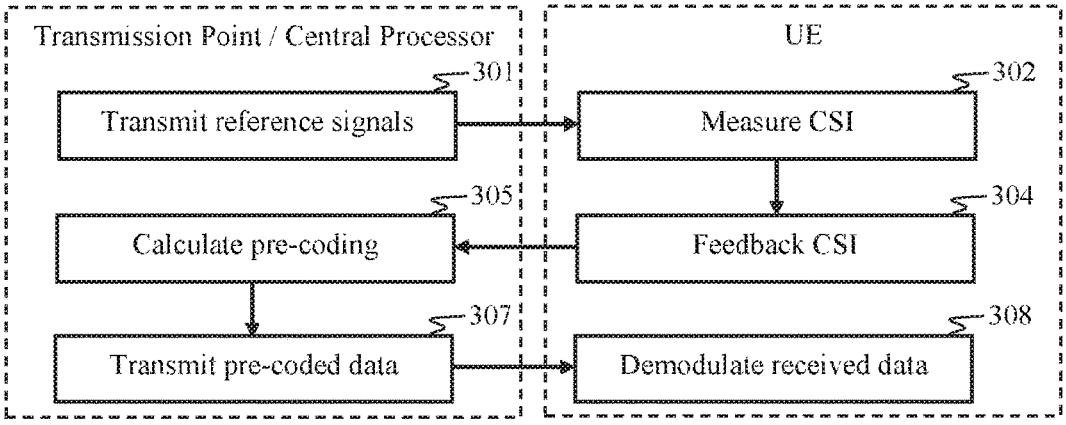


Figure 3A

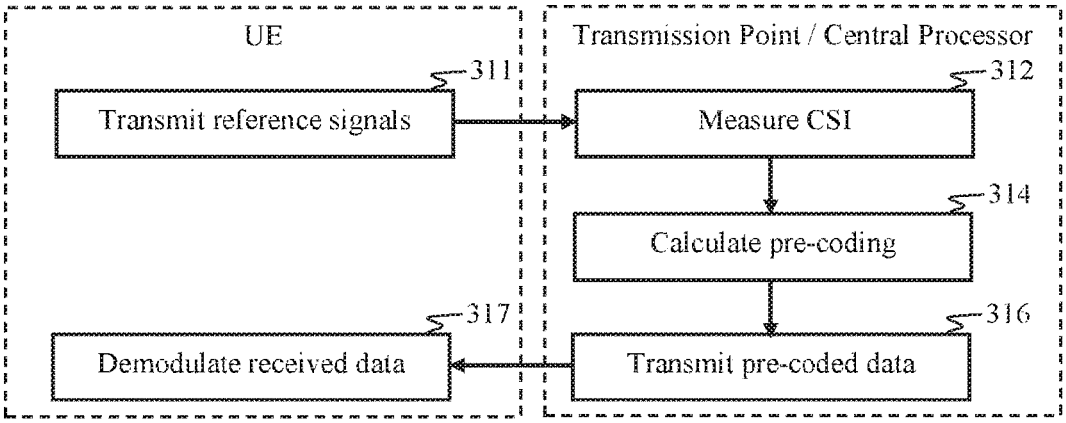


Figure 3B

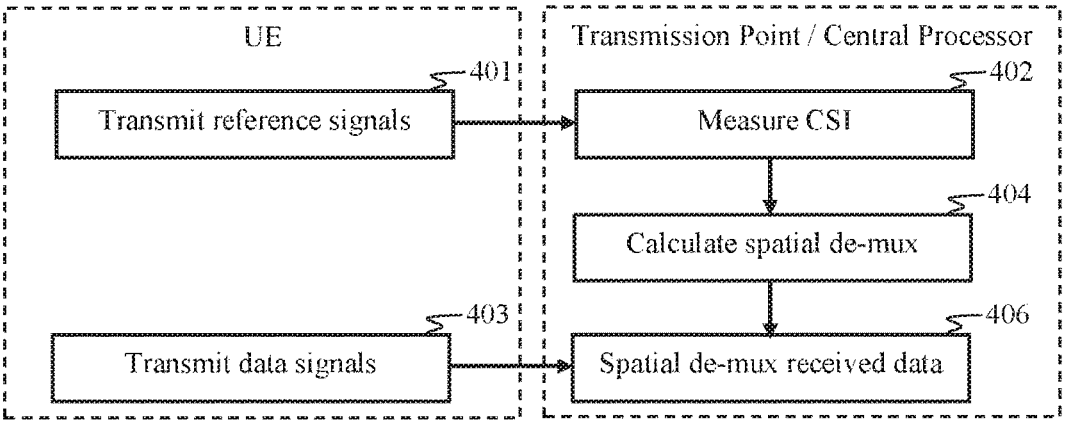


Figure 4A

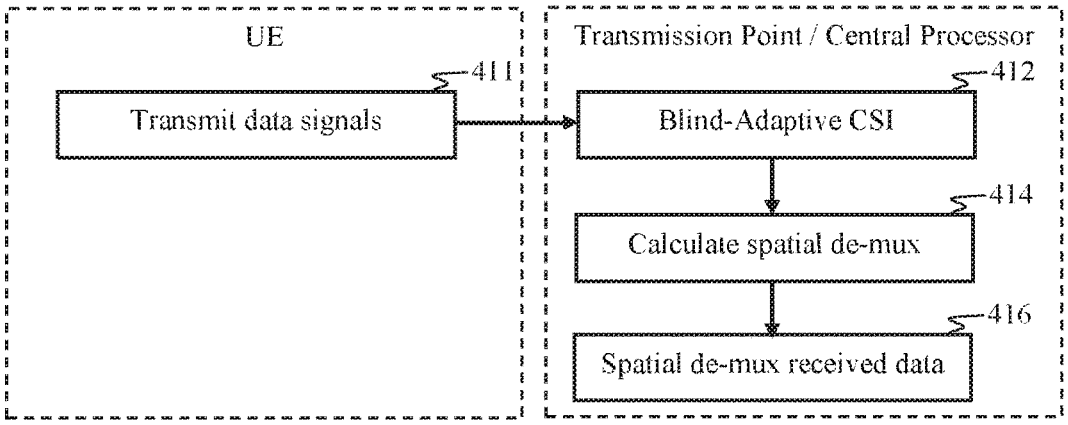


Figure 4B

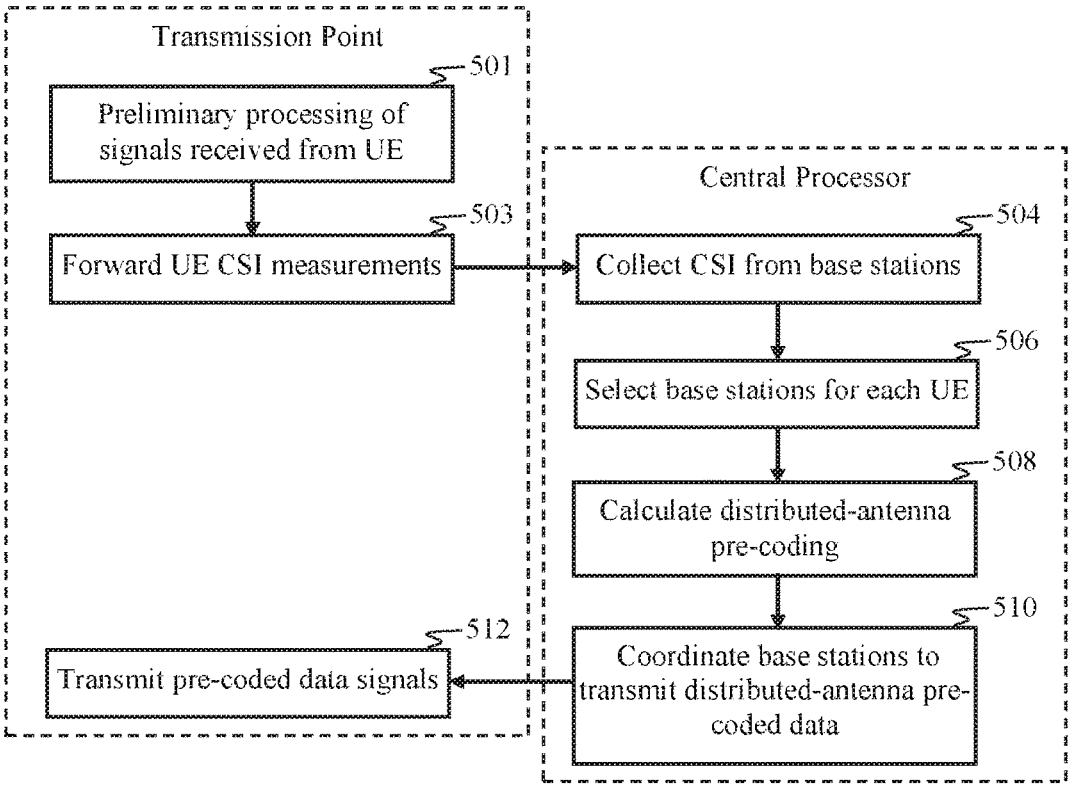

Transmission Point
501
Preliminary processing of signals received from UE
503
Forward UE CSI measurements
512
Transmit pre-coded data signals
Central Processor
504
Collect CSI from base stations
506
Select base stations for each UE
508
Calculate distributed-antenna pre-coding
510
Coordinate base stations to transmit distributed-antenna pre-coded data

Figure 5

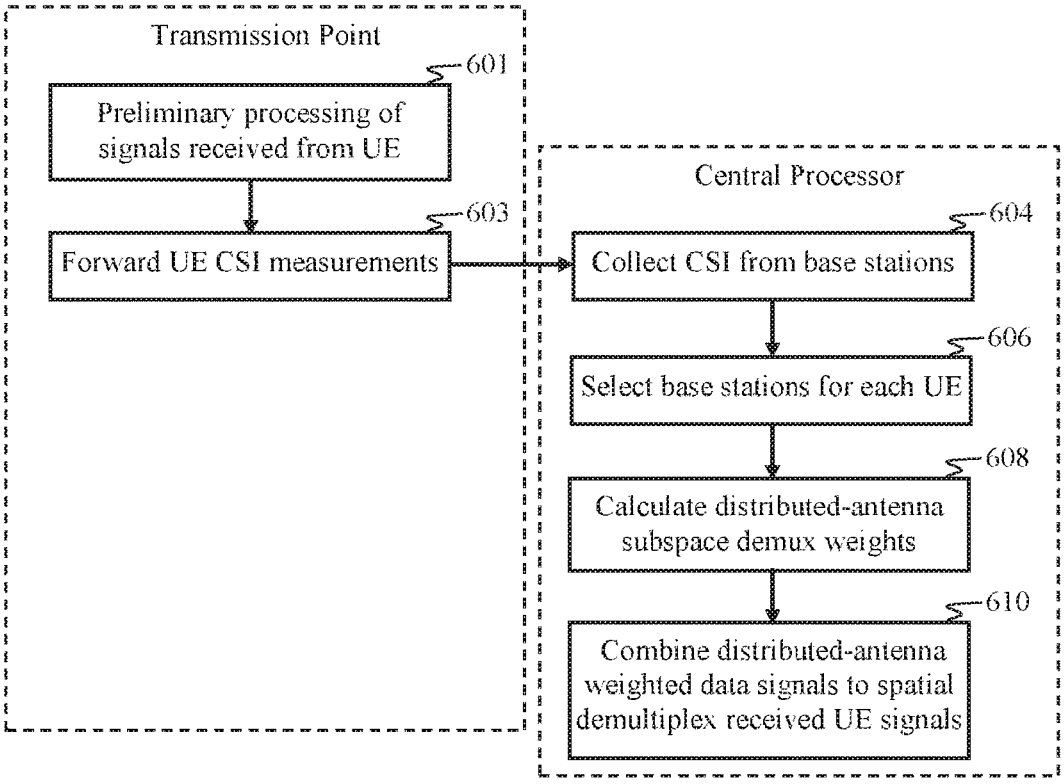

Transmission Point
601
Preliminary processing of signals received from UE
603
Forward UE CSI measurements
Central Processor
604
Collect CSI from base stations
606
Select base stations for each UE
608
Calculate distributed-antenna subspace demux weights
610
Combine distributed-antenna weighted data signals to spatial demultiplex received UE signals

Figure 6

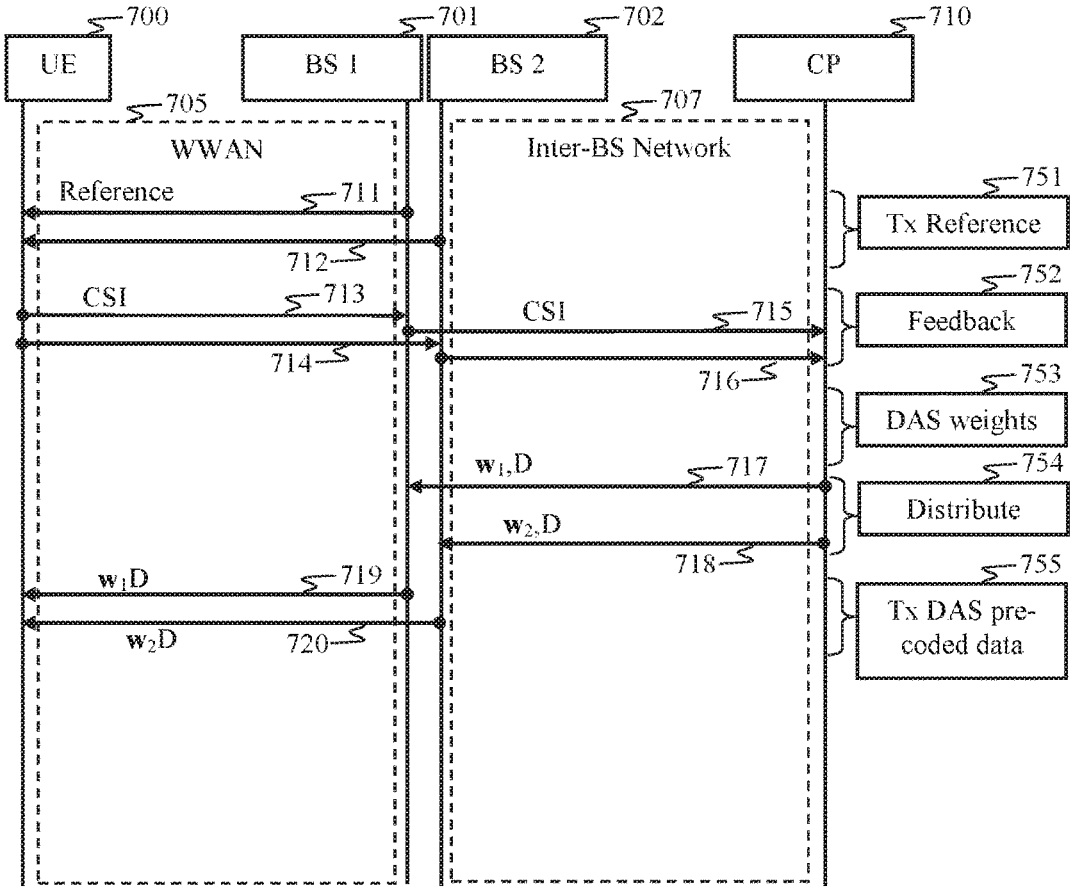

700
UE
701
BS 1
702
BS 2
710
CP
705
WWAN
707
Inter-BS Network
Reference
711
712
CSI
713
714
CSI
715
716
751
Tx Reference
752
Feedback
753
DAS weights
754
Distribute
755
Tx DAS pre-coded data
w1,D
717
w2,D
718
w1D
719
w2D
720

Figure 7

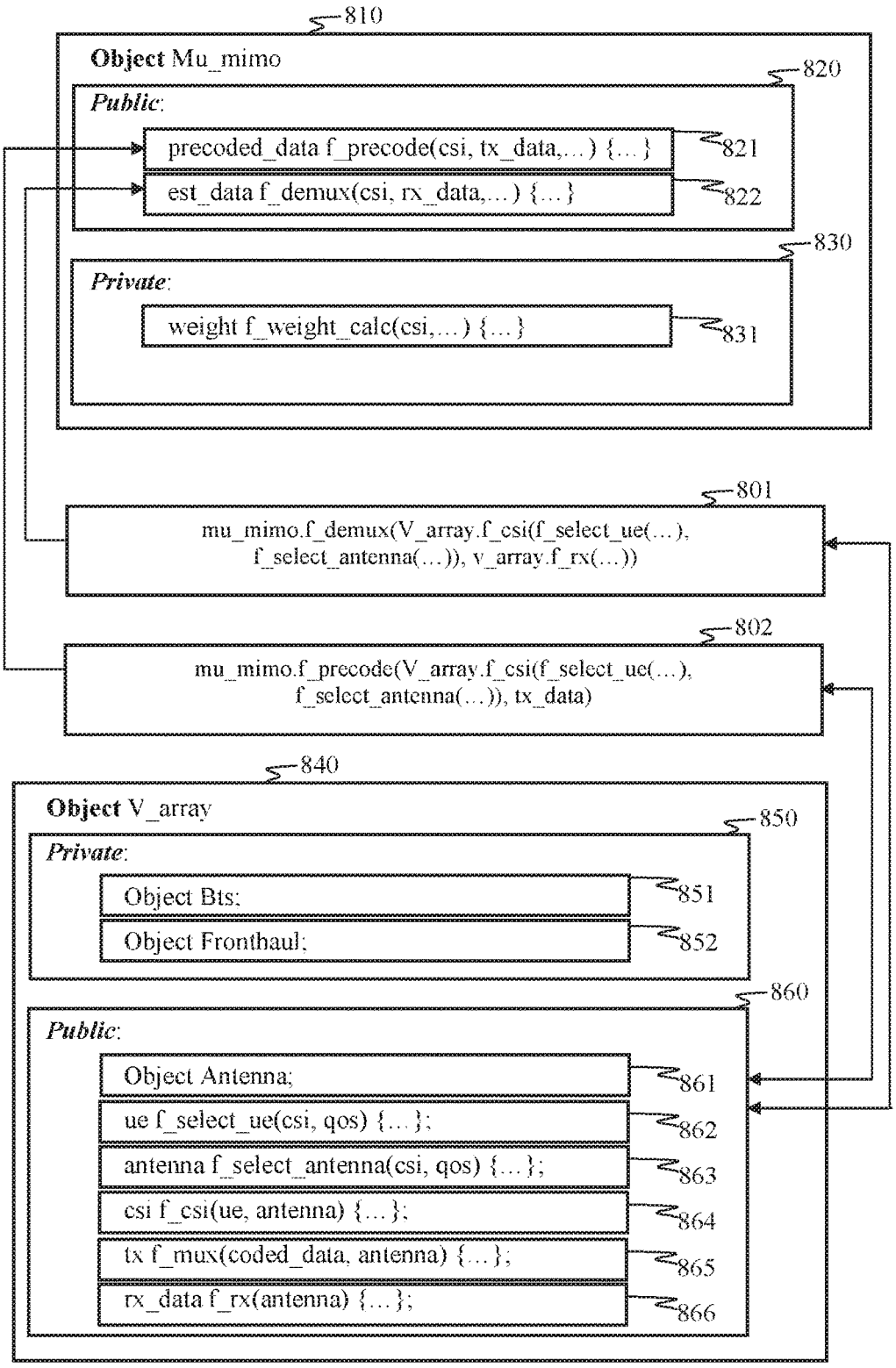

810
Object Mu_mimo
820
Public:
precoded_data f_precode(csi, tx_data,…) {…}
821
est_data f_demux(csi, rx_data,…) {…}
822
830
Private:
weight f_weight_calc(csi,…) {…}
831
801
mu_mimo.f_demux(V_array.f_csi(f_select_ue(…), f_select_antenna(…)), v_array.f_rx(…))
802
mu_mimo.f_precode(V_array.f_csi(f_select_ue(…), f_select_antenna(…)), tx_data)
840
Object V_array
850
Private:
Object Bts;
851
Object Fronthaul;
852
860
Public:
Object Antenna;
861
ue f_select_ue(csi, qos) {…};
862
antenna f_select_antenna(csi, qos) {…};
863
csi f_csi(ue, antenna) {…};
864
tx f_mux(coded_data, antenna) {…};
865
rx_data f_rx(antenna) {…};
866

Figure 8

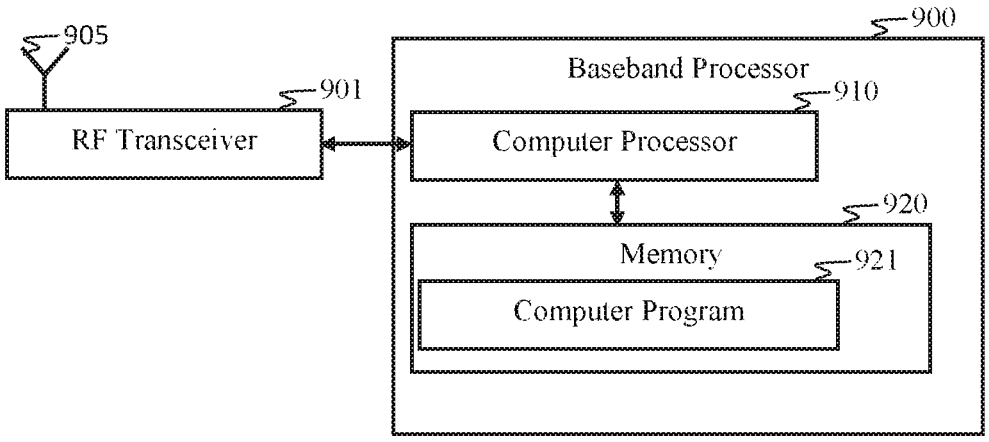

905
900
Baseband Processor
901
910
RF Transceiver
Computer Processor
920
Memory
921
Computer Program

Figure 9

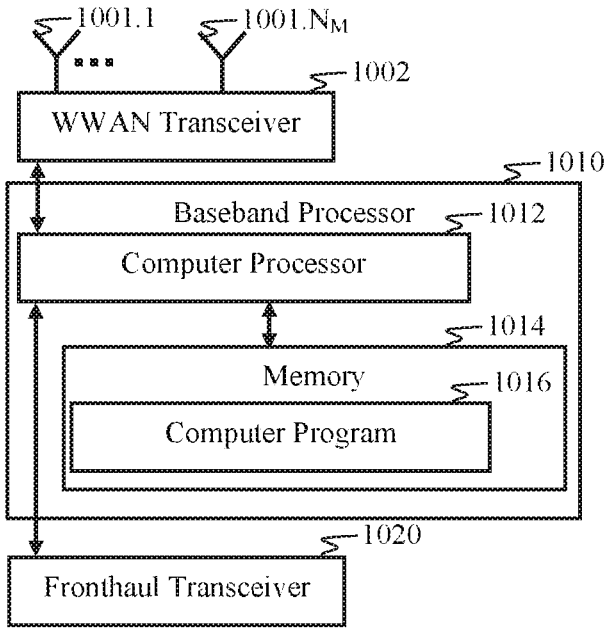

1001.1
1001.N_M
1002
WWAN Transceiver
1010
Baseband Processor
1012
Computer Processor
1014
Memory
1016
Computer Program
1020
Fronthaul Transceiver

Figure 10

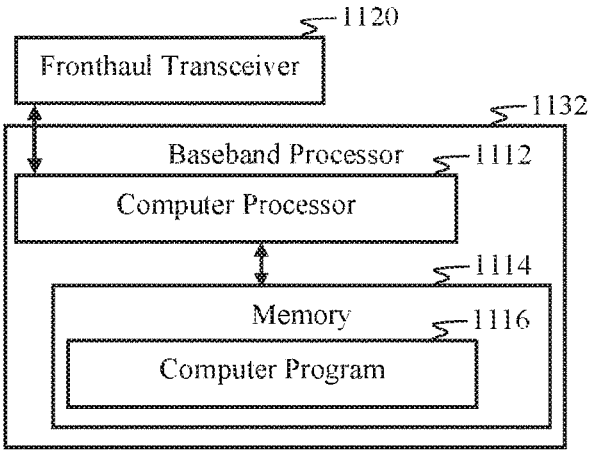


Figure 11A

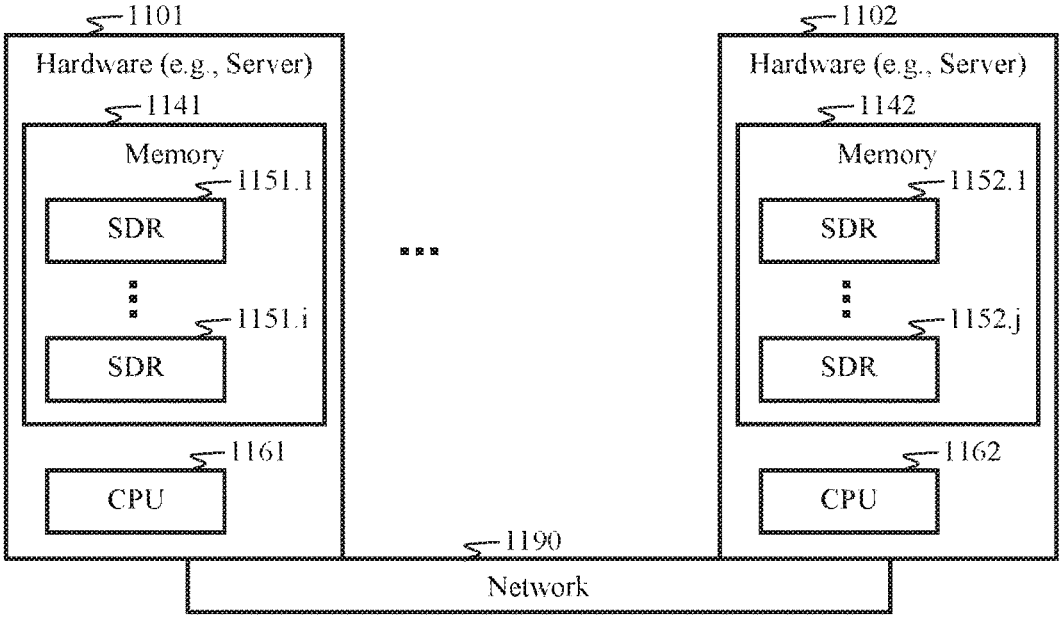


Figure 11B

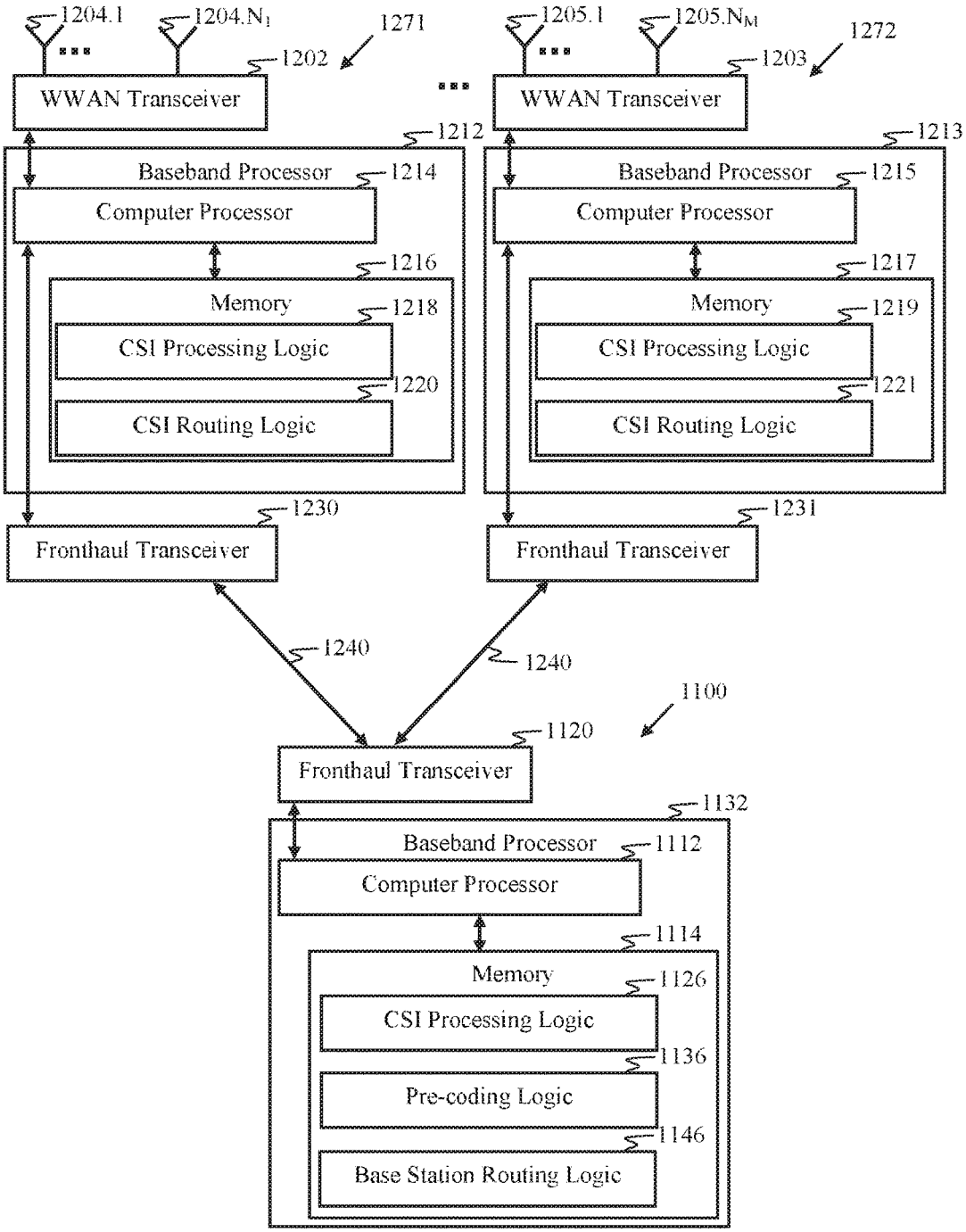

1204.1
1204.N1
1271
1205.1
1205.NM
1272
1202
1203
WWAN Transceiver
WWAN Transceiver
1212
1213
Baseband Processor
1214
Baseband Processor
1215
Computer Processor
Computer Processor
1216
1217
Memory
1218
Memory
1219
CSI Processing Logic
CSI Processing Logic
1220
1221
CSI Routing Logic
CSI Routing Logic
1230
1231
Fronthaul Transceiver
Fronthaul Transceiver
1240
1240
1100
1120
Fronthaul Transceiver
1132
Baseband Processor
1112
Computer Processor
1114
Memory
1126
CSI Processing Logic
1136
Pre-coding Logic
1146
Base Station Routing Logic

Figure 12

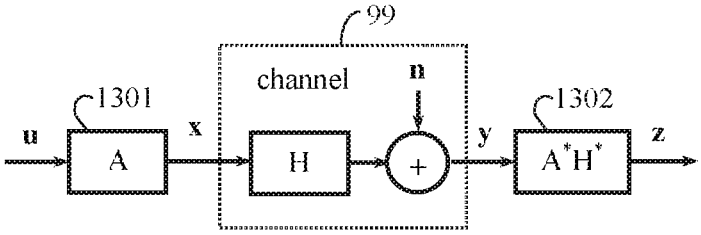


Figure 13A

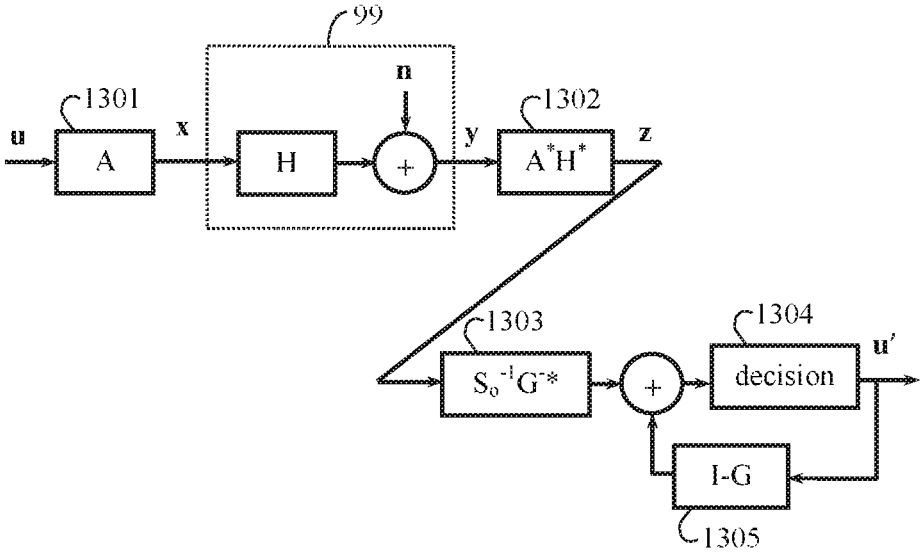


Figure 13B

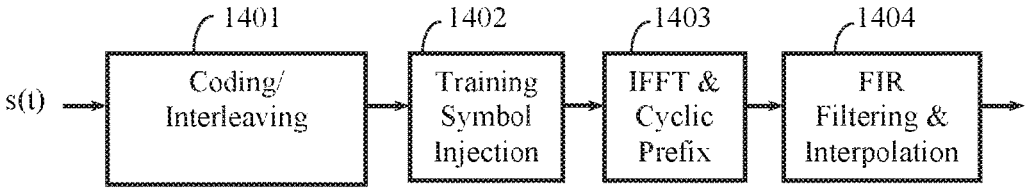


Figure 14A

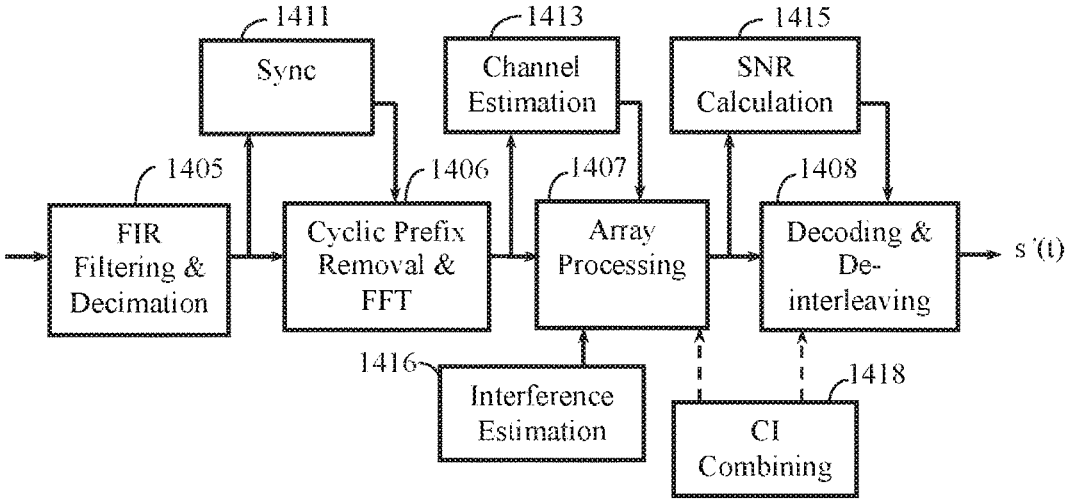


Figure 14B

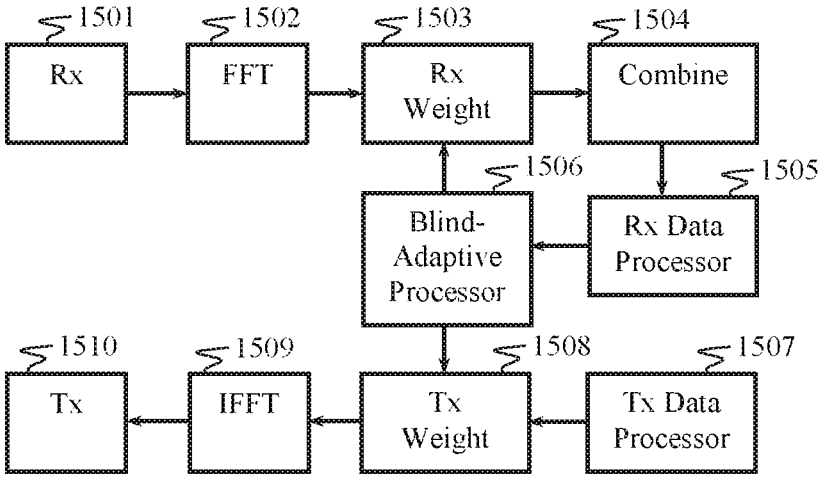

1501
Rx
1502
FFT
1503
Rx Weight
1504
Combine
1506
Blind-Adaptive Processor
1505
Rx Data Processor
1510
Tx
1509
IFFT
1508
Tx Weight
1507
Tx Data Processor

Figure 15

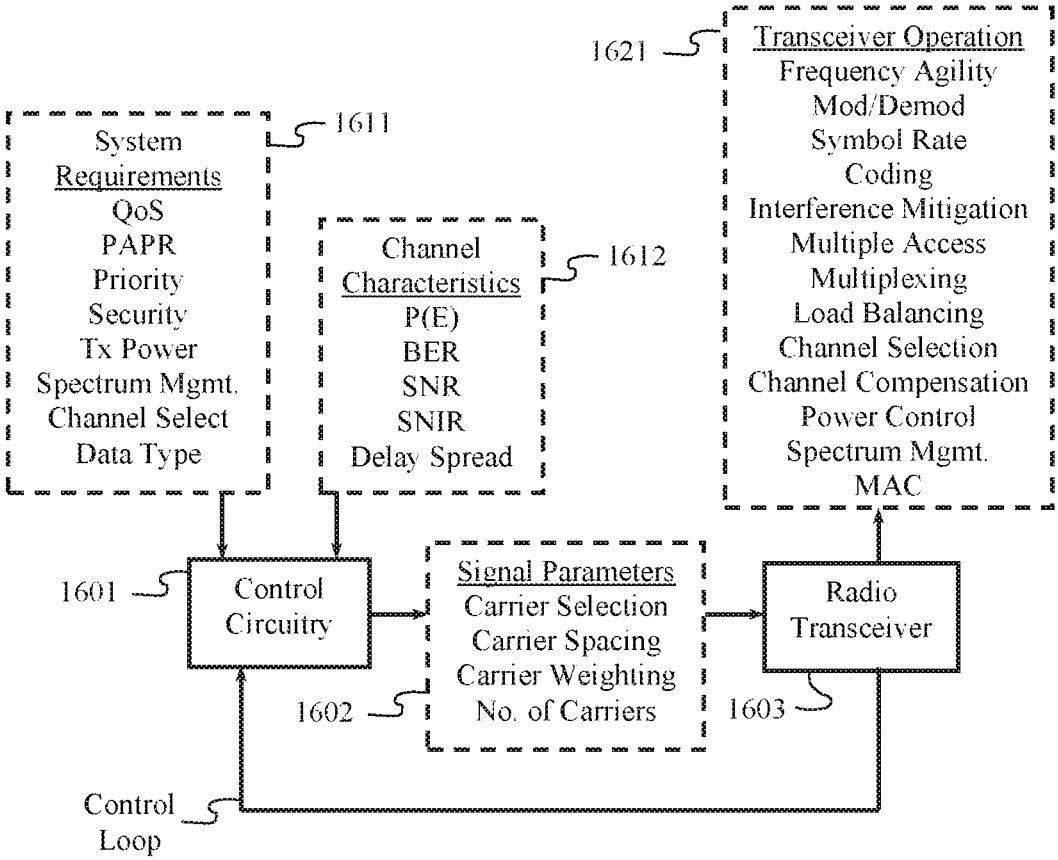

1621
Transceiver Operation
Frequency Agility
Mod/Demod
Symbol Rate
Coding
Interference Mitigation
Multiple Access
Multiplexing
Load Balancing
Channel Selection
Channel Compensation
Power Control
Spectrum Mgmt.
MAC
1611
System
Requirements
QoS
PAPR
Priority
Security
Tx Power
Spectrum Mgmt.
Channel Select
Data Type
1612
Channel
Characteristics
P(E)
BER
SNR
SNIR
Delay Spread
1601
Control
Circuitry
Signal Parameters
Carrier Selection
Carrier Spacing
Carrier Weighting
No. of Carriers
1602
Radio
Transceiver
1603
Control
Loop

Figure 16

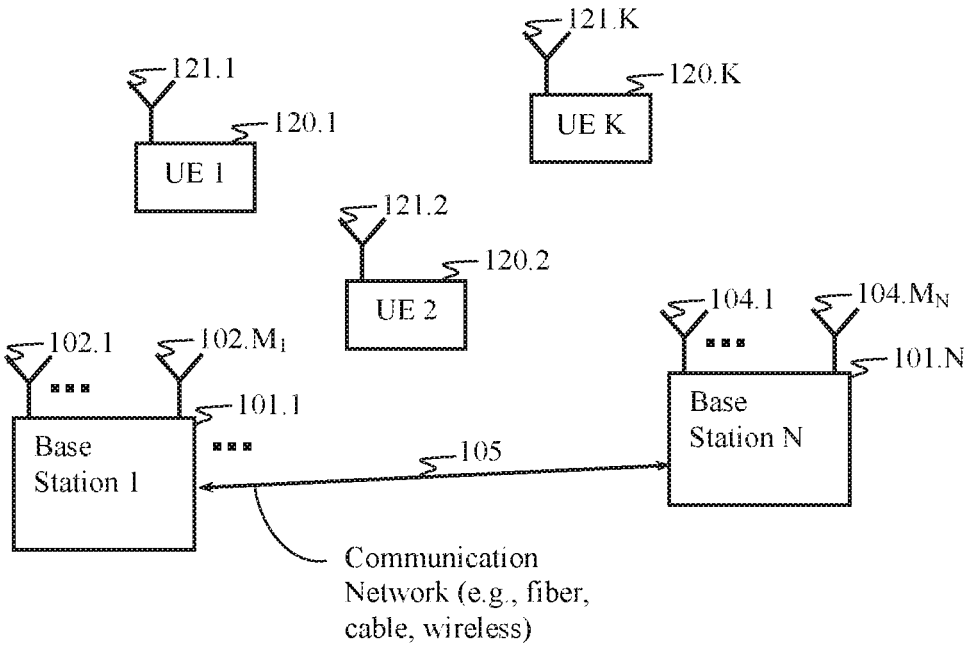

121.K
120.K
UE K
121.1
120.1
UE 1
121.2
120.2
UE 2
104.1
104.M_N
101.N
102.1
102.M_1
101.1
Base Station 1
Base Station N
105
Communication Network (e.g., fiber, cable, wireless)

Figure 17

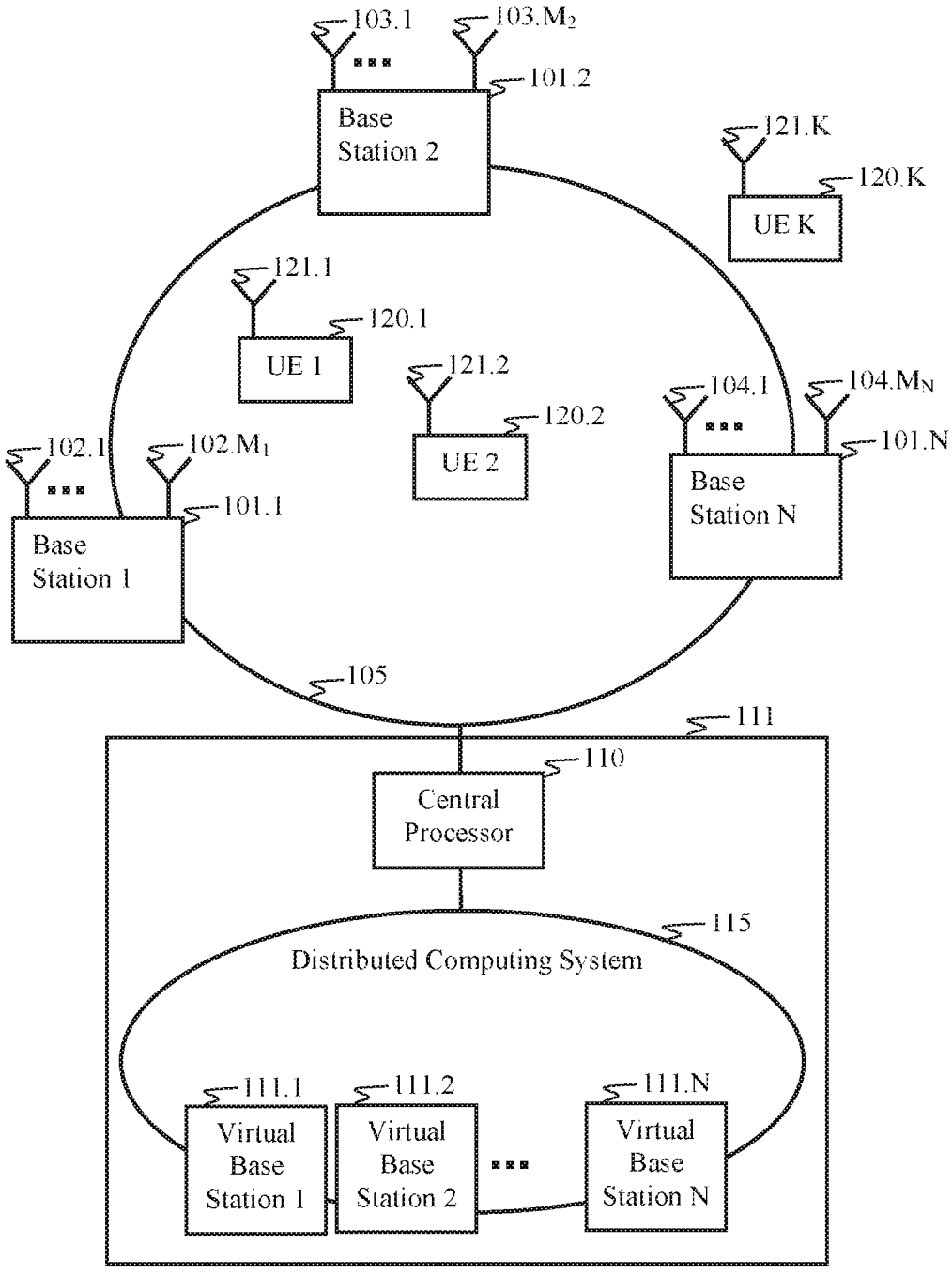

103.1
103.M2
101.2
Base Station 2
121.K
120.K
UE K
121.1
120.1
UE 1
121.2
120.2
UE 2
104.1
104.MN
101.N
Base Station N
102.1
102.M1
101.1
Base Station 1
105
111
110
Central Processor
115
Distributed Computing System
111.1
111.2
111.N
Virtual Base Station 1
Virtual Base Station 2
Virtual Base Station N

Figure 18

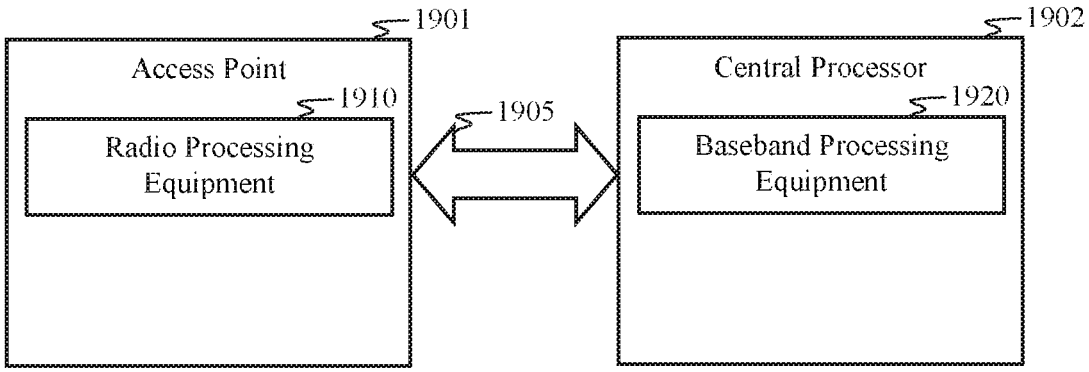

1901
Access Point
1910
Radio Processing Equipment
1905
1902
Central Processor
1920
Baseband Processing Equipment

Figure 19

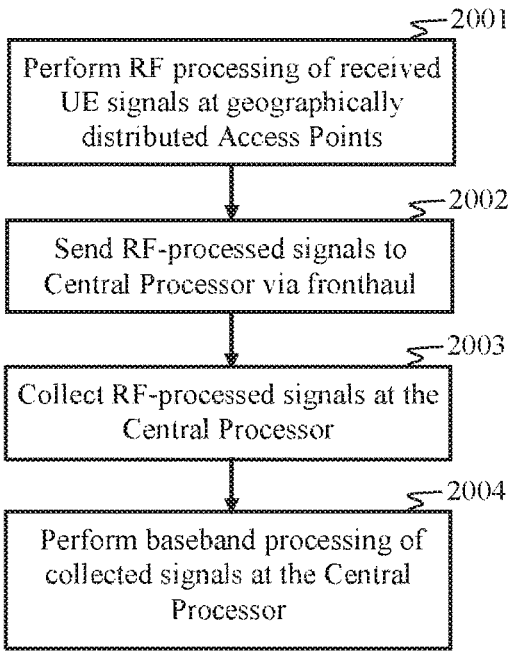


Figure 20A

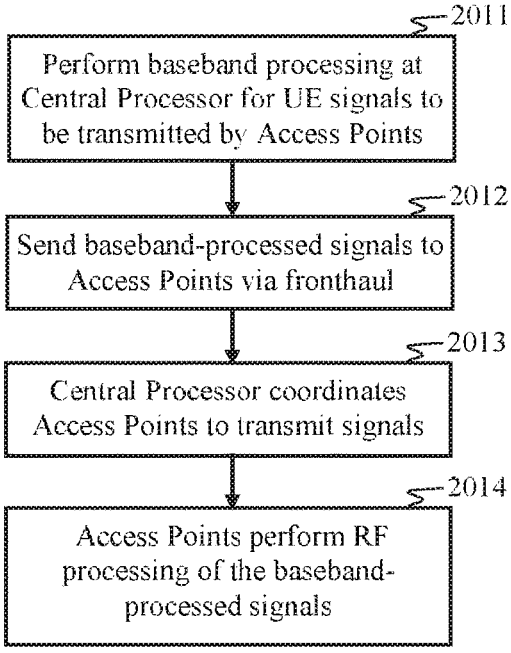


Figure 20B

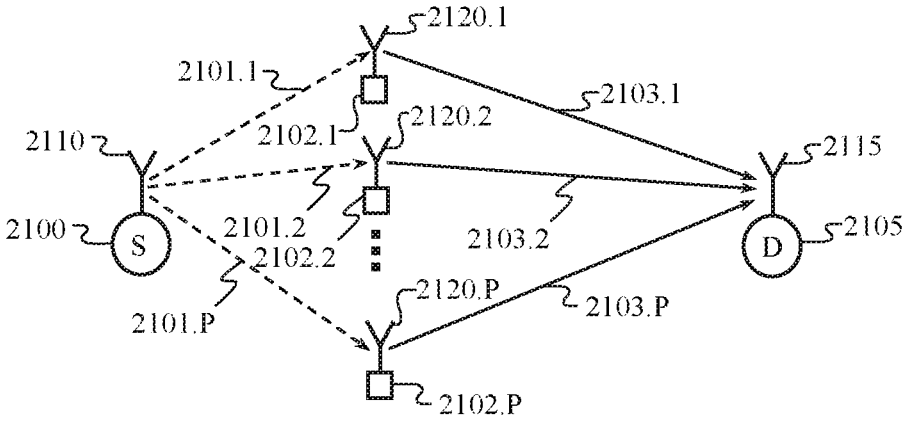

2120.1
2101.1
2103.1
2102.1
2120.2
2110
2115
2100
S
2101.2
2102.2
2103.2
D
2105
2120.P
2103.P
2101.P
2102.P

Figure 21

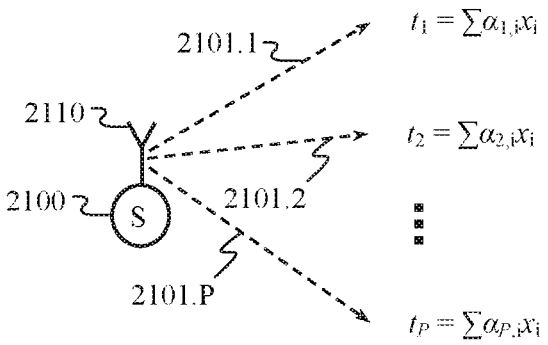


Figure 22A

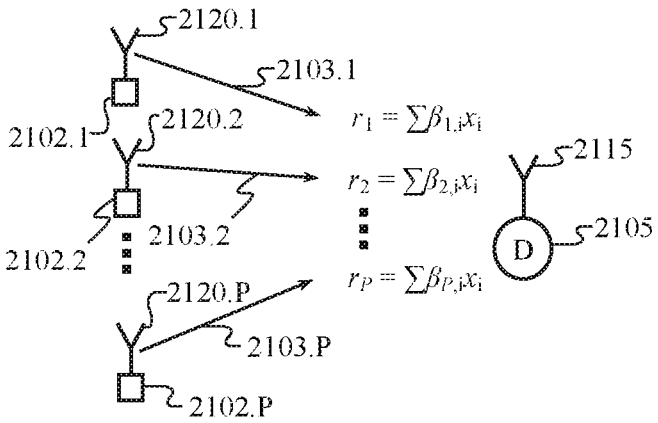


Figure 22B

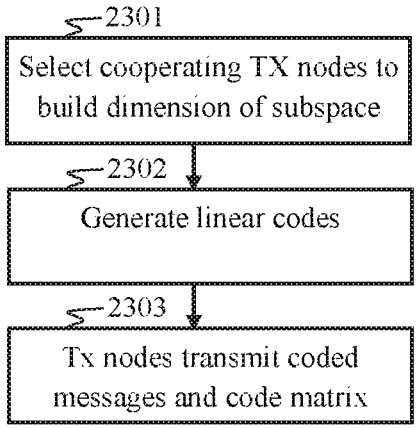


Figure 23A

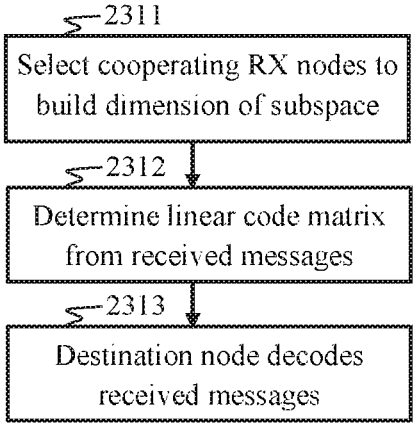


Figure 23B

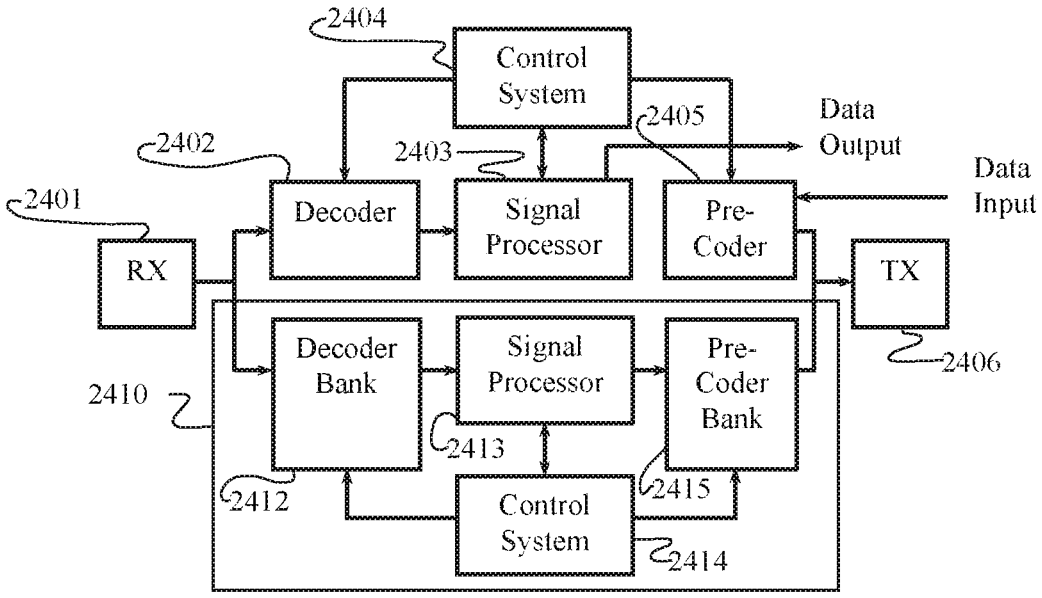


Figure 24A

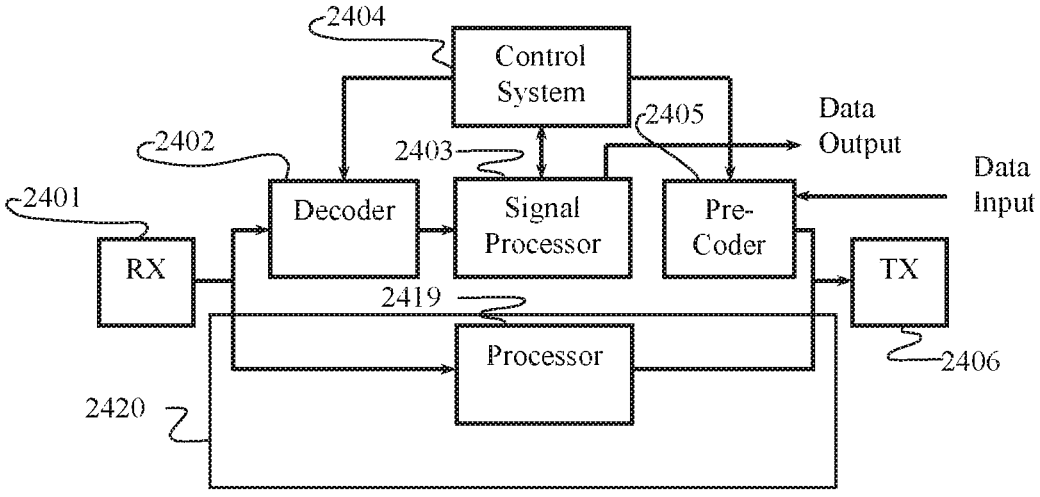


Figure 24B

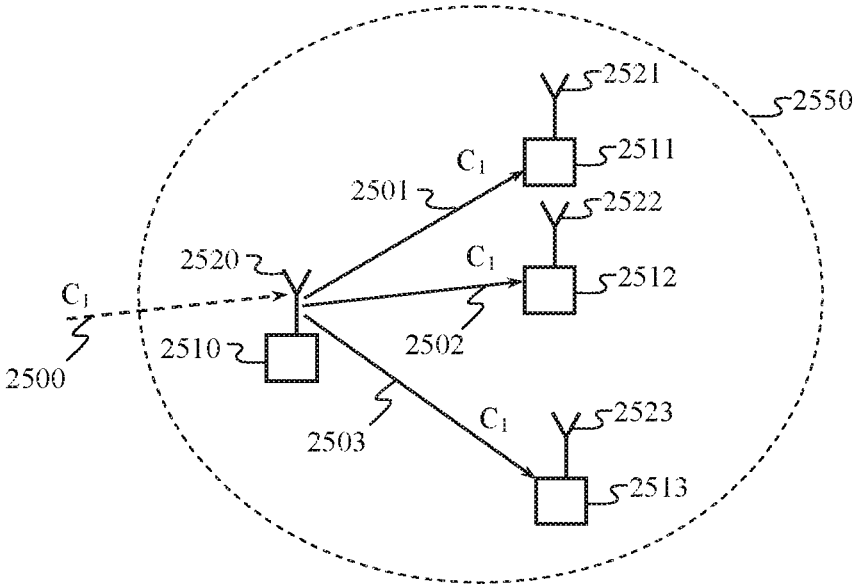


Figure 25A

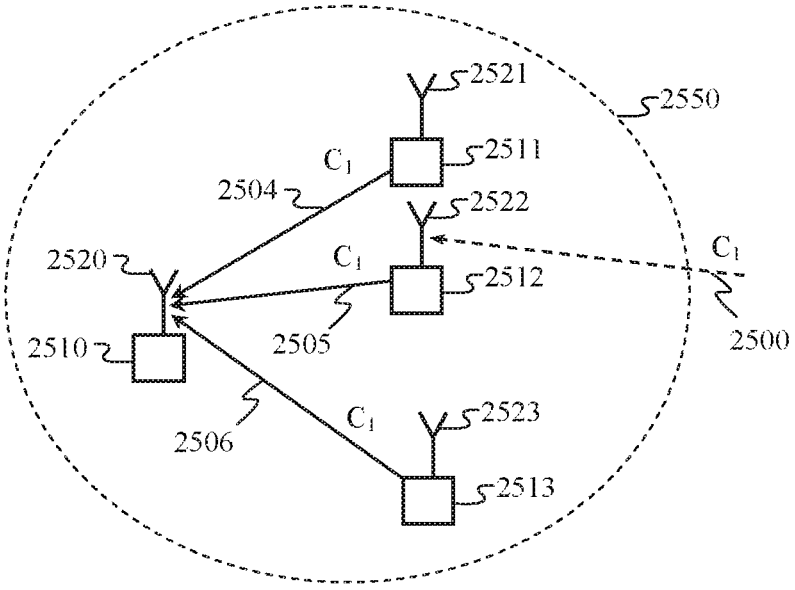


Figure 25B

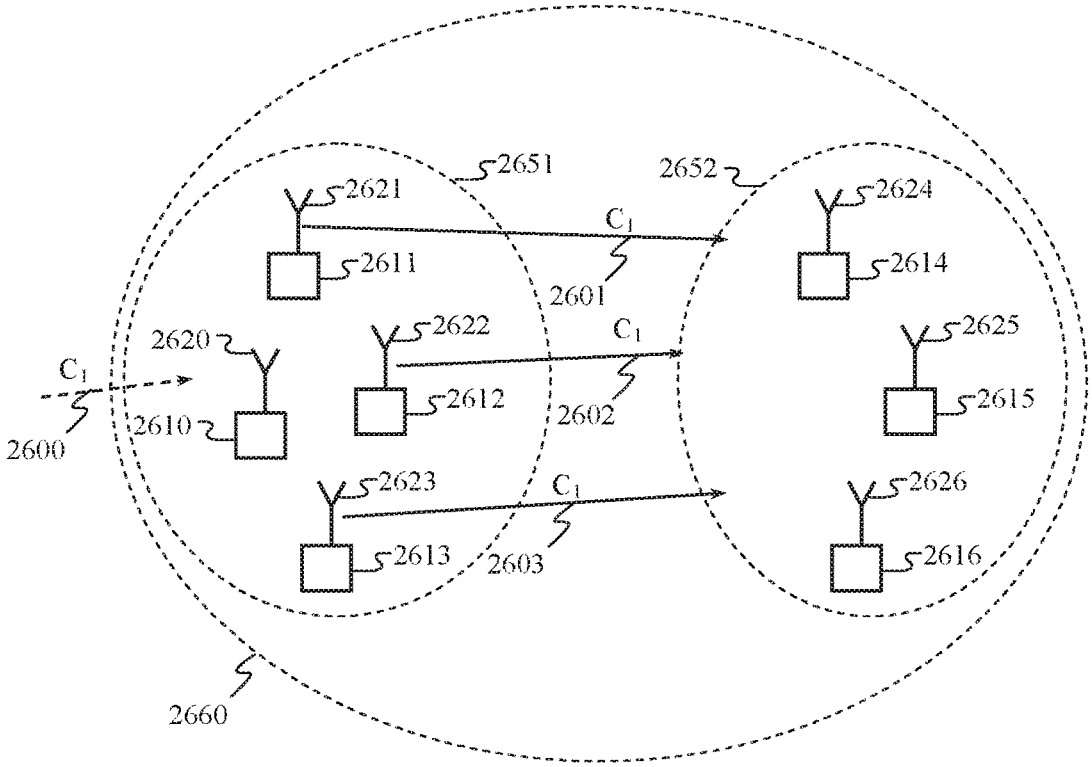

2651
2652
2621
2624
C1
2611
2614
2601
2620
2622
C1
2625
C1
2612
2615
2610
2602
2600
2623
C1
2626
2613
2603
2616
2660

Figure 26

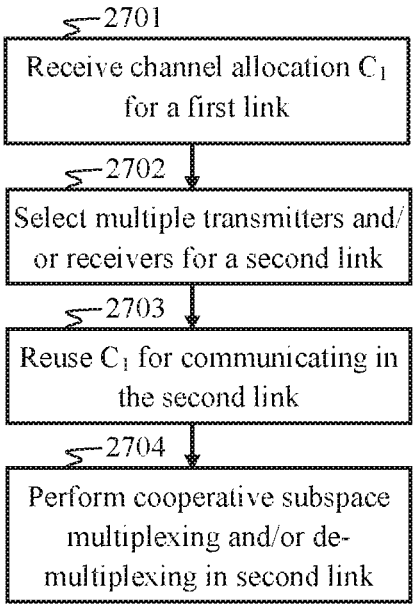

2701
Receive channel allocation C_1 for a first link
2702
Select multiple transmitters and/or receivers for a second link
2703
Reuse C_1 for communicating in the second link
2704
Perform cooperative subspace multiplexing and/or de-multiplexing in second link

Figure 27

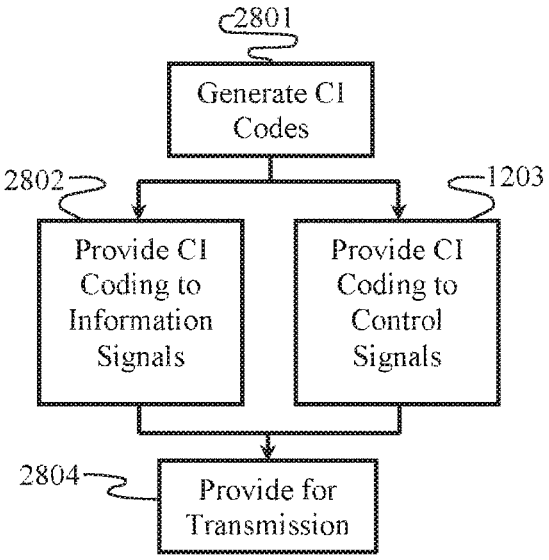


FIG. 28A

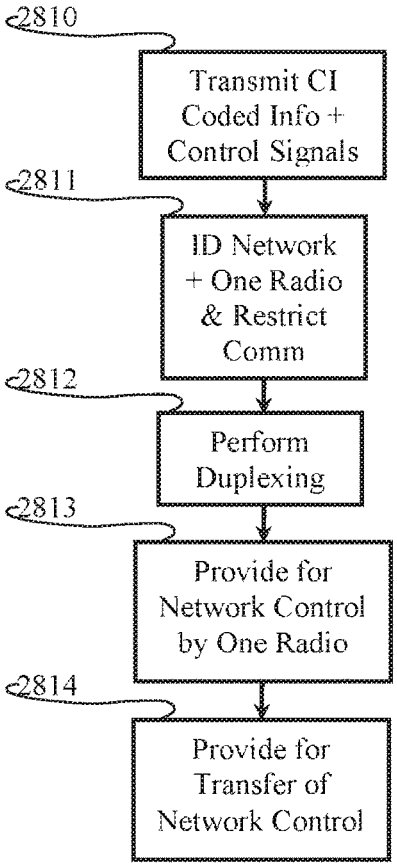


FIG. 28B

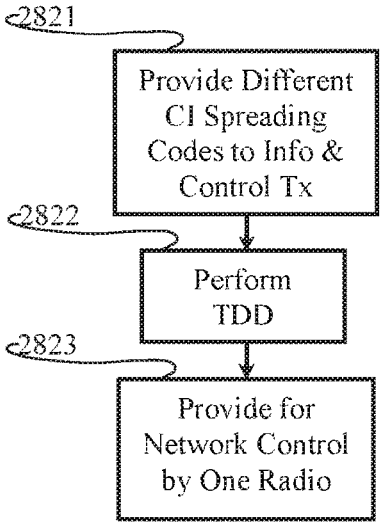


FIG. 28C

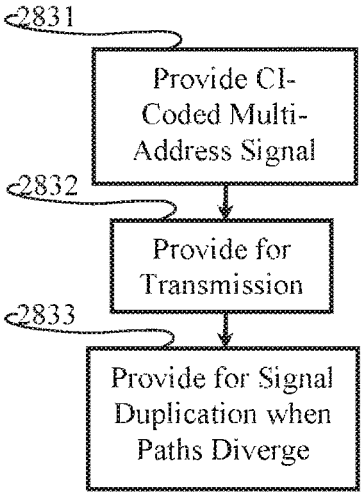


FIG. 28D

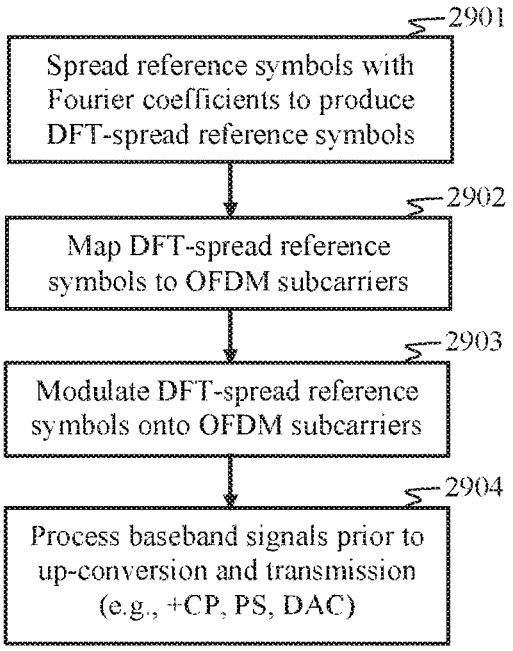


Figure 29A

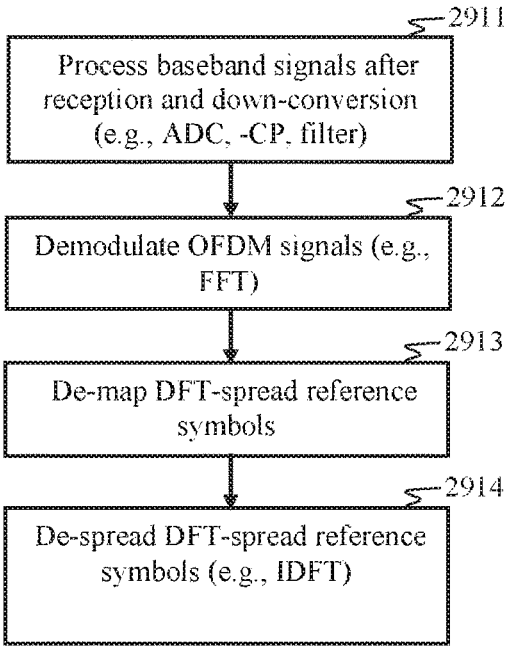


Figure 29B

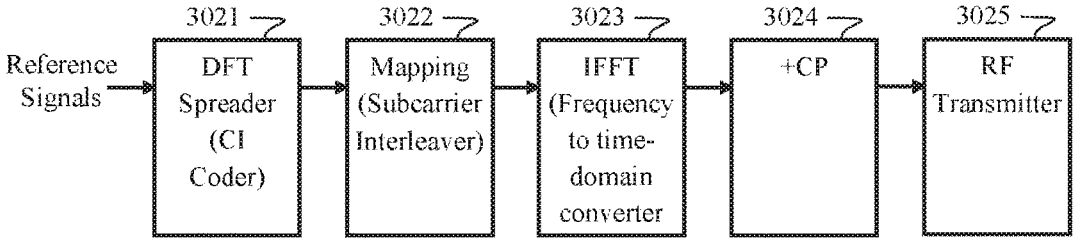


Figure 30A

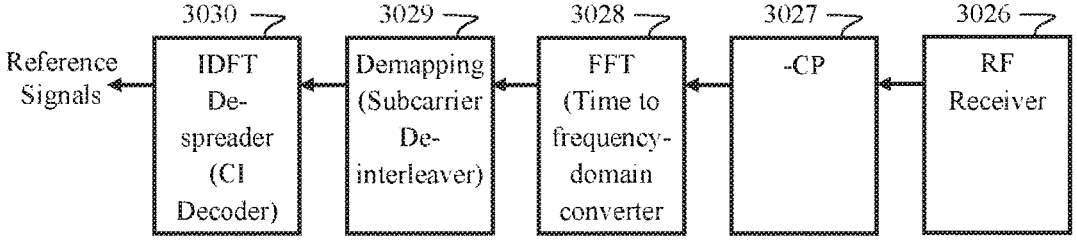


Figure 30B

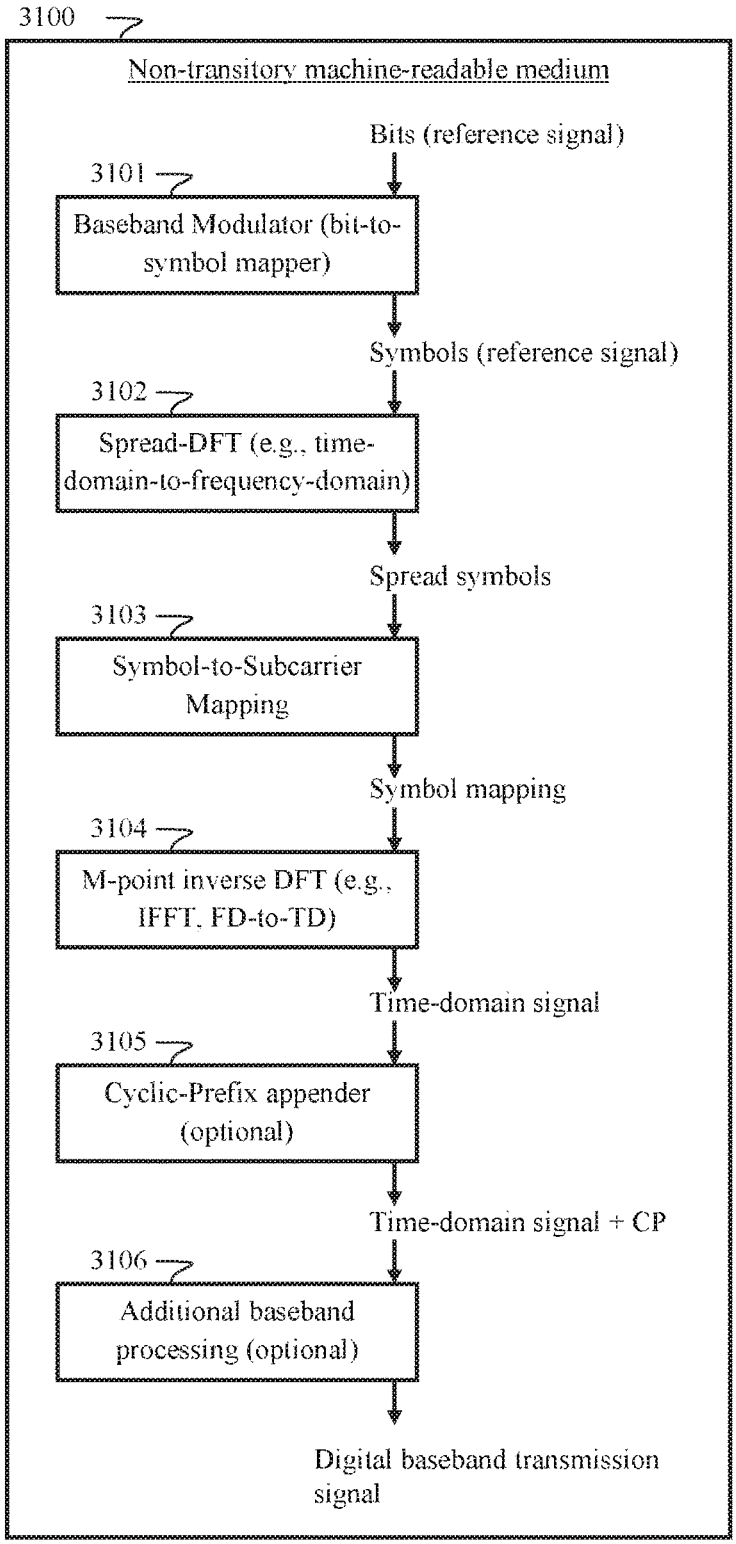

3100
Non-transitory machine-readable medium
Bits (reference signal)
3101
Baseband Modulator (bit-to-symbol mapper)
Symbols (reference signal)
3102
Spread-DFT (e.g., time-domain-to-frequency-domain)
Spread symbols
3103
Symbol-to-Subcarrier Mapping
Symbol mapping
3104
M-point inverse DFT (e.g., IFFT, FD-to-TD)
Time-domain signal
3105
Cyclic-Prefix appender (optional)
Time-domain signal + CP
3106
Additional baseband processing (optional)
Digital baseband transmission signal

Figure 31

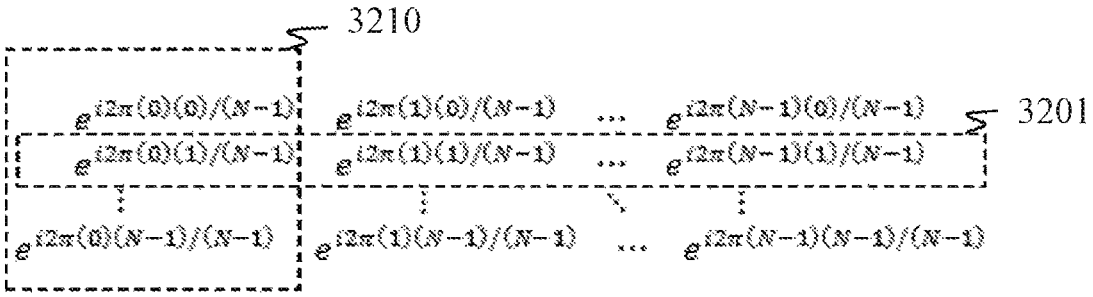

3210
3201
$e^{i2\pi(0)(0)/(N-1)}$
$e^{i2\pi(1)(0)/(N-1)}$
...
$e^{i2\pi(N-1)(0)/(N-1)}$
$e^{i2\pi(0)(1)/(N-1)}$
$e^{i2\pi(1)(1)/(N-1)}$
...
$e^{i2\pi(N-1)(1)/(N-1)}$
$e^{i2\pi(0)(N-1)/(N-1)}$
$e^{i2\pi(1)(N-1)/(N-1)}$
...
$e^{i2\pi(N-1)(N-1)/(N-1)}$

Figure 32

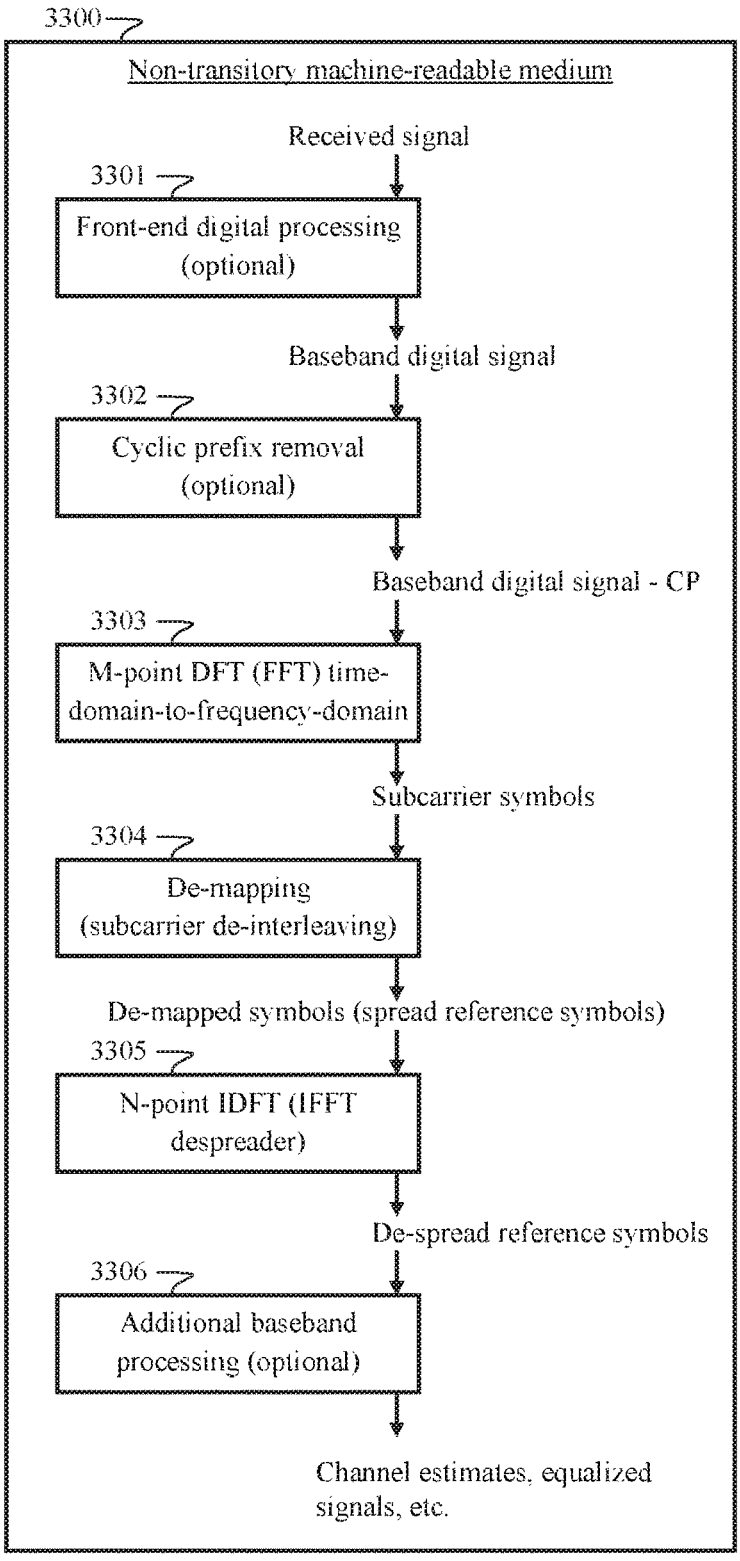

3300
Non-transitory machine-readable medium
Received signal
3301
Front-end digital processing (optional)
Baseband digital signal
3302
Cyclic prefix removal (optional)
Baseband digital signal - CP
3303
M-point DFT (FFT) time-domain-to-frequency-domain
Subcarrier symbols
3304
De-mapping (subcarrier de-interleaving)
De-mapped symbols (spread reference symbols)
3305
N-point IDFT (IFFT despreader)
De-spread reference symbols
3306
Additional baseband processing (optional)
Channel estimates, equalized signals, etc.

Figure 33

PRE-CODING IN MULTI-USER MIMO

RELATED APPLICATIONS

This application is a Continuation-in-Part of U.S. patent application Ser. No. 14/168,466 filed Jan. 30, 2014, which is a Continuation-in-Part of U.S. patent application Ser. No. 11/187,107 filed Jul. 22, 2005, now U.S. Pat. No. 8,670,390, which claims priority to Provisional Appl. No. 60/598,187, filed Aug. 2, 2004, and which is a Continuation-in-Part of U.S. patent application Ser. No. 10/145,854, filed May 14, 2002, each of which is expressly incorporated by reference in its entirety. The patent applications, U.S. patent application Ser. No. 15/149,382, filed May 9, 2016; U.S. patent application Ser. No. 13/116,984, filed May 26, 2011; U.S. patent application Ser. No. 12/328,917, filed Dec. 5, 2008, now U.S. Pat. No. 7,965,761; U.S. patent application Ser. No. 11/621,014, filed Jan. 8, 2007, now U.S. Pat. No. 7,593,449; U.S. patent application Ser. No. 10/131,163, filed Apr. 24, 2002, now U.S. Pat. No. 7,430,257; and U.S. Provisional Application 60/286,850, filed Apr. 26, 2001 are expressly incorporated by reference in their entireties.

BACKGROUND

I. Field

The present invention relates generally to wireless communication networks, and more specifically to spread Orthogonal Frequency Division Multiplexing.

II. Background

The background description includes information that may be useful in understanding the present inventive subject matter. It is not an admission that any of the information provided herein is prior art or relevant to the presently claimed inventive subject matter, or that any publication, specifically or implicitly referenced, is prior art.

Communication over the spatial modes of a point-to-point MIMO channel was developed in the early 90s [e.g., S. J. Shattil, U.S. Pat. No. 6,211,671] then gradually extended to multi-user (MU-) MIMO channels [e.g., S. J. Shattil, U.S. Pat. No. 6,008,760].

In a conventional cellular communication system, transmissions to different users are formed independently. Hence, the transmission to one user can act as interference to other users. Because the system forms the transmission to each user independently, the system has no way of knowing how a transmission to a particular user will impact other users in the vicinity. As a result, interference between cells is a main factor limiting the performance of current cellular systems. For users near a cell boundary, inter-cell interference is especially problematic.

Fading and interference are the two key challenges faced by designers of mobile communication systems. While fading puts limits on the coverage and reliability of any point-to-point wireless connection, e.g., between a base station and a mobile terminal, interference in prior-art networks restricts the reusability of the spectral resource (time, frequency slots, codes, etc.) in space, thus limiting the overall spectral efficiency expressed in bits/sec/Hz/base station.

The conventional approach to interference mitigation is spatial reuse partitioning, which prevents any spectral resource from being re-used within a certain cluster of cells. Typically, the frequency re-use factor is much less than unity such that the level of co-channel interference is low. Thus, interference is controlled by fixing the frequency reuse pattern and the maximum power spectral density levels of each base station. Some CDMA systems allow for full frequency re-use in each cell, but at the expense of severe interference at the cell edge, resulting in a significant data rate drop at the terminals and a strong lack of fairness across cell users. Some interference mitigation can be achieved via limited inter-cell coordination, such as soft handover techniques. Inter-cell interference is typically treated as noise at the receiver side and is handled by resorting to improved point-to-point communications between the base station and the mobile station using efficient coding and/or single-link multiple-antenna techniques.

Some of the proposals for increasing the capacity of cellular networks include using more spectrum, increasing the number of transmit/receive antennas on each station, using dedicated beams to serve users, and micro-cell deployment. However, none of these approaches adequately address inter-cell interference, which is a primary bottleneck for spectral efficiency.

In the traditional cellular architecture, each base station only connects to a fixed number of sector antennas that cover a small area and only provide transmission/reception in its coverage area. Ideally, in such networks, the coverage areas of different base stations do not substantially overlap, as the system capacity is limited by interference. In these networks, interference makes it difficult to improve spectrum efficiency and network capacity. Another drawback to traditional cellular systems is that the base stations are built on proprietary platforms as a vertical solution.

Operators of prior-art cellular systems are faced with many challenges. For example, the high complexity of traditional base stations requires costly initial investment, site support, site rental, and management support. Building more base station sites imposes substantial infrastructure and operational expenses on the network operator. Furthermore, since the base stations can't share processing power with each other, network energy efficiency, processing efficiency, and infrastructure utilization efficiency are low because the average network load is typically far lower than the peak load. Specifically, each base station's processing capability can only benefit the active users in its cell. Thus, a base station's processing capability is wasted when the network load within its cell is low, while at other times it may be oversubscribed. Also, an idle or lightly loaded base station consumes almost as much power as it does under peak loads.

These and other drawbacks of the prior art can be reduced or eliminated by exemplary aspects of the disclosure.

As explained above, prior-art broadband wireless technologies are band-limited or interference-limited, meaning that their spectral efficiency reaches an upper limit set by the laws of Physics, such as indicated by the Shannon formulas. While the spatial domain adds another dimension to exploit via cell planning and sectoring, increasing the cell density (e.g., micro-cells, pico-cells, femto-cells) beyond a certain point fails to mitigate the performance decline as more users demand services. This is because smaller cells result in increased inter-cell interference, which establishes a practical upper bound for cell density. While the spectral efficiency of prior-art technologies is limited by the laws of Physics, the demand for data bandwidth keeps growing. As a result, today's cellular networks are already experiencing declining data rates per user.

Thus, there is a compelling need in the broadband wireless industry for systems and methods of wireless communications in which network performance is not hard-limited by the laws of Physics, but rather increases according to advances in computer processing technologies, such as

indicated by Moore's law. Only systems and methods such as disclosed herein can meet the growing demands for broadband wireless data services.

SUMMARY

Aspects of the disclosure describe cooperative-MIMO processing which comprise MIMO processing wherein the multiple input (MI) comprises downlink transmissions from multiple base transceiver stations and the multiple output (MO) comprises uplink transmissions to multiple base transceiver stations. Aspects of the disclosure also indicate that cooperative-MIMO processing can employ user equipment (UEs). In accordance with some aspects, combinations of base transceiver stations and UEs are configured for cooperative-MIMO processing.

In accordance with the deficiencies of the prior art, some aspects of the disclosure can eliminate problems due to inter-cell interference near cell boundaries by simply eliminating the cell boundaries. For example, unlike soft hand-off in which two base stations merely employ the same radio channel to serve a handset at a cell boundary, geographically distributed base stations can be coordinated to function together as a distributed antenna system with overlapping coverage areas and configured to perform subspace antenna array processing. Since subspace antenna array transmissions can produce constructive and destructive interference zones (i.e., amplified-signal and cancelled-signal zones) in a rich scattering environment, provisioning of radio resources in accordance with networks and methods disclosed herein can benefit from types of spatial reuse that far outperform cellular-based (e.g., honeycomb) spatial reuse schemes that rely on signal attenuation via path loss.

Whereas prior-art cellular systems strive to reduce inter-cell and intra-cell interference, aspects of the disclosure exploit interference to achieve substantial performance gains. Some exemplary aspects dramatically improve system performance, including throughput, coverage, signal quality, and spectral efficiency, by exploiting inter-cell (and/or intra-cell) interference. Furthermore, since capacity in a downlink multi-user MIMO system depends on the number of transmitting antennas, coordinating multiple geographically distributed base transceiver stations to cooperatively perform multi-user MIMO processing can effectively increase the number of transmitting antennas, and thus, downlink system capacity (which can translate into a combination of serving more users, increasing data rates per user, and improving quality metrics of the communication links). Some aspects of the disclosure produce similar benefits for uplink performance in a multi-user MIMO system.

In some aspects, radio transceivers operating in networks disclosed herein can perform either or both client and server operations. By way of example, a UE may be configured to operate as a base transceiver antenna in a Cooperative-MIMO configuration with one or more base transceiver systems, thereby increasing the rank of the channel matrix, which enables more subspace channels to be employed in the uplink and/or downlink. The UE may be coordinated with the one or more base transceiver systems via a fronthaul network, including the radio access network (e.g., the WWAN). By way of example, a base transceiver system may be configured to operate as a UE in a local group of UEs organized in a Cooperative-MIMO configuration. The base transceiver can be configured to communicate with the local group via a local area network (e.g., a UE fronthaul network used to coordinate the group of UEs) in order to increase the rank of the channel matrix employed for uplink and/or downlink subspace processing.

Aspects of the disclosure may be provided for achieving a large number of objectives and applications which are too numerous to list herein. Therefore, only some of the objects and advantages of exemplary aspects are discussed in the Summary and in the Detailed Description. In some aspects of the disclosure, interference is dealt with using cooperative MIMO so as to increase the number of co-channel links that can coexist with acceptable quality of service. For example, in the high-SNR regime, this figure of merit corresponds to the maximum number of concurrent interference-free transmissions, which is referred to as the multiplexing gain of the network, or the number of degrees of freedom in the information-theoretic terminology.

Some aspects of the disclosure provide various types of interference-aware multi-cell coordination. For example, in some aspects, base stations no longer tune separately their physical and link/MAC layer parameters (power level, time slot, subcarrier usage, beamforming coefficients, etc.) or decode independently of one another, but instead coordinate their coding and/or decoding operations on the basis of global channel state and user data information exchanged over fronthaul (e.g., backhaul) links among multiple cells. Coordination protocols can exploit existing fronthaul links (e.g., WiMax, 4G LTE, optical fiber) or may require a design upgrade to accommodate additional overhead. There are various degrees of cooperation, offering a trade-off between performance gains and the amount of overhead placed on fronthaul and/or other channels, including over-the-air feedback channels.

In some aspects of the disclosure, such as disclosed in the '850 application, certain network control functions are performed in a cooperative fashion by a central processing unit for a set of cooperating base transceiver stations. The central processing unit can be incorporated in one of the cooperating base transceiver stations, which can be connected with any of the other cooperating base transceiver stations via a low-latency, high-capacity fronthaul network. Various network control functions can be performed by the central processing unit, including resource allocation (e.g., scheduling) and power control.

In some aspects of the disclosure, antenna array processing performed by the central processing unit can mitigate inter-cell interference caused by simultaneous transmissions scheduled on the same frequency resource by nearby base transceiver stations. In one aspect, the central processing unit coordinates beamforming (e.g., calculates array-processing weights from channel measurements and coordinates transmissions of the base transceiver stations) such that one base transceiver station provides for coherent combining of its transmissions at a target UE while at least one other base transceiver station produces transmissions that destructively combine at the target UE. In another aspect, the central processing unit is configured to perform joint processing of subspace signals for coordinated multi-point transmissions, wherein multiple base transceiver stations serve a target UE with subspace-coded transmissions. For example, multiple base transceiver stations can be provided with subspace pre-coding weights calculated from channel measurements, and their transmissions can be coordinated such that the set of base transceiver stations functions jointly as an array of transmitters that produces multiple non-interfering subspace channels. Specifically, first portions of subspace-coded transmissions from antennas on multiple ones of the base transceiver stations combine coherently at the target UE to produce at least a first data

stream, whereas at least second portions of the subspace-coded transmissions from different ones of the base transceiver stations combine destructively at the target UE to cancel at least a second data stream, wherein the at least second data stream is intended for at least one other UE. Subspace processing in the disclosed aspects can include various techniques, including, but not limited to, maximum ratio combining (MRC), zero-forcing (ZF), and minimum mean square error (MMSE) techniques.

In one aspect of the disclosure, a network of M connected J-antenna base stations can serve a total of MJ terminals in an interference-free manner simultaneously, regardless of how strong the interference is. To achieve this remarkable result, multi-user spatial pre-coding and decoding can be employed on the downlink and uplink, respectively.

In accordance with some aspects of the disclosure, a cloud radio access network (C-RAN) comprises multiple geographically distributed base transceiver stations, a high-bandwidth low-latency optical transport network (e.g., a fronthaul network), and a central processor. The base transceiver stations are connected to the central processor via the fronthaul network. Furthermore, the central processor may comprise distributed computing resources. For example, the central processor may comprise (or be communicatively coupled to) high-performance programmable processors and real-time virtualization technology. Some aspects employ a software defined radio (SDR) platform.

In one aspect of the disclosure, a C-RAN system comprises base transceiver stations that operate solely as radio units (e.g., remote radio heads), while the RAN baseband processing is performed at a central processor within the operator's network. Fronthaul links, such as fiber optic links or wireless links, connect each base transceiver station to the central processor. The centralization of both uplink and downlink baseband processing at the central processor enables many benefits, including allowing the central processor to perform cancellation of the downlink-uplink interference, since the downlink signal is known at the central processor.

Centralized signal processing disclosed herein greatly reduces the amount of base transceiver equipment needed to cover the same area. Cooperative processing, such as Cooperative-MIMO in a distributed antenna system, provides higher spectrum efficiency. Real-time cloud infrastructure (which can be based on an open platform and utilize base station virtualization) enables processing aggregation and dynamic resource allocation, reducing the power consumption and increasing the infrastructure utilization rate. This network architecture is advantageous for LTE-Advanced, which requires tight coordination between neighboring cells, as such coordination is facilitated at the central processor where RAN baseband functions of the base transceiver stations are pooled.

In another aspect of the disclosure, methods for providing C-RAN communications comprise performing RAN baseband processing at a central processor, while a distributed antenna system comprising a network of geographically distributed base transceiver stations acts solely as down-converters in the uplink and up-converters in the downlink. The fronthaul links carry baseband information. In one aspect, in the uplink, UE signals received by the base transceiver stations are forwarded to the central processor, which performs joint decoding. In another aspect, in the downlink, the central processor performs pre-coding and then communicates the resulting baseband signals via the fronthaul links to the base transceiver stations. Each base transceiver station simply up-converts the baseband signal and transmits it to the UEs.

With centralized processing of the C-RAN architecture, power consumption due to air conditioning and other equipment at the base transceiver sites can be reduced. In many aspects, the distance from the base transceiver stations to the UEs can be decreased, since Cooperative-MIMO processing can mitigate the effects of interference between base transceiver stations, allowing for a much higher density of base transceiver stations. With smaller cells, the power required for signal transmission is reduced, which can decrease power consumption in both the RAN and the UEs. Furthermore, because baseband processing is implemented via a shared resource among a large number of base transceiver stations, more efficient utilization of processing resources and lower power consumption can be achieved.

In aspects of the disclosure, the base station baseband processors and site support equipment are aggregated in a centralized location. This centralized management and operation can be far more efficient than managing a large number of base station sites in a traditional RAN network. If each base transceiver station's functionality is simpler, the size, cost, and power consumption can be reduced. Thus, base transceiver stations can be smaller, less expensive, and easier to deploy with minimum site support and management requirements. Centralized operation also facilitates sharing of the control signaling, traffic data, and channel state information in the system, which can enable joint processing and scheduling to mitigate inter-cell interference and improve spectral efficiency.

In some aspects of the disclosure relating to non-transitory computer-readable medium with instructions stored thereon, the term "virtual" is used. While virtualization typically refers to the abstraction of computer resources in which the physical characteristics of a computing platform are hidden from users and/or applications, the term, virtual, can also relate to an abstraction of a network configuration wherein signal-processing functions do not require certain details of a distributed antenna system. In some aspects, portions of methods and systems that provide for channel characterization and calculating antenna array weights for subspace multiplexing and/or demultiplexing do not require certain information about the distributed antenna system. For example, some of the signal-processing functions can be independent of whether the system comprises a conventional antenna array or a plurality of separate RAN transceivers communicatively coupled together via a fronthaul network. Some signal-processing functions can be independent of whether they are performed at a base transceiver station or at a central processor to which the base transceiver station is communicatively coupled. This enables MIMO and other baseband processing to be performed at the central processor.

In some aspects of the disclosure, central processing comprises distributed computing. Thus, a network operator can dynamically allocate processing resources within a centralized baseband pool to different virtualized base stations and different air interface standards. This allows the operator to efficiently support a variety of air interfaces and adjust to varying network loads across different geographical areas. Within a centralized baseband pool, physical layer processing resources can be efficiently managed and allocated via real time virtualization. Thus, a base station instance can be adapted through the flexible resource combination, which can adjust, allocate, and re-allocate resources based on each virtualized base station's require-

ments in order to meet its demands. This provides Cooperative-MIMO operations with the required processing resources dynamically. Furthermore, centralizing the hardware platform can provide cost effectiveness for managing, upgrading, and expanding the base station network.

In accordance with some aspects of the disclosure, a plurality of transmitting nodes is employed by a source node to build the dimension of the subspace spanned by the coded transmissions. In one aspect, the plurality of transmitting nodes is selected to ensure that a set of pre-coded transmissions is characterized by sufficient rank to allow a destination node to decode received signals. For example, selecting a sufficient number of transmitting nodes and encoding (e.g., pre-coding) original data signals can produce a sufficient number of linearly independent (i.e., algebraically unique) combinations of the original data signals to permit the destination node(s) to resolve the original data signals. The transmitting nodes can be selected based on channel measurements and/or their geographic locations such as to ensure that their transmissions are uncorrelated. Each of the transmitting nodes transmits a subset of a total number (i.e., plurality) of subspace-coded components and a corresponding code matrix, wherein at least one of the transmitting nodes has a rank that is insufficient for decoding the plurality of subspace coded components (e.g., a destination node needs to receive signals from a plurality of the transmitting nodes in order to achieve sufficient rank for decoding the received signals). The corresponding code matrix can take the form of a preamble (or header) that comprises the code matrix. When the codes comprise channel-specific codes based on the naturally random channel, then the codes comprise random codes.

As disclosed in some aspects herein, the transmitting nodes can function as routers, relays, repeaters, etc., configured to encode received signals prior to retransmission or simply pass through received signals prior to retransmission. In some aspects, the transmitting nodes can combine multiple signals to be transmitted. In some aspects, the naturally random channel provides random linear coding to transmissions, such as when transmitting nodes are selected to produce transmissions with uncorrelated multipath effects (e.g., fading).

In accordance with some aspects of the disclosure, a destination node can employ a plurality of receiving nodes to cooperatively receive a plurality of subspace-coded components and their corresponding code vectors, wherein the rank of at least one of the receiving nodes is insufficient for decoding the coded components. Thus, receiving nodes can function as routers, relays, repeaters, etc. The destination node builds up the dimension of the subspace spanned by code vectors it collects from the receiving nodes so it can decode the coded components. For example, the destination node can receive signals from multiple receiving nodes in order to decode the subspace-coded components. The receiving nodes can be selected to provide uncorrelated channels.

As disclosed herein, intervening nodes can function as either or both transmitting nodes and receiving nodes. Whereas in conventional routing, intervening nodes simply replicate and forward their received packets, cooperative network coding (such as disclosed in the '163 application) enables relay nodes to combine information received from multiple links for subsequent transmissions. The '163 application discloses various types of linear network codes, including polyphase codes derived from a discrete Fourier transform and random codes, such as derived from the natural randomness of wireless multipath channels, and combinations thereof.

In some aspects of the disclosure, assigned wireless network channels (such as network channels allocated to a particular frequency band and time interval) are reused. For example, cooperative subspace processing (e.g., Cooperative-MIMO) generates a plurality of parallel subspace channels that can simultaneously occupy the same spectral resource. If OFDM is employed, this means that multiple parallel spatial subchannels can occupy the same set of OFDM subcarriers, or tones. In some aspects, cooperative subspace processing provides for communicatively coupling together multiple geographically distributed transceivers (e.g., base transceiver stations and/or wireless client devices) via a fronthaul network to enable joint processing operations.

In some aspects of the disclosure, a network channel is allocated to a transceiver operating in a first network, wherein the transceiver is part of a group of transceivers comprising a second network. The network channel is reused by the group of transceivers for communicating in the second network in a manner that avoids interfering with the first network. By way of example, the group of transceivers employs spatial multiplexing, such as cooperative subspace processing, to mitigate interference between the first network and the second network.

In one aspect of the disclosure, a transceiver employs a channel allocation for a first communication link in a first group of transceivers comprising a first network. A second group of transceivers that is different from the first group but comprises the transceiver reuses the channel allocation for communicating in at least a second communication link. The second group is configured to employ any of various interference-mitigation techniques that permit the reuse of the channel allocation while minimizing co-channel interference with the first network. In some aspects, the second group is configured to employ interference-mitigation techniques that mitigate the effects of co-channel interference in the second link due to transmissions in the first link.

By way of example, if the channel allocation is for a downlink channel, the second group can perform either or both transmit-side and receive-side spatial multiplexing to cancel interference from transmissions in the first link that could interfere with one or more receivers in the second link. If the channel allocation is for an uplink channel, the second group can perform transmit-side spatial multiplexing to cancel interference from transmissions in the second link that could interfere with receivers employing the first link. The second group can perform either or both transmit-side and receive-side spatial multiplexing to cancel interference due to transmissions in the first link that could interfere with one or more receivers employing the second link.

As described throughout the '163 application, aspects disclosed herein can be implemented in a cloud-based SDR platform.

In some aspects of the disclosure, an OFDM transmitter is configured to produce a CI-OFDM transmission signal, such as a Discreet Fourier Transform (DFT)-spread OFDM signal. For example, an OFDM spreader (such as a CI coder) is configured to spread a plurality of reference-signal symbols with Fourier coefficients to generate a DFT-spread reference signal. A mapper is configured to map DFT-spread reference symbols to a plurality of OFDM subcarriers. An OFDM modulator modulates the DFT-spread reference symbols onto the OFDM subcarriers to produce an OFDM transmission signal, which can have low peak to average

power ratio (PAPR). Various techniques, such as interleaving the OFDM subcarriers, combining the spreading with spatial precoding, and pulse shaping are also disclosed.

Groupings of alternative elements or aspect of the disclosed subject matter disclosed herein are not to be construed as limitations. Each group member can be referred to and claimed individually or in any combination with other members of the group or other elements found herein. One or more members of a group can be included in, or deleted from, a group for reasons of convenience and/or patentability. When any such inclusion or deletion occurs, the specification is herein deemed to contain the group as modified, thus fulfilling the written description of all Markush groups used in the appended claims.

All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided with respect to certain embodiments herein is intended merely to better illuminate the inventive subject matter and does not pose a limitation on the scope of the inventive subject matter otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the inventive subject matter.

Additional features and advantages of the invention will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The features and advantages of the invention may be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims. These and other features of the invention will become more fully apparent from the following description and appended claims, or may be learned by the practice of the invention as set forth herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Flow charts depicting disclosed methods comprise "processing blocks" or "steps" may represent computer software instructions or groups of instructions. Alternatively, the processing blocks or steps may represent steps performed by functionally equivalent circuits, such as a digital signal processor or an application specific integrated circuit (ASIC). The flow diagrams do not depict the syntax of any particular programming language. Rather, the flow diagrams illustrate the functional information one of ordinary skill in the art requires to fabricate circuits or to generate computer software to perform the processing required in accordance with the present disclosure. It should be noted that many routine program elements, such as initialization of loops and variables and the use of temporary variables are not shown. It will be appreciated by those of ordinary skill in the art that unless otherwise indicated herein, the particular sequence of steps described is illustrative only and can be varied. Unless otherwise stated, the steps described below are unordered, meaning that the steps can be performed in any convenient or desirable order.

FIG. **1** is a block diagram of a communication system architecture in accordance with an exemplary aspect of the invention.

FIG. **2** illustrates a network configuration for super-array processing in accordance with some aspects of the invention.

FIG. **3**A is a flow diagram of a super-array processing method in accordance with an aspect of the invention.

FIG. **3**B is a flow diagram of a super-array processing method in accordance with an aspect of the invention in which channel information is estimated from measurements of reference signals transmitted by the UEs. The reciprocal nature of the channel can enable channel estimation of received uplink signals to be used to calculate pre-coding for the downlink channel.

FIGS. **4**A and **4**B are flow diagrams depicting spatial demultiplexing implemented via multi-cell MIMO cooperation in wireless networks.

FIG. **5** is a flow diagram depicting a method in accordance with an aspect of the disclosure in which multiple geographically distributed transmission points are coupled to a central processor via a fronthaul network, and the central processor calculates pre-coding weights for spatial multiplexing and coordinates the transmission points to transmit subspace pre-coded downlink signals to multiple UEs.

FIG. **6** is a flow diagram depicting a method in accordance with an aspect of the disclosure in which multiple geographically distributed transmission points are coupled to a central processor via a fronthaul network, and the central processor is configured to perform spatial demultiplexing of UE uplink transmissions received by the distributed transmission points.

FIG. **7** is a flow diagram depicting messages passed between UEs, base transceiver stations, and a central processor corresponding to a super-array processing method.

FIG. **8** comprises pseudo-code that depicts data structures and processing functions that can be implemented by a computer processor programmed to perform methods, such as super-array processing methods, in accordance with aspects of the disclosure.

FIG. **9** is a block diagram of a UE that can be configured to operate in accordance with aspects of the disclosure.

FIG. **10** is a block diagram of a base transceiver station that can be configured to operate in accordance with aspects of the disclosure.

FIG. **11**A is a block diagram of a central processor that can be configured to operate in accordance with aspects of the disclosure.

FIG. **11**B is a block diagram that depicts a cloud-based software-defined radio, which can be implemented in accordance with many different aspects of the disclosure.

FIG. **12** is a block diagram of a super-array processing system comprising a central processor communicatively coupled to multiple geographically distributed base transceiver stations via a fronthaul network.

FIG. **13**A is a flow diagram of a subspace processing method configured in accordance with some aspects of the disclosure.

FIG. **13**B is a flow diagram of a subspace processing method that employs decision feedback configured in accordance with some aspects of the disclosure.

FIGS. **14**A and **14**B are block diagrams that illustrates method and apparatus implementations of radio transceivers in accordance with aspects of the disclosure.

FIG. **15** is a block diagram of a transceiver in accordance with some aspects of the disclosure.

FIG. **16** is a block diagram depicting functional aspects of transceivers according to aspects of the disclosure.

FIG. **17** depicts a network comprising multiple geographically distributed base transceiver stations communicatively coupled together via a fronthaul network. The base transceiver stations are configurable to jointly process signals in a radio access channel that serves multiple UEs. In some aspects of the disclosure, at least one of the base transceiver stations coordinates joint processing.

FIG. **18** depicts a cloud radio access network comprising multiple geographically distributed base transceiver stations communicatively coupled to a central processor via a fronthaul network, wherein the central processor comprises a distributed computing system. In such aspects, combinations of central processing and distributed computing can provide for pooling and virtualizing base station processing, such as via an SDR.

FIG. **19** depicts a coordinated multipoint network wherein a plurality of access points are communicatively coupled to a central processor via a fronthaul network, and wherein at least some of the access points' signal processing functions (such as RAN baseband processing) are pooled at the central processor. Apparatus implementations corresponding to this aspect of the disclosure include providing for relocating access point baseband processing equipment to the central processor, which can greatly reduce the capital expense and operating expense associated with the access point network.

FIGS. **20**A and **20**B are flow charts depicting methods wherein geographically distributed access points perform RF processing in a radio access network and a central processor performs corresponding RAN baseband processing. In some aspects the corresponding RAN baseband processing is performed by a distributed computing system.

FIG. **21** depicts a network topology comprising a source node, a destination node, and a plurality of intervening nodes. This and other network topologies shown herein depict some aspects of the disclosure, including cooperative-MIMO, cooperative subspace coding along multiple network paths, simultaneously employing multiple network paths as a single communication link, providing for reusing spectral resources across multiple links, etc.

FIGS. **22**A and **22**B depict signal transmissions propagating in a network with multiple intervening nodes between a source node and a destination node. Selecting the intervening nodes as part of a transmit and/or receive cooperative subspace processing operation can build the rank of the subspace coding matrix of coded signals propagating through the network, thus providing a sufficient number of linearly independent combination of original data to permit subspace demultiplexing at the destination node.

FIG. **23**A is a flow diagram that illustrates aspects of the disclosure pertaining to cooperative subspace multiplexing.

FIG. **23**B is a flow diagram that illustrates aspects of the disclosure pertaining to cooperative subspace demultiplexing.

FIGS. **24**A and **24**B are block diagrams depicting transceiver apparatus and method aspects configured to perform routing and/or relaying.

FIGS. **25**A and **25**B are block diagrams that depicts channel reuse, such as may be configured between a plurality of networks.

FIG. **26** depicts a cooperative-MIMO network configured to employ channel reuse.

FIG. **27** is a flow diagram that depicts channel reuse methods in accordance with some aspects of the disclosure.

FIG. **28**A is a flow diagram that depicts a method for producing CI-coded transmissions of user data and control signals. Such methods may be performed by a UE for uplink transmissions in a radio access network.

FIG. **28**B is a flow diagram depicting a method that employs CI spreading codes to spread user data and control signals.

FIG. **28**C is a flow diagram that depicts a method that employs CI spreading codes and time division duplexing.

FIG. **28**D is a flow diagram that depicts a routing method that employs CI spreading and is configurable for operating in cooperative, peer-to-peer, multi-hop, and mesh networks.

FIG. **29**A is a flow diagram that depicts a CI signal generation method in accordance with some aspects of the disclosure. A UE can be configured to perform such methods to generate an uplink transmission.

FIG. **29**B is a flow diagram that depicts a CI signal processing method in accordance with some aspects of the disclosure. A base transceiver station or a central processor may employ such methods for processing received transmissions comprising DFT-spread uplink signals transmitted by a UE.

FIG. **30**A is a block diagram of a CI-OFDM transmitter according to some aspects of the disclosure, and FIG. **30**B is a block diagram of a CI-OFDM receiver configured in accordance with some aspects of the disclosure.

FIG. **31** is a block diagram that depicts a non-transient computer-readable memory comprising a set of instructions stored therein and executable by a processor to perform methods in accordance with aspects of the disclosure.

FIG. **32** illustrates an invertible transform matrix that can be employed in some aspects of the invention.

FIG. **33** is a block diagram that depicts a non-transient computer-readable memory comprising a set of instructions stored therein and executable by a processor to perform methods in accordance with aspects of the disclosure.

DETAILED DESCRIPTION

The terms "backhaul" and "fronthaul" can be used interchangeably in some aspects of the disclosure. A fronthaul is similar to a backhaul, which, at its simplest, links a radio access network to a wired (e.g., cable or optical fiber) network. A fronthaul can comprise a backhaul, or a portion of a backhaul. For example, a fronthaul can comprise a connection between one or more centralized controllers and remote stand-alone radio heads. A fronthaul connects a central processor to multiple base transceiver stations. A fronthaul connects multiple base transceiver stations together when one or more of the base transceiver stations functions as a central processor. As used herein, a fronthaul may comprise a traditional backhaul network. For example, a fronthaul can comprise at least a portion of S1 and/or X2 interfaces. A fronthaul may be part of a base station network. In Pat. Appl. Ser. No. 60/286,850, it is disclosed that a fronthaul can comprise optical fiber, wired, and/or radio networks. In one aspect of the disclosure, point-to-point fiber links provide high bandwidth and low latency. In another aspect, radio (e.g., microwave) links can provide high bandwidth and low latency, and can be substantially less expensive to implement than fiber. Furthermore, wireless links enable mobile radios and/or other radio transceivers (e.g., remote radio equipment) to be networked together via a radio fronthaul, such as disclosed in patent application Ser. No. 10/131,163. Accordingly, a fronthaul can comprise any combination of wireless, wired, and optical fiber links that communicatively couple together a group of radio transceivers configured to perform cooperative MIMO. Here, a group of radio transceivers is also referred to as a "micro-cell" and a "pico-cell" in the '163 application, and as a "local group" and a "micro-network" in patent application Ser. No. 11/187,107, all of the patents and patent applications mentioned herein being incorporated by reference in their entireties.

Pre-coding is defined herein to comprise its ordinary and customer meaning known to those of ordinary skill in the art.

By way of example, in the '163 application, pre-coding is described in the context of antenna array transmission systems with the terms, "pre-transmission processing," "pre-distortion," "channel compensation," "transmit filtering," "spatial interferometry multiplexing," and "subspace processing." The '163 application also discloses directive and retro-directive adaptation methods for calculating antenna array weights for transmission in a distributed antenna system. In one example, subspace pre-coding weights are calculated from measurements of received signals, the measurements comprising channel state information.

User Equipment (UE), as used herein, may be fixed or mobile and comprises any device used directly by an end user (or client device) to communicate in a radio access network. For example, a UE can be a cellular handset, a laptop equipped with a mobile broadband adaptor, a wearable computer, a PDA, a tablet, or any other user device configured to communicate with a Wireless Wide Area Network (WWAN). A WWAN is also referred to as a radio access network (RAN). A UE comprises an RF transceiver for fixed and/or mobile clients receiving data streams over the downlink channel of the WWAN and transmitting data via the WWAN's uplink (UL) channel. While a UE is defined in the Universal Mobile Telecommunications System (UMTS) and 3GPP Long Term Evolution (LTE) as any device that connects to a base station NodeB or eNodeB as specified in the ETSI 125/136-series and 3GPP 25/36-series of specifications, UEs include equivalent devices, such as mobile stations in GSM systems and client devices in other wireless networks. As used herein, a UE may also be referred to as a subscriber device, mobile terminal, user terminal, wireless terminal, subscriber terminal, client terminal, subscriber unit, mobile unit, subscriber device, mobile device, wireless device, client device, client terminal, client unit, mobile network device, mobile handset, wireless handset, or some other terminology indicating a WWAN-enabled client device.

In general, the various embodiments of the UE can include, but are not limited to, cellular mobile devices, personal digital assistants (PDAs) having wireless communication capabilities, portable computers having wireless communication capabilities, image capture devices such as digital cameras having wireless communication capabilities, gaming devices having wireless communication capabilities, music storage and playback appliances having wireless communication capabilities, Internet appliances permitting wireless Internet access and browsing, as well as portable units or terminals that incorporate combinations of such functions. Examples of UEs are provided in 3GPP technical specification (TS) 36.306, Release 8, the disclosure of which is incorporated herein by reference in its entirety.

A Base Transceiver Station interfaces the fronthaul network with the WWAN channel. Base transceiver stations of one embodiment comprise access points consisting of a Digital-to-Analog Converter (DAC)/Analog-to-Digital Converter (ADC) and a radio frequency (RF) chain to convert the baseband signal to RF. A base transceiver station contains radio frequency transmitter(s) and receiver(s) for communicating directly with UEs. In some cases, the base transceiver station is a simple RF transceiver equipped with a power amplifier/antenna, and the RF signal is carried to the base transceiver station via RF-over-fiber technology as disclosed in the '850 and '163 applications. In other aspects, base transceiver stations are equipped to perform at least some RAN baseband processing operations, such as disclosed in the '850 and '163 applications. Additional features and aspects of base transceiver stations are described throughout the disclosure and in the aforementioned patent applications, which are incorporated by reference. As used herein, a base transceiver station may also be referred to as a base station, an access point, a NodeB, an evolved NodeB (eNodeB), or some other terminology. In accordance with some aspects of the disclosure, a base transceiver station is a network node.

A "network node" or "node," as used herein, is an active electronic device that is communicatively connected to a network via one or more connectors and is configured for sending, receiving, and/or forwarding information over a communication channel. A node can have multiple network connectors for a given network. For example, a node can have multiple antennas. A single device, such as a base station or a user terminal, with multiple network connectors is a single node. In a distributed network, nodes can be clients, servers, and/or peers. A peer can sometimes serve as a client and sometimes as a server. Nodes can include super nodes, which route data for other networked devices as well as themselves.

A Central Processor can include one or more servers interfacing the Internet (or other external networks) with the fronthaul. In a hierarchical network architecture, a central processor couples to the base transceiver stations and provides coordination and control for those stations. One or more base transceiver stations may function as a central processor, such as in a flat network architecture. In an LTE network, eNodeB(s) and/or access gateways can be configured to perform central processor functions. In some aspects of the disclosure, network control functions typically performed by a central processor may be assigned to any of various nodes in the network, including UEs.

In some aspects of the disclosure, the central processor computes the multi-user MIMO baseband processing and sends pre-coded data to geographically distributed base transceiver stations for downlink transmission. In some aspects, the central processor computes the multi-user MIMO baseband processing to provide spatial demultiplexing of uplink signals received by the geographically distributed base transceiver stations. In some aspects, the central processor can comprise a particular type of base transceiver station designed for certain specialized features, such as transmitting training signals for time/frequency synchronization of the base transceiver stations and/or the UEs, receiving/transmitting control information from/to the UEs, receiving the channel state information or channel quality information from the UEs, etc. In some aspects, a central processor is also referred to as a central processing facility, a cloud computing center, a cloud, a data center, a data center cloud, a central controller, a radio network controller, or a central control hub. In some aspects, a central processor can comprise multiple data centers.

Various aspects of the disclosure are described below. It should be apparent that the teachings herein may be embodied in a wide variety of forms and that any specific structure, function, or both being disclosed herein are merely representative. Based on the teachings herein one skilled in the art should appreciate that an aspect disclosed herein may be implemented independently of any other aspects and that two or more of these aspects may be combined in various ways. For example, an apparatus may be implemented or a method may be practiced using any number of the aspects set forth herein. In addition, such an apparatus may be implemented or such a method may be practiced using other structure, functionality, or structure and functionality in addition to or other than one or more of the aspects set forth herein.

The use of any and all examples, or exemplary language (e.g. "such as") provided with respect to certain embodiments herein is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention otherwise claimed. No language in the specification should be construed as indicating any non-claimed element essential to the practice of the invention. The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment or aspect described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments or aspects.

In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the invention. It should be understood, however, that the particular aspects shown and described herein are not intended to limit the invention to any particular form, but rather, the invention is to cover all modifications, equivalents, and alternatives falling within the scope of the invention as defined by the claims.

FIG. **1** is a block diagram of a communication system architecture in accordance with an exemplary aspect of the invention. A plurality N of base stations **101.1-101**.N are communicatively coupled to a central processing facility **110** (i.e., a central controller) via a communication network **105**. Each base station **101.1-101**.N comprises an antenna system for communicating with one or more mobile units (e.g., User Equipment) **120.1-120**.K. For example, the first base station **101.1** may comprise a first antenna array comprising a plurality M_1 of antennas **102.1-102**.M_1, and the Nth base station **101**.N may comprise an Nth antenna array comprising a plurality M_N of antennas **104.1-104**.M_N. A plurality K of mobile units **120.1**, **120.2**, and **120**.K are shown, each having its own antenna system **121.1**, **121.2**, and **121**.K, respectively. Each antenna system **121.1**, **121.2**, and **121**.K may comprise one or more antennas. The communication network **105** that communicatively couples the base stations **101.1-101**.N to the central processing facility **110** may comprise a fiber network, a cable (i.e., wired) network, a wireless network, or any combination thereof.

In one aspect of the invention, the signal-processing architecture provides base stations **101.1-101**.N that are essentially "dumb terminals." For example, many of the signal processing operations typically performed at a base station **101.1-101**.N may be transferred to a central processor (e.g., the central processing facility **110**) that is connected to the plurality of base stations **101.1-101**.N. In some aspects of the invention, a minimal amount of signal processing is performed at each base station **101.1-101**.N. For example, each base station **101.1-101**.N can perform basic signal-processing tasks, such as amplification, RF filtering, frequency conversion (e.g., frequency up-conversion and/or frequency down-conversion), and/or other RF signal-processing processing functions. After basic signal processing, signals received by one or more antennas at each base station **101.1-101**.N are coupled into at least one communication channel (e.g., network **105**) linked to the central processing facility **110**. Functions of the base station **101.1-101**.N may be limited to cleaning up the received RF signal, amplifying it, and processing the signal with respect to coupling it into the network **105**. Signals from different antennas **102.1-102**.M_1 and **104.1-104**.M_N may be transmitted on different channels (e.g., on different waveguides), or they may be multiplexed onto the same channel (e.g., with respect to wavelength division, time division, frequency division, polarization division, subspace, phase space, code division, mode division, directionality, etc.).

The central processing facility **110** processes each of the received signals from the communication channel(s). For example, the central processor **110** removes the individual signals from one or more communication channels. The removal process can include demultiplexing the signals on the channel(s). In some aspects, the central processor **110** frequency-converts the received signals to baseband, intermediate, or radio-frequency signals prior to processing. Beam-forming can be performed in RF, IF, and/or after conversion to baseband.

Thus, in some aspects of the invention, by relocating most (or all) of the base station processing operations to the central processing facility, the capital expenditures and operating costs of the radio access network can be greatly reduced. This can also facilitate rapid and less costly network upgrades and expansion. In one aspect, all the RF processing of the radio access network signals is performed at the base transceiver stations, whereas baseband processing is performed at the central processing facility. Baseband signals of the radio access network are communicated between the base transceiver stations and the central processing facility via a fronthaul radio network, some other wireless network, waveguide (e.g., cable), an optical fiber network, or a combination thereof. RF processing of the fronthaul network signals (which is different than RF processing of the radio access network signals) may be performed by the base transceiver stations and the central processing facility.

As depicted in FIG. **1**, signal-processing operations performed at the central processing facility **110** can include spatial multiplexing and/or spatial demultiplexing **114.1**, routing **114.2**, and power control **114.3**. The central processing facility **110** can be configured to perform super-array processing. In one aspect of the invention, the central processing facility **110** comprises a super array processing system **112**. In some aspects of the invention, the super array processing system **112** comprises one or more subsystems or modules, such as a spatial multiplexing/demultiplexing system **114.1**, a routing system (e.g., router) **114.2**, and a power control system **114.3**.

In one aspect of the invention, the super array processing system **112** comprises one or more general-purpose computers programmed to function as a special-purpose computer configured to perform various aspects of the disclosure, such as Cooperative-MIMO processing in a distributed antenna system. In another aspect, the super array processing system **112** comprises one or more special-purpose processors, such as integrated circuits, discrete circuits, and/or other specialized hardware configured to perform Cooperative-MIMO processing. As disclosed herein, a distributed computing system may be employed for implementing aspects of the invention, such as spatial multiplexing, spatial demultiplexing, and/or baseband signal processing operations typically performed by base transceiver stations. Such distributed computing systems may comprise a network of general-purpose computers (programmed to function as a special-purpose computers), such as servers, located in one or more data centers. A distributed computing system may comprise a network of special-purpose processors or a combination of special-purpose processors and general-purpose computers. Similarly, components of system **112**, as well as any other components, processors, systems, and devices mentioned in the disclosure, may each comprise one or more general-purpose computers, one or more special-purpose processors, or combinations thereof, and may optionally comprise a distributed computing platform.

In accordance with some aspects of the invention, the centralized architecture simplifies physical-layer system upgrades, since processing equipment used for multiple base stations **101.1-101**.N resides at a common location (i.e., the central processing facility **110**). Upgrades to improved modulation schemes, new receiver combining techniques, enhanced array-processing, etc. can be provided at the central processing facility **110** instead of at each base station **101.1-101**.N. Similarly, adding or upgrading base station antennas (e.g., antennas **102.1-102**.M_1 and **104.1-104**.M_N) is simplified since the antennas installed at each base station **101.1-101**.N may simply be coupled to the central processing facility **110** via the communication network **105**. Adding base stations to the network can be quick and less costly due to the low cost and complexity of each base station **101.1-101**.N. Thus, any signal-processing upgrade associated with the base stations **101.1-101**.N is performed at the central processor **110**.

In aspects of the invention that employ spatial multiplexing/demultiplexing, the system capacity scales linearly with the number of base station antennas (e.g., antennas **102.1-102**M_1 and **104.1-104**.M_N) within range of the UEs **120.1-120**.K. This is because the spatial multiplexing gain (i.e., the number of independent data streams that can be sent concurrently over MIMO subchannels) is proportional to the number of antennas **102.1-102**M_1 and **104.1-104**.M_N serving the UEs **120.1-120**.K.

Unlike conventional MIMO in which all of the transmitting antennas reside on a single device (e.g., a single base station), a cooperative-MIMO transmitting system in accordance with aspects of the disclosure comprises antennas residing on multiple devices (e.g., the base stations **101.1-101**.N). The super array processing system **112** coordinates the base stations **101.1-101**.N to synthesize an antenna system comprising geographically distributed antennas, which provides superior decorrelation of the transmission paths between transmitting antennas and receiving antennas in the MIMO system. Since MIMO antennas in prior-art systems reside on a single device, the length of the MIMO array is only a few wavelengths, which is usually insufficient for providing the spatial selectivity required to match the spatial multiplexing gain to the number of transmitting antennas. Thus, in prior-art MIMO systems, the rank of the MIMO channel matrix is typically less than its dimension. Adding more antennas to a prior-art MIMO system almost always results in diminishing levels of return with respect to capacity, whereas aspects of the invention solve this problem.

Since the system (depicted in FIG. **1**) capacity scales linearly with the number of base station antennas, particularly if the antennas are geographically distributed, it is advantageous to add more base stations as UE density increases. There are several benefits to doing this. Unlike prior-art cellular systems, inter-cell interference is not a problem in the radio access network depicted in FIG. **1**. Rather, it is exploited for spatial multiplexing gain, whereas enormous effort is made in today's cellular systems to avoid inter-cell interference, particularly for smaller cells. In aspects of the invention, base stations can be added in the general vicinity of increased user density without cell planning and extensive modifications to the radio access network. The central processing facility **110** immediately adapts to the new radio access network architecture to add capacity to the target area.

Since optimal spatial multiplexing gain is typically achieved when SNR is high (e.g., close to a MIMO base transceiver station), distributed antenna systems disclosed herein can provide closely proximal base transceivers for UEs throughout the coverage area that provide both high SNR and spatial selectivity. Unlike prior-art cellular systems in which each UE is linked to a single base station until it is handed off to another base station, aspects of the invention provide for maintaining concurrent links between the UE and multiple base stations throughout the UE's session. Thus, as the UE moves through the coverage area, it maintains a consistently high SNR. In other aspects of the invention, Cooperative-MIMO processing on the client side can provide distributed antenna systems comprising cooperating UEs that enable similar MIMO benefits.

In some aspects of the disclosure, all of the base station processing is performed in the central processing facility **110** (which may be an offsite data center as long as latency constraints are met) instead of by the individual base stations **101.1-101**.N. Thus, even at very high densities of UEs, not only can all UEs remain connected to the network, but the UEs do not incur the overhead normally incurred by large numbers of UEs sharing one base station in a cell.

The central processing facility **110** could be scaled indefinitely to accommodate increasing UE density and data demands. As the number of UEs and demand grows, not only is it easy to deploy additional base stations, as described above, but it is easy to expand the computing capability in the central processing facility **110** to accommodate the added base stations.

In accordance with some aspects of the invention disclosed in the '163 application, a distributed (e.g., cloud) computing environment may be employed to perform the base station processing. Also, the '163 application discloses that the base station processing may be performed in an SDR. Thus, the implementation of the base station processing may occur entirely on general-purpose CPUs. One implementation of the central processing facility **110** in accordance with previously cited disclosure could include a data center comprising multiple switches and general-purpose servers that connect to the fronthaul network **105** via general-purpose digital links, such as 10 GbE or other links.

FIG. **2** illustrates a network configuration for super-array processing in accordance with some aspects of the invention. In one aspect, multiple mobile units (e.g., UEs **120.1-120**.K) are each serviced by multiple base stations (e.g., base stations **101.1-101**.N) simultaneously. In one aspect of the invention, each base station **101.1-101**.N comprises an antenna array. For example, the first base station **101.1** comprises an M_1-element array **102.1-102**.M_1, a second base station **101.2** comprises an M_2-element array **106.1-106**.M_2, and the Nth base station **101**.N comprises an M_N-element array **104.1-104**.M_N. In super-array processing, the base station arrays (e.g., arrays **102.1-102**.M_1, **106.1-106**.M_2, and **104.1-104**.M_N) are configured to work together to exploit the propagation environment, such as to enhance signal reception for each mobile user **120.1-120**.K, reduce power transmission requirements, and mitigate undesired interference.

For the purpose of describing an exemplary aspect of the invention, signals transmitted by mobile unit **120.1** may be received at multiple base station antenna arrays (e.g., at base stations **101.1**, **101.2**, and **101**.N). Adapting each base station antenna beam pattern (e.g., beam patterns **201.1**, **201.2**, and **201**.N) can enhance reception of signals transmitted by each mobile unit **120.1-120**.K. Transmissions to each mobile unit **120.1-120**.K can also be enhanced. For example, a transmission from base station **101.2** intended for mobile unit **120.2** may cause interference at mobile unit **120.1**. However, this interference can be mitigated by

including a cancellation signal in the transmission from base station **101.1** and/or base station **101**.N. Since all of the base stations **101.1-101**.N in this exemplary aspect are connected to the central processing facility **110**, signal processing at this facility **110** can be performed to allow multiple base stations to work together and thereby enhance the radio coverage, bandwidth efficiency, and power efficiency.

With respect to each mobile unit **120.1-120**.K, all of the interfering signals transmitted by the multiple base transceiver stations **101.1-101**.N coherently combine to produce the exact waveform intended for that mobile unit with a high SNR (e.g., SINR). For example, first portions of waveforms transmitted by the multiple base transceiver stations **101.1-101**.N combine coherently at a first mobile unit (e.g., **101.1**) to produce a first set of data signals intended for the first mobile unit **101.1**. Similarly, second portions of the transmitted waveforms combine coherently at a second mobile unit (e.g., **101.2**) to produce a second set of data signals intended for the second mobile unit **101.2**. However, the first portions combine destructively to cancel at the second mobile unit **101.2** and the second portions combine destructively to cancel at the first mobile unit **101.1**. In some aspects of the invention, the high-SNR waveforms exist only in a small volume around the corresponding intended mobile unit. Since these highly localized regions of high SNR are synthesized interference zones, the diameter of these three-dimensional regions (such as may be indicated by a full-width half-maximum amplitude or power) can be less than a wavelength.

Propagation effects due to sparse antenna arrays are described in U.S. patent application Ser. No. 09/906,257, which is incorporated by reference in its entirety. When randomly spaced sources (or equivalently, sources transmitting random carrier frequencies) are employed, interference patterns (i.e., superpositions of the transmitted signals) away from the main lobe (i.e., where signals are configured to combine coherently, or in phase) tend to have little variation between minima and maxima, particularly when many sources (or frequencies) are employed.

In the spatial dimensions, a rich scattering environment can provide a large number of effective sources (i.e., each scatterer is an effective source). It is anticipated that some aspects of the invention may employ very large numbers of transmitters to generate signals that coherently combine in 3-dimensional space at a desired receiver(s). When very large numbers (e.g., hundreds or more) of transmitters and/or effective sources are employed, the signal amplitude (or power) can fall off dramatically at a short distance (even a fraction of a wavelength) from the superposition peak. The signal levels can remain at a consistently low SNR throughout 3-dimensional space except, perhaps, very close to the transmitters. With a sufficiently large number of transmitters, it may be possible to transmit signals from each transmitter that are so low in power that the signals intended for a particular user device are indistinguishable from background noise throughout almost all of the coverage area except in a small volume at the user device where they coherently combine. Thus, some aspects of the invention can provide a type of physical-layer low probability of interception/low probability of detection (LPI/LPD) benefit due to spatial processing that is analogous to LPI/LPD benefits of ultra-wideband signals. Such LPI/LPD benefits can enhance security in wireless networks.

Array processing can be performed at the central processor **110** to adapt transmission and reception beam patterns to improve one or more operating criteria, such as signal-to-noise, signal-to-noise plus interference, probability of error, bit error rate, etc. Various aspects include the use of known training sequences and pilot signals, as well as blind adaptive techniques. Open-loop and/or closed-loop feedback techniques can be used.

In one aspect, each UE may be assigned an orthogonal uplink pilot. However, the maximum number of orthogonal pilots is limited by the duration of the coherence interval divided by the channel delay spread. Thus, aspects of the invention may employ any of various channel estimation algorithms, such as blind techniques, that circumvent the use of pilots altogether. By way of example, the '163, '854, and '107 applications disclose blind techniques that jointly estimate the channels and the payload data.

Even though the propagation channel is reciprocal (between uplink and downlink in time-division duplex systems), the RF front-ends in the base transceivers and UEs may not be reciprocal between the uplink and downlink. Accordingly, calibration of the hardware to ensure reciprocity may be performed, such as disclosed in the '163 application.

The array-processing aspects of the invention can also be used in conjunction with control of other system operating parameters, including, but not limited to, power control, throughput, bandwidth, channel coding (e.g., convolutional, block, trellis, etc.), and frequency band scheduling. In one aspect, the system reduces the transmit power of a mobile unit when array processing enhances the signal-to-noise-plus-interference of that unit's radio link. In another aspect, the level of array processing is adjusted with respect to some quality factor associated with each unit. For example, array processing may be performed only for units that exceed a certain degree of signal degradation, require a certain amount of throughput, or have a predetermined quality-of-service level (QOS). Array processing can be used for data links in a system that provides data and voice services, since digital links require a higher QOS. Array processing can be used to compensate for signal-quality degradation for units assigned to interfering channels.

It should be appreciated that signal processing at the central processing facility **110** may be performed by multiple computer processors via distributed computing (e.g., cloud computing) such as disclosed in the '163 application. In some aspects, the base station signal processing at the central processing facility **110** can be implemented in a real-time SDR to provide for software-defined networks that enable more dynamic organization of resources, such as disclosed in the '163 application. The central processor **110** may comprise one or more servers in a data center configured to compute baseband waveforms using an SDR, such as described in the '163 application.

Since multiple base transceiver stations **101.1-101**.N are employed to serve each UE **120.1-120**.K via Cooperative-MIMO subspace processing, it is advantageous for the coverage areas of base transceiver stations **101.1-101**.N employing the same spectral resources to overlap. This is contrary to how cellular base stations are positioned in a conventional cellular network. Prior-art base stations conform to a cellular layout that is carefully planned to minimize transmission overlap. However, aspects of the disclosure are not constrained to such cell plans because subspace processing can produce constructive and destructive interference zones throughout the radio access network's coverage area to enable spectral reuse, potentially for very large numbers of UEs, even UEs that are in close proximity to each other (e.g., on the order of a few wavelengths, or even less). This enables universal spectral reuse while facilitating deployment of the radio access network infrastructure. In

some aspects, the base transceiver stations **101.1-101**.N can be placed pseudo-randomly throughout the radio access network, such as to take advantage of locations that are convenient and/or less costly, and with less concern about coverage area and the presence of obstructions in the propagation environment.

In some aspects, since each UE **120.1-120**.K is concurrently served by multiple base transceiver stations **101.1-101**.N with overlapping coverage areas, a failure of a small number of base transceiver stations **101.1-101**.N is less likely to cause a service disruption. Rather, the spatial multiplexing/demultiplexing **114.1** can adapt to changes in the configuration of the base transceiver stations **101.1-101**.N, such as to ensure uninterrupted service.

The spatial multiplexing/demultiplexing **114.1** can perform various spatial processing techniques, including (but not limited to) ZF, MMSE, MRC, and/or successive interference cancellation. In some aspects, MRC can offer certain advantages due to the ease in which it can be implemented in a distributed manner and its computational simplicity (e.g., when used for demultiplexing, received uplink signals can be multiplied by the conjugate channel responses, and pre-coding downlink transmissions is similarly simplified). The combination of the MRC receiver (for the uplink) and its counterpart, maximum ratio pre-coding (for the downlink) comprise matched filtering, which is disclosed in the '163 and '854 applications. MRC can be advantageous when channel responses associated with different terminals are substantially uncorrelated.

As disclosed in the '163 application, the fronthaul network **105** can take various forms, including a mesh architecture. Since at least some of the fronthaul links **105** can be wireless (such as disclosed in the '850 application), and given that the base transceiver stations **101.1-101**.N can comprise remote radio heads (or other simple radio transceivers), as disclosed in the '850 application, the base transceiver station **101.1-101**.N hardware can be a fraction of the cost of prior-art base stations and can be deployed more quickly. Furthermore, as disclosed in the '163, '854, and '107 applications, UEs **120.1-120**.K and other devices (not shown) in the radio access network can function as base transceiver stations, such as to dynamically adapt to increased network loads and/or increased UE density, compensate for base station outages, and/or expand the coverage area.

FIG. **3**A is a flow diagram of a super-array processing method in accordance with an aspect of the invention. A plurality of base transceiver stations (e.g., transmission points, or access points) is configured to transmit reference signals **301**, which are measured by UEs to calculate channel state information **302**. For example, the '850 application discloses that reference signals, which include known training sequences and pilot signals, are transmitted, and a channel model is developed by a receiver upon receiving the transmitted reference signals. The channel state information can comprise channel information relative to multiple base station antennas residing on multiple geographically distributed base stations.

The UEs feedback the channel state information to the transmission points **304**, and the transmission points and/or the central processor calculate pre-coding weights **305** therefrom. The '850 application discloses that open-loop and/or closed-loop feedback may be employed. While channel state information can comprise quantized channel estimates, channel state information can comprise alternative indicators, such as codewords. In some aspects of the invention, such as disclosed in the '850 application, step **305** comprises selecting UE's for which array processing is to be performed, wherein only UE's having a predetermined quality-of-service level are selected. In some aspects disclosed in the '850 application, different levels of array processing may be performed, the level of array processing being selected with respect to a quality factor associated with each UE.

Multiple transmission points are coordinated by the central processor to transmit the pre-coded data **307** to each UE. In some aspects of the invention, such as in accordance with the disclosure of the '163 application, step **305** and/or **307** comprises selecting a portion of the network to serve a particular UE. For example, a predetermined set of transmission points is selected to process transmissions to a particular UE based on received pilot signal power. Upon receiving the transmissions, each UE demodulates the received signals **308**. Since UE's may comprise antenna arrays, such as disclosed in the '850 application, step **308** may comprise array processing, including MIMO processing.

In accordance with one aspect of the invention disclosed in the '163 application, network processing functions are computed by a plurality of spatially separated processors. For example, the central processor can be replaced by a distributed computing system. The distributed computing system can comprise a plurality of transmission points. In some aspects, the distributed computing system can comprise UE's, repeaters, and/or other network equipment.

In accordance with aspects disclosed in the '850 application, super-array processing comprises a coordinated multipoint technology which sends and receives signals from multiple sectors or cells to a given UE. By coordinating transmission among multiple cells, interference from other cells can be reduced and the power of the desired signal can be increased.

In one aspect of the invention, signaling over a fronthaul network can be used between base stations (e.g., eNodeB's) to coordinate among cells. In another aspect of the invention, multiple remote radio equipments (RREs) are connected via an optical fiber fronthaul carrying a baseband signal between cells and a central eNodeB, which performs the RAN baseband signal processing and control, so the radio resources between the cells can be controlled at the central eNodeB. Other aspects of the invention include combinations of distributed control based on independent eNodeB configurations and centralized control based on RRE configurations.

FIG. **3**B is a flow diagram of a super-array processing method in accordance with an aspect of the invention in which channel information is estimated from measurements of reference signals transmitted by the UEs. This exemplary method can be useful when time division duplexing (TDD) is employed, such as wherein the uplink and downlink channels assigned to each UE share the same frequency band. For estimation of channels at the transmitter in TDD networks, one can rely on the reciprocity of the uplink and downlink channels so that channel estimation on the uplink can be used for downlink transmission.

In one aspect of the invention, each UE transmits a known reference signal **311**, such as one or more known training sequences and/or pilot signals, which are described in the '850 application. The transmitted reference signals are received by antennas of multiple base transceivers, and the channel state information is measured **312** by the base transceiver stations and/or at least one central processor. As disclosed in the '850 application, the channel state information can comprise frequency-domain channel state information. In one aspect, measured channel state information is

coupled by the base transceiver stations to the central processor to be used for calculating pre-coding weights **314**. In accordance with another aspect, the central processor performs steps **312** and **314**. As disclosed in the '163 application, steps **312** and **314** can comprise reference-signal processing, blind adaptive techniques, directive, and/or retro-directive techniques. Communication between the base transceiver stations and the at least one central processor is provided by a high speed network backbone, or fronthaul, which may comprise optical fiber, wired connections, wireless connections, or any combination thereof. Pre-coded data is transmitted **316** by multiple transmission points under the control of the central processor. Each UE receives pre-coded transmissions from multiple transmission points and demodulates the received data **317**.

In one aspect of the invention, joint transmissions by multiple cells (i.e., base transceiver stations) to a given UE employ the same time and frequency radio resources. Dynamic cell selection provides for selecting a portion of the base station network to serve a particular UE. Furthermore, UE's can be selected for array processing, such as based on a UE's quality of service level. Pre-coding between the cells provides for coherent transmission, which results in in-phase combining at the receiver. With uplink multi-cell reception, the signal from a UE is received by multiple cells and combined. The UE does not need to be aware of whether multi-cell reception is occurring, so it should have little impact on the radio interface specifications.

As described in the '850 application, some aspects of the invention provide for sharing data and channel state information among groups of base stations to coordinate their transmissions in the downlink and jointly process the received signals in the uplink. These techniques can effectively turn otherwise harmful inter-cell interference into useful signals, enabling significant power gain, increased channel rank, and/or diversity advantages. While some systems disclosed herein describe cellular base stations by way of example, it should be appreciated that additional and/or alternative radio transceivers may be employed, including fixed relay stations, remote radio heads, mobile stations, peer-to-peer radio transceivers, access points, and combinations thereof.

FIGS. **4**A and **4**B are flow diagrams depicting spatial demultiplexing implemented via multi-cell MIMO cooperation in wireless networks. In dense networks where interference emerges as the key capacity-limiting factor, multi-cell cooperation can dramatically improve the system performance. Remarkably, such techniques can literally exploit inter-cell interference by allowing the user data to be jointly processed by several interfering base stations, thus mimicking the benefits of a large virtual MIMO array.

In FIG. **4**A, UE's transmit reference signals **401** and data signals **403**. Transmitted reference signals received by multiple base transceiver stations are measured to generate channel state information **402**, from which spatial demultiplexing weights are calculated **404**. In one aspect of the invention, a central processor measures the channel state information **402** and calculates demultiplexing weights **404** for a geographically distributed set of base transceiver stations. In another aspect of the invention, each base transceiver station measures the channel state information **402**, which is then forwarded to at least one central processor. In some aspects of the invention, distributed computing may be employed for calculating the spatial demultiplexing weights **404**. For example, computational parts of step **404** may be performed by multiple base transceiver stations. The central processor then demultiplexes the data transmissions **406** received from the UEs.

In FIG. **4**B, the transmission points and/or the central processor employ blind-adaptive processing, such as disclosed in the '163 application, to demultiplex received data transmissions. Data signals transmitted **411** by the UE are received and processed by multiple base transceiver stations and at least one central processor. Blind adaptive processing provides channel state information **412**, which is used to calculate spatial demultiplexing weights **414**, which are used to demultiplex **416** the data transmissions received from the UEs.

FIG. **5** is a flow diagram depicting a method in accordance with some aspects of the invention in which multiple transmission points and at least one central processor cooperate to produce subspace pre-coded downlink transmissions to multiple UEs. A base transceiver station (e.g., a transmission point) performs preliminary processing **501** of signals received from at least one UE and communicates channel state information corresponding to each UE to at least one central processor **503**. The channel state information can include channel measurements made by the UEs and/or the base transceiver stations. Thus, step **501** can comprise measuring the channel(s) of each UE. The central processor collects channel state information communicated by multiple base transceiver stations **504**, selects which base transceiver stations will serve each UE **506**, calculates the distributed-antenna pre-coding **508**, and coordinates the base transceiver stations to transmit pre-coded data signals to the UEs **510**. Each base transceiver station then transmits pre-coded data signals to the UEs **512**.

A base transceiver station (or transmission point), as used throughout the disclosure, can comprise a NodeB (such as employed in a UTRAN system) or an eNodeB (such as employed in an EUTRAN system). A central processor, as used throughout the disclosure, can include a radio network controller (RNC) in a UTRAN system or an eNodeB in an EUTRAN system. EUTRAN consists only of eNodeBs on the network side. The eNodeB performs tasks similar to those performed by the NodeBs and RNC together in UTRAN.

E-UTRA uses OFDM-MIMO antenna technology depending on the terminal category and can use subspace pre-coding for the downlink to support more users, higher data rates, and lower processing power. In the uplink, LTE uses both OFDMA and Carrier Interferometry (also called Single-Carrier Frequency-Division Multiple Access (SC-OFDMA)), such as disclosed throughout the '850 and '163 applications. This mitigates the very high peak-to-average power of conventional OFDM. For the uplink, in release 8 and 9, multi-user MIMO/Spatial division multiple access (SDMA) is supported.

LTE supports both Frequency-division duplex (FDD) and TDD modes. While FDD makes use of paired spectra for UL and DL transmission separated by a duplex frequency gap, TDD splits one frequency carrier into alternating time periods for transmission from the base station to the terminal and vice-versa. Both modes have their own frame structure within LTE, and these are aligned with each other. Thus, similar hardware can be used in the base stations and user terminals.

FIG. **6** is a flow diagram depicting a method in accordance with some aspects of the invention in which multiple transmission points and at least one central processor cooperate to perform distributed spatial demultiplexing of uplink transmissions received from multiple UEs. A base transceiver

station (e.g., a transmission point) performs preliminary processing **601** of uplink signals received from at least one UE and communicates channel state information corresponding to each UE to at least one central processor **603**. The channel state information can include channel measurements made by the UEs and/or the base transceiver stations. Thus, in some aspects, step **601** can comprise measuring the channel(s) of each UE. The central processor collects channel state information communicated by multiple base transceiver stations **604**, selects multiple base transceiver station antennas (including antennas on different base stations) from which signals will be combined for each UE **606**, calculates the distributed-antenna demultiplexing weights **608**, and performs spatial demultiplexing **610** to separate multiple same-band signals transmitted by the UEs and received by multiple base transceiver stations.

With respect to aspects of the disclosure, a multi-antenna wireless communication system, such as one employing Coordinated Multipoint transmission and/or reception, can mitigate inter-cell interference. In such a system, multiple antennas are deployed across a plurality of geographically contiguous cells (or sub-cells) and connected to a central processor, e.g., via a fast backhaul. This architecture enables the central processor to jointly process downlink signals transmitted from and/or uplink signals received at the multiple antennas, in order to mitigate inter-cell interference.

In accordance with some aspects of the disclosure, to jointly process downlink signals transmitted from the multiple antennas, in particular, the central processor is provided with information characterizing the associated downlink channel responses. If the system employs FDD, the served UEs measure these downlink channel responses and feed them back to the central processor. If the system instead employs TDD, the downlink channel responses can advantageously be estimated from uplink signals received at the multiple antennas based on the assumption that for TDD, the downlink channel can be inferred from the uplink channel (e.g., the uplink and downlink channels can be reciprocal).

This assumption of reciprocity between the downlink and uplink channel, however, may sometimes be inaccurate in a multi-antenna system. For instance, each of the multiple antennas is connected to a corresponding transceiver that comprises a transmit-receive radio frequency (RF) chain. These transmit-receive RF chains may have different frequency responses, due for example to differences in the transfer characteristics of the components (e.g., analog filters, power amplifiers, etc.) making up those RF chains. If the RF chains of the multiple antennas do not have identical frequency responses, the assumption of reciprocity no longer proves accurate, which in turn can prevent advantageous estimation of the downlink channel responses from uplink signals. Accordingly, the RF chains can be initially, and perhaps periodically, calibrated with one another to account for differences in their frequency responses, such as disclosed in U.S. Pat. No. 6,211,671, which is incorporated by reference in its entirety.

FIG. **7** is a flow diagram depicting messages passed between network devices corresponding to steps in a super-array processing method. Such flow diagrams can assist a software developer in designing software modules with instructions on non-transient computer-readable memory that program a computer processor to perform methods disclosed herein.

In one aspect of the invention, a reference signal is transmitted **751**, from which channel state information is calculated. For example, each antenna on each of a plurality of base stations **701** and **702** can transmit a reference signal (**711** and **712**, respectively), such as a known training signal or a pilot tone, which a UE **700** receives and processes to determine its channel state information.

In a feedback step **752**, the UE transmits its channel state information **713** and **714** back to its respective base station **701** and **702**. The base stations **701** and **702** relay the channel state information (e.g., messages **715** and **716**) received from their UEs to at least one central processor **710**.

As should be appreciated from the disclosure, an alternative step **751** can comprise the base stations **701** and **702** receiving transmitted reference signals from the UEs (such as UE **700**) and estimating the channels therefrom. Then the feedback step **752** comprises the base stations **701** and **702** relaying the channel state information **715** and **716** to the at least one central processor **710**.

In step **753**, the central processor **710** calculates distributed antenna system weights w_1 and w_2 **753** based on the channel state information **715** and **716**. In a cooperative-MIMO demultiplexing step (not shown), the weights can be used to demultiplex interfering data streams (not shown) in the uplink channels between the UEs **700** and base stations **701** and **702** routed to the central processor **710**.

Cooperative-MIMO multiplexing provides for employing the distributed antenna system weights for pre-coding data D to be transmitted to each UE **700**. For example, weight vectors w_1 and w_2 are used to pre-code a data matrix, and the pre-coded data signals **717** and **718** are routed to their respective base stations **701** and **702**. The base stations **701** and **702** transmit signals **719** and **720** comprising the pre-coded data to the UEs **700**.

As illustrated in FIG. **8**, software developed in accordance with aspects of the invention may comprise functionality that is separable into multiple independent and interchangeable modules. In some aspects, a module may comprise a software object. In some applications, a module may comprise a container that contains other objects. While the scale of a module may vary depending on the programming language and the application, modules are typically designed to perform logically discrete functions and interact via well-defined interfaces. It should be appreciated that in some aspects of the disclosure, modules can comprise data objects, and such data objects reside in physical memory of a computing device and can comprise executable instructions stored in memory that cause a processor to execute steps that give rise to the disclosed functionality as described below.

FIG. **8** comprises pseudo-code that depicts data structures and processing functions that can be implemented by a computer processor programmed to perform methods in accordance with aspects of the invention, including methods disclosed in the '850 application. An object, such as a virtual array object, V_array **40**, can comprise methods and data structures that package distributed-array assets (e.g., antenna systems of different base transceivers, radio signal processors associated with those antenna systems, baseband signal processing systems in the base transceivers and/or in the central processor(s), and front-haul networks) in a manner that conceals certain details. For example, the V_array object **840** may comprise a private section **850** in which a combination of data structures and functions can only be accessed within the object **840**. By way of example, objects Bts **851** and Fronthaul **852** are private members. Private data structures and functions can conceal implementation details of the object's **840** interface (e.g., how Public functions are implemented and how Public data structures are created).

The virtual antenna array object **840** includes an implementation, which is typically expressed by one or more

functions, such as functions **862-866**. The implementation contains the working code that corresponds to the elements declared in the interface, such as the Antenna object **861**. Functions **862-866** may call other functions which may be internal and/or external to the object **840**. By way of example, function f_select_ue(. . .) **862** selects UEs based on some predetermined quality factor, such as disclosed in the '850 application. Function f_select_antenna(. . .) **863** selects antennas in the array to serve a particular UE, such as disclosed in the '163 application. Function f_csi(. . .) measures channel state information for each antenna/UE combination, such as disclosed in the '850 application. Function f_mux(. . .) provides for spatial multiplexed transmission of pre-coded data across the array of antennas (which may reside on multiple geographically distributed base stations), such as disclosed in the '850 application. Function f_rx(. . .) receives data from a predetermined set of antennas residing on multiple geographically distributed base stations, such as disclosed in the '850 application.

In one aspect of the invention, each Antenna object **861** is associated with an antenna on a base transceiver station (indicated by the Bts object **851**), so the virtual antenna array can include antennas associated with different base stations, such as disclosed in the '850 application. The base transceiver stations can be connected to a central processor via a fronthaul network, such as disclosed in the '850 application. Thus, the virtual array object **840** can comprise one or more Fronthaul objects **852** associated with communications between the Antenna objects **861**.

In some aspects of the invention, the virtual antenna array object **840** conceals information related to its antenna elements being distributed across multiple base transceivers (and/or UEs). For example, in some aspects, the virtual antenna array object **840** conceals information about fronthaul networks communicatively coupling signals between the antenna elements and signal processors (such as baseband processors, including MIMO processors). Thus, each virtual antenna array object **840** can conceal network communications within an object-oriented interface.

In accordance with some aspects of the invention, the virtual antenna array object **840** is part of a distributed control environment that provides services, such as access, interaction, and control of base transceiver antennas in a network of geographically distributed base transceivers.

A module interface expresses the data and/or functional elements that are provided and required by the module. For example, the virtual antenna array object **840** could receive as its input an element indicating a particular UE. Thus, a virtual antenna array could be created for each UE. The elements defined in the interface are usually detectable by other modules. In one aspect of the invention, quality factors and signal strength are some of the parameter by which physical antennas distributed across multiple base transceivers can be selected for inclusion in the virtual antenna array object **840**. In some aspects, a quality factor or signal strength comprises a measurement of a known training signal. Elements may comprise various data structures, such as lists, arrays, queues, stacks, and other objects. Each data structure has associated operations that may be performed on it and pre-conditions and constraints on the effects of those operations.

Once a virtual array object **840** is created, it may be passed as an argument to another module, such as a multi-user MIMO object, Mu_mimo **810**. For example, function calls **801** and **802** access functional elements **822** and **821**, respectively, in the Mu_mimo object's **810** interface **820**. In some aspects, arguments in the function calls **801** and **802** can comprise function calls in the V_array object's **840** interface.

The f_precode(. . .) function **821** employs channel state information (csi) to generate a set of antenna array weights (such as via a private function, f_weight(. . .) **831**). The weights are used by function **821** to pre-code a data set (tx_data) to produce pre-coded data (precoded_data). The pre-coded data can then be transmitted by the f_mux(. . .) function **865** in the same virtual array object **840** used by the f_precode function **821**. Thus, in accordance with some aspects of the invention, the f_precode function **821** can perform multi-user MIMO pre-coding for an array of geographically distributed antennas. The f_demux(. . .) function **822** processes channel state information (csi) and received data (rx data) from the virtual antenna array **840** to demultiplex the received data.

In the uplink, MIMO receiver processing techniques can be used to efficiently exploit the spatial dimensionalities of the MIMO channel to increase WWAN capacity. In aspects of the invention, from an algorithmic perspective, there is no discernible difference in processing a plurality of different transmissions from a single UE configured for MIMO versus processing one signal from each of a plurality of different UEs configured only for Single Input, Multiple Output (SIMO). Similarly, in some aspects of the invention in which fronthaul latency is either negligible or compensated for, there is no algorithmic difference in MIMO receiver processing whether the receiving array comprises antennas employed on multiple base transceiver stations or an antenna array on a single base transceiver station. In the downlink, in some aspects of the invention in which fronthaul latency is either negligible or compensated for, there is no algorithmic difference in MIMO transmitter processing whether the transmitting array comprises antennas employed on multiple base transceiver stations or an antenna array on a single base transceiver station. For these reasons, at least some implementation details of the virtual array object **840** can be concealed from the multi-user MIMO object **810**.

A MIMO system employs multiple (N_T) transmit antennas and multiple (N_R) receive antennas for data transmission. A MIMO channel formed by the N_T transmit and N_R receive antennas may be decomposed into N_C independent channels, wherein $N_C \leq \min\{N_T, N_R\}$. Each of the N_C independent channels is also referred to as a spatial subchannel (or subspace channel) and corresponds to a dimension. In one common MIMO system implementation, the N_T transmit antennas are located at and associated with a single transmitter system, and the N_R receive antennas are similarly located at and associated with a single receiver system. A Cooperative-MIMO system can be effectively formed for a multiple access communication system having a set of base transceiver stations communicatively coupled together and coordinated to concurrently communicate with a number of UEs. In this case, each base transceiver station and each terminal can be equipped with one or more antennas. A Cooperative-MIMO system can be effectively formed for a multiple access communication system having a multiple UEs communicatively coupled together and coordinated to concurrently communicate with at least one base transceiver station. In this case, the base transceiver station is typically equipped with multiple antennas and each terminal can be equipped with one or more antennas. However, if geographically distributed base transceiver stations are employed, each base transceiver station can be equipped with one or more antennas.

The wireless links between the distributed base transceiver station antennas and the UE antennas are modeled as a complex channel matrix H of dimensions $K \times N_T$, where K is the aggregate number of UE antennas and N_T is the number of distributed antennas. H_{DL} is the DL channel matrix and H_{UL} is the UL channel matrix. Channel reciprocity holds if DL and UL are set to the same carrier frequency:

$$H_{DL}=H_{UL}^{T}=H$$

where the superscript symbol, "^{T}", denotes the transpose matrix operation.

In one aspect of the invention, channel estimation is initiated with transmission of a training signal by each of the antennas of a plurality N of base stations. Assuming M antennas per base station, there are N·M training signal transmissions.

Each UE receives each training signal through each of its antenna(s) and frequency down-converts the training signal to baseband, where it is digitized and processed. Signal characterization logic, such as represented by function f_csi(. . .) **864** characterizes the channel from the received training signal (e.g., identifying phase and amplitude distortions, such as in the case of a flat fading channel, or calculating a channel impulse response) and stores the characterization in memory. Some aspects of this characterization process are similar to that of prior-art MIMO systems, with a notable difference being that the each UE only computes the characterization vector for its own antenna(s) rather than for all K antennas, and each UE is configured to perform channel characterization from training signals transmitted from multiple base transceiver stations. In other aspects of the invention, function f_csi(. . .) **864** characterizes the channel from training signals transmitted by the UEs. Thus, function f_csi(. . .) **864** may reside on the base transceiver stations and/or the central processor. In accordance with some aspects of the invention, software objects, and even components with software objects disclosed herein may reside on multiple devices, including UEs, base transceiver stations, and central processors.

In accordance with one aspect of the invention, each UE produces a sub-matrix of a full cooperative-MIMO channel matrix H. For example, if a UE has one antenna (or it has multiple antennas and a combining system that combines signals received by the multiple antennas), then a channel estimate corresponding to a training signal transmitted by one antenna of one of the base stations is an element of a $1 \times N_T$ vector, where N_T is the total number of base station antennas, expressed by $N_T=\Sigma_{n=1}^{N} M_n$, where N is the number of base stations, and M_n is the number of antennas corresponding to an nth base station. In some aspects, a channel estimate comprises a complex-valued flat-fading coefficient. In some aspects, a channel estimate comprises a matrix, such as an impulse response vector.

In accordance with an aspect of the invention, a first UE having a single antenna generates a $1 \times N_T$ vector of channel characterization data: $[H_{1,1}, H_{1,2}, \ldots, H_{1,N_T}]$. A second UE having a single antenna generates a $1 \times N_T$ vector of channel characterization data: $[H_{2,1}, H_{2,2}, \ldots, H_{2,N_T}]$. A kth UE having a single antenna generates a $1 \times N_T$ vector of channel characterization data: $[H_{k,1}, H_{k,2}, \ldots, H_{k,N_T}]$. This channel characterization data can be a data set (e.g., csi) within the V_array object **840**.

Based on channel conditions and/or proximity of a UE to each base station, a particular set of base stations may be selected to serve the UE. For example, this selection process may be performed by the f_select_antenna(. . .) function **863**. Thus, one or more UEs may be assigned to a subset of the total number of base stations. In such instances, values of the channel characterization data corresponding to a non-serving base station relative to a UE may equal zero. In some cases, certain values of the full cooperative-MIMO channel matrix H, such as matrix elements corresponding to indices of non-serving base station antennas relative for a particular UE, may be set to zero

In some aspects of the invention, a kth UE comprises multiple N_k antennas configured to perform MIMO. For each UE's antenna, a channel estimate corresponding to a training signal transmitted by one antenna of one of the base stations is an element of a $1 \times N_T$ vector. Thus, the kth UE can generate an $N_k \times N_T$ submatrix of the full cooperative-MIMO channel matrix H.

The UEs upload their channel characterization sub-matrices to the base stations via the WWAN, and the sub-matrices are communicated to the central processor via the fronthaul network. Thus, in some aspects, the f_csi(. . .) function **864** can comprise components distributed across UEs, base stations, and one or more central processors. As the central processor collects the channel characterization sub-matrices, they are stored as the full $K \times N_T$ cooperative-MIMO channel matrix H, where K is the total number of UE antennas and N_T is the total number of base station antennas.

Since each UE is an independent device, each UE often receives its own unique data stream. Thus, in some aspects of the invention, the central processor sources multiple data streams and routes them as separate data streams intended for each UE. In order to do this, the central processor comprises precoding logic for precoding the signals transmitted from each antenna of each of the base stations based on the signal characterization matrix H. In one aspect of the invention, the pre-coding logic is implemented via one or more software instructions, such as the f_precode(. . .) function **821** in the Mu_mimo object **810**. The central processor then routes the precoded data (or the precoding weights and data symbols) to the plurality of base stations. Routing can be part of the f_precode(. . .) function **821**, or it can comprise a separate function call. Thus, each base station antenna is configured to transmit a subspace-coded data sequence which is a function of the data symbols and the channel matrix H.

In one aspect of the invention, cooperative MIMO improves the uplink communications (i.e., the link from the UEs to the Base Stations). In this aspect, the channel from each UE is continually analyzed and characterized by uplink channel characterization logic residing in each base transceiver station or central processor, which may be implemented by the f_csi(. . .) function **864**. For example, each UE may transmit a training signal, which the channel characterization logic analyzes (e.g., as in a typical MIMO system) to generate the channel characterization matrix H.

As described throughout the '163 application, the '854 application, and the '107 application, all of which are incorporated by reference in their entireties, various spatial processing techniques may be employed. Such processing techniques may be included within the f_precode **821** and f_demux **822** functions.

In one aspect of the invention, f_demux **822** performs linear spatial processing on the received signals (for a non-dispersive MIMO channel with flat fading) or space-time processing on the received signals (for a dispersive MIMO channel with frequency selective fading). The spatial processing may be achieved using linear spatial processing techniques such as a channel correlation matrix inversion technique, a minimum mean square error (MMSE) technique, and others. These techniques may be used to null out

the undesired signals and/or to maximize the received SNR of each of the constituent signals in the presence of noise and interference from the other signals. The space-time processing may be achieved using space-time processing techniques such as an MMSE linear equalizer, a decision feedback equalizer (DFE), a maximum-likelihood sequence estimator (MLSE), and others. In some aspects, iterative cancellation techniques, such as successive interference cancellation may be employed.

In some aspects of the invention, f_precode **821** performs directive and/or retro-directive techniques for calculating antenna array weights for transmission in a distributed antenna system. Such techniques are disclosed in the '163 application. In some aspects of the invention, as disclosed in the '187 application, eigenvalue-decomposition approaches, such as singular value decomposition, may be employed for transmitter spatial processing.

For example, a MIMO channel formed by the N_T transmit antennas comprising multiple transmission nodes (e.g., base stations) and N_R receive antennas comprising multiple UEs can be characterized by an $N_R \times N_T$ channel response matrix H for each OFDM subband, wherein each matrix element $h_{i,j}$ of H denotes coupling or complex channel gain between transmit antenna j and receive antenna i. For simplicity, the MIMO channel is assumed to be full rank with $S=N_T \leq N_R$.

For data transmission with eigensteering, eigenvalue decomposition can be performed on a correlation matrix of H to obtain S eigenmodes of H, as follows:

$$R=H^H \cdot H=E \cdot \Lambda \cdot E^H,$$

where R is a correlation matrix of H; E is a unitary matrix whose columns are eigenvectors of R; Λ is a diagonal matrix of eigenvalues of R; and "^{H}" denotes a conjugate transpose.

A unitary matrix U is characterized by the property $U^H U=I$, where I is the identity matrix. The columns of a unitary matrix are orthogonal to one another, and each column has unit power. The matrix E is also called an "eigenmode" matrix or a "transmit" matrix and may be used for spatial processing by the central processor to transmit data on the S eigenmodes of H. The eigenmodes may be viewed as orthogonal spatial channels obtained through decomposition. The diagonal entries of Λ are eigenvalues of R, which represent the power gains for the S eigenmodes. The eigenvalues in Λ may be ordered from largest to smallest, and the columns of E may be ordered correspondingly. Singular value decomposition may also be performed to obtain matrices of left and right eigenvectors, which may be used for eigensteering.

For data transmission with eigensteering, the transmitting entity may perform spatial processing for each subband as follows:

$$z=E \cdot s,$$

where s is a vector with up to S data symbols to be sent on a particular subband; and z is a vector with N_T spatially processed symbols for the subband. In general, D data symbols may be sent simultaneously on D (best) eigenmodes of H for each subband, where $1 \leq D \leq S$. The D data symbols in s are spatially processed with D columns of E corresponding to the D selected eigenmodes.

For data transmission with a spatial spreading matrix, such as a CI spatial spreading matrix, the transmitting entity may perform spatial processing for each subband as follows:

$$z_{ss}=V \cdot s$$

where V is a spatial spreading matrix for the subband; and z_{ss} is a vector with up to N_T spread symbols for the subband. Each data symbol in s is multiplied with a respective column of V to obtain up to N_T spread symbols.

In general, D data symbols may be sent simultaneously on each subband with matrix spreading, where $1 \leq D \leq S$. The D data symbols in s may be multiplied with a $N_T \times D$ spreading matrix V(k) to obtain N_T spatially processed symbols for z_{ss}. Each spatially processed symbol for each subband includes a component of each of the D data symbols being sent on the subband. The N_T spatially processed symbols for each subband are then transmitted on the S spatial channels of H.

As disclosed throughout the '187 application, any of various water-filling or water-pouring schemes may be employed to optimally distribute the total transmission power over the available transmission channels, such as to maximize spectral efficiency. For example, water-filling can be used to adapt individual UE transmission powers such that channels with higher SNRs are provided with correspondingly greater portions of the total transmit power. A transmission channel, as defined herein, may include a spatial (e.g., a sub-space) channel, a space-frequency channel, or some other channel defined by a set of orthogonalizing properties. Similarly, water filling may be used at a physically connected (i.e., wired) antenna array. The transmit power allocated to a particular transmission channel is typically determined by some predetermined channel-quality measurement, such as SNR, SINR, BER, packet error rate, frame error rate, probability of error, etc. However, different or additional criteria may be employed with respect to power allocation, including, but not limited to, UE battery life, load balancing, spatial reuse, power-control instructions, and near-far interference.

The modulation and channel coding for each transmission channel may be adapted with respect to the corresponding SNR. Alternatively, transmission channels may be grouped with respect to their data-carrying capability. Thus, groups of transmission channels may share common modulation/coding characteristics. Furthermore, transmission channels having particular SNRs may be used for particular communication needs. For example, voice communications may be allocated to channels having low SNRs, and thus, data-carrying capabilities. In some cases, transmission channels that fail to achieve a predetermined threshold SNR may be eliminated. In one embodiment of the invention, water filling is employed such that the total transmission power is distributed over selected transmission channels such that the received SNR is approximately equal for all of the selected channels.

In accordance with some aspects of the invention, hardware systems, such as UEs, base transceiver stations, and central processors, can include a processing element capable of executing processing threads or tasks.

As depicted in FIG. **9**, a UE can include a controller, such as at least one computer or data processor **910**, at least one non-transitory computer-readable memory medium embodied as a memory **920** that stores a program of computer instructions **921**, and at least one suitable radio frequency (RF) transmitter/receiver **901** for bidirectional wireless communications with multiple base transceiver stations via one or more antennas **905**.

As depicted in FIG. **10**, a base transceiver station includes a controller, such as at least one computer or a data processor **1012**, at least one computer-readable memory medium embodied as a memory **1014** that stores a program of computer instructions **1016**, and at least one suitable RF transceiver **1002** for communication with the UEs via one or more antennas **1001.1**-**1001.**N_M. The base transceiver station is coupled via a fronthaul transceiver **1020** to a data and

control path to the central processor, such as a network control element. In one aspect of the invention, the fronthaul may be implemented as an Si interface. In another aspect, the fronthaul may comprise an X2 interface. In another aspect, the fronthaul can comprise a direct eNodeB internal interface (e.g., optical fiber connection) such as a connection between a radio remote head and an eNodeB.

Thus, there is some central unit where several base transceiver stations are connected as such, with the goal being that the base transceiver stations (e.g., transmission points, macro eNodeBs, etc.) are centrally controlled together. The control can be at the location of a macro eNodeB, but could also be at a different location.

As depicted in FIG. **11**A, a central processor, such as a network control element, comprises a controller, such as at least one computer or a data processor **1112**, at least one computer-readable memory medium embodied as a memory **1114** that stores a program of computer instwctions **1116**, and at least one fronthaul transceiver **1120** coupled to a data and control path (i.e., a fronthaul network) between the central processor and multiple base transceiver stations.

At least one of the programs **921**, **1016**, and **1116** is assumed to include program instructions that, when executed by the associated computer processor(s), enable the corresponding device(s) to operate in accordance with the exemplary aspects of the invention.

The '163 application discloses SDR platforms that enable dynamic implementations of a full protocol stack, including Physical-layer processing. Some aspects are disclosed in the context of software-defined networks, such as to enable more dynamic organization of resources. Disclosed software radio implementations include instantiations of virtual base stations.

In some disclosed aspects, software radio provides associated control operations, such as identifying a particular transmission protocol used by a particular device, reserving channels for transmission, monitoring channel use (including channel reservation and channel release), requesting data transmissions and/or state information from remote devices, attaching tags to data streams for identification and/or access control, and providing instructions to remote transceivers to adjust or control processing, transmit status information, and/or identification.

By way of example, and with respect to implementing base transceiver station processing in a central processor or in a distributed computing system, a software-defined radio in accordance with one aspect of the invention can provide a base station instantiation for a UE. Specifically, the software-defined radio can perform base station processing functionality in combination with Cooperative-MIMO subspace processing to use a plurality of geographically distributed base transceiver stations that communicate with the UE via the radio access network. In an LTE network, this means that the software-defined radio implements a virtual eNodeB to support the LTE protocol stack for that user while providing for subspace coding to support spatial multiplexing.

In one aspect, when a UE joins the network, the SDR might provide for requesting identification, performing channel reservation, and requesting state information (e.g., channel state information) from the UE. The combination of software-defined radio and Cooperative-MIMO implemented with virtualized base station processing via the central processor or even distributed (e.g., cloud) computing enables each UE to be served independently of other UEs concurrently employing the same spectrum, and possibly using the same base transceiver station hardware. This is because Cooperative-MIMO subspace processing enables multiple non-interfering subspace channels in the same spectrum to be used by each UE, even closely spaced UEs, which can eliminate the need for other multiple access partitioning of the spectral resource (such as via TDMA, OFDMA, CDMA, etc.). When the UE ends its connection with the network, the SDR releases the channel and its instantiated virtual base station.

In accordance with some aspects, consolidation of processing from multiple base stations to a central processor (e.g., an offsite data center) constitutes a virtual base station that employs multiple antennas of different base transceiver stations and remote (and possibly software-defined) base station processing. Further aspects distribute the base station processing over multiple processing cores via distributed (e.g., cloud) computing. As disclosed in the '163 application, multiple different transmission protocols may be employed simultaneously. Thus, SDR instances (e.g., virtual base stations) employing different protocol stacks may coexist within the same software-defined radio and can be implemented concurrently within the same spectrum.

A CI-based software radio can extend adaptive link-layer techniques to the physical layer. This enables more efficient use of the spectrum by dynamically adjusting physical-layer characteristics to current channel conditions, network traffic, and application requirements. CI can significantly improve wireless network performance and functionality by adapting to different requirements for bandwidth, error rate, latency, link priority, and security.

Embodiments of a CI-based communication system may include interactive capabilities between the physical layer and higher layers such that a response to changing conditions and operational requirements can be directed to an appropriate physical-layer function. For example, a base station or central processor in a mobile wireless network can dynamically create channels (e.g., spatial multiplexing channels) depending on the number of mobile units in its coverage area and their service requirements. When additional units enter the area, the system can be reconfigured accordingly.

In ad-hoc networks, base station functions (e.g., routing, power control, synchronization, geo-location services, etc.) may be distributed among various devices. Aspects of the disclosure can also include adapting base-station and access-point functions to maintain link quality and perform load balancing (including managing power budgets for devices acting as routers and relays, managing system spectrum allocations, and/or adjusting cell boundaries to adapt to changing user demands, power budgets, and spectrum use). Thus, in some aspects, the super-array processing system **112** may include a power control **114.3**.

Bandwidth can be dynamically allocated to uplink and downlink channels depending on network traffic characteristics. Units requiring real-time or broadband services may be assigned to dedicated channels, whereas units having bursty data requirements may be assigned to a shared channel. Aspects of the invention can provide for combinations of time-domain and frequency-domain processing to produce signals having desired physical-layer characteristics.

SDRs disclosed in the '163 application are configured to provide for various signal processing objectives for implementing multiple-access protocols (e.g., DS-CDMA, TDMA, OFDM, MC-CDMA), channel coding, modulation (e.g., phase modulation, frequency modulation, amplitude modulation, time-offset modulation, etc., including different constellations (e.g., binary, M-ary), multiplexing (e.g.,

TDM, FDM, CDM), formatting (e.g., frame length, headers, payload length, etc.), source coding, providing for frequency agility (e.g., frequency hopping, variable aggregate bandwidth, frequency selectability, etc.), encryption, and/or subchannel coding.

FIG. **11**B is a block diagram that depicts a cloud-based software-defined radio, such as disclosed in the '163 application. A plurality of hardware components (such as servers **1101** and **1102**) are communicatively coupled together via a network **1190**. Server **1101** comprises at least one processor (e.g., CPU **1161**) and at least one memory **1141**. Similarly, server **1102** comprises at least one processor (e.g., CPU **1162**) and at least one memory **1142**. A software-defined radio platform can comprise a plurality of signal-processing software components residing in one or more of the memories **1141** and **1142** of the hardware components, **1101** and **1102**, respectively. By way of example, SDRs **1151.1-1151**.*i* are stored in memory **1141**, and SDRs **1152.1-1152**.*j* are stored in memory **1142**. By way of example, the hardware components **1101** and **1102** may include a computer main frame or a workstation.

Although not shown, interfaces can couple the hardware components **1101** and **1102** together, such as via the network **1190**. Such interfaces disclosed in the '163 application include radio interfaces for a radio network. The network **1190** may comprise various types of networks, including a bus. Also disclosed in the '163 application is the concept of interfaces for the software components (e.g., **1151.1-1151**.*i* and **1152.1-1152**.*j*) as it relates to software design, such as object oriented design. Interaction and inter-connectivity between software and hardware interfaces is also contemplated for coupling together hardware and/or software components.

The SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j* may include local and/or remote computer programs configured to process signals, such as for various physical-layer signal processing, including baseband processing. For example, the SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j* may include one or more programs for performing digital signal processing. One or more of the SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j* may provide control signals to one or more hardware components such as to select, adapt, or otherwise reconfigure signal processing.

The memory can comprise various types of storage mediums (e.g., disk drive, tape drive, CR Rom, DVD, flash memory, or any other storage device) for storing application programs (e.g., the SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j*) and data. Hardware and/or the software may perform A/D conversion, as necessary. In some applications, modulation and/or demodulation may be performed digitally with any combination of software and hardware.

In one set of aspects of the invention, a software component (such as at least one of the SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j*) residing at a remote receiver location (e.g., a base transceiver station) receives signals transmitted in the radio access network, processes the received signals, and conveys some control information in the data stream (e.g., in a header or pilot channel) to hardware components residing in another location (e.g., at a central processor or another base transceiver station). Signal-processing operations may be distributed throughout a network in a way that balances processing loads and/or communication-resource (e.g., spectrum use) loads. Alternatively, in a Cooperative-MIMO network wherein UEs cooperate with a base transceiver station to perform joint processing for spatial multiplexing and/or demultiplexing signals, most of the signal processing may be performed by the base transceiver station (and/or the central processor) to reduce the cost and complexity (and power usage) of the UEs. As described with respect to centralized processing of base transceiver operations, RF processing is performed at each base transceiver station, and most or all of the baseband signal processing may be performed at a central processing facility.

In one set of aspects of the disclosure, software can be uploaded to a remote transceiver (e.g., base transceiver station) via one or more communication channels. This simplifies software updates and enhances signal-processing versatility of the network. In another set of aspects, software updates can be uploaded to a central processor (e.g., a cloud network organized by a central processor) where most or all of the baseband processing is performed.

Software-based radios can provide adaptability to different communication standards. The '163 application discloses various systems and techniques that can migrate many different transmission protocols to a common high-performance SDR platform that is suitable for all applications. In some aspects of the disclosure, the SDR platform can be configured to enable coexistence of different standard systems within the same spectrum. For example, the power emission, frequency band, or other configuration parameters of a legacy radio access network can be adjusted to accommodate the adoption of new transmission protocols while avoiding harmful interference with the legacy protocol.

As new wireless standards are developed to enhance data rate and coverage in the radio access network, the base transceiver stations and/or central processors can be updated to support those standards. In some aspects, only the central processor(s) needs to be updated. By way of example, the central processor may comprise distributed computing resources, such as multiple servers residing in one or more data centers. The servers may comprise hardware components of an SDR platform.

In one aspect, the base transceiver stations and/or central processors are SDRs equipped with programmable computational capability, such as FPGA, DSP, CPU, GPU, and/or GPGPU, configured to run algorithms for baseband signal processing in the radio access network. If the standard is upgraded, new baseband algorithms can be uploaded to the central processors and/or from the central processors to the base transceiver stations to reflect the new standard. This SDR feature allows for continuous upgrades to the radio access network, such as when new technologies are developed to improve overall system performance.

In one aspect of the disclosure, a cloud SDR network comprises a multi-user MIMO system implemented with cooperative-MIMO over a plurality of geographically distributed base transceiver stations communicatively coupled to a central processor. The central processor is configured to perform at least some of the baseband processing in the radio access network. In some aspects, the central processor and the base transceiver stations are configured to exchange information to reconfigure system parameters, such as to dynamically adapt to changing conditions of the radio access network, including the network architecture (such as described in the '187 application).

As disclosed with respect to coordinated multipoint systems with a central processor configured to perform cooperative MIMO, the base transceiver stations in a cloud SDR network can be configured to generate simultaneous non-interfering wireless links to serve different UEs with different multiple access techniques (e.g., TDMA, FDMA, CDMA, OFDMA, etc.) and/or different modulation/coding schemes. For example, if the base transceiver stations perform RF processing and the central processor performs just

baseband processing, the SDRs can be configured to perform baseband processing. Based on the active UEs in the radio access network and the standard(s) they use for their wireless links, the SDRs implemented by the central processor (such as SDRs in a distributed computing environment) can instantiate virtual base station processes in software, each process configured to perform the baseband processing that supports the standard(s) of its associated UE(s) while utilizing a set of the base transceiver stations within range of the UE(s).

In accordance with one aspect of the invention, baseband waveforms from multiple ones of the SDRs **1151.1-1151.***i* and **1152.1-1152.***j* are coupled into the Super-Array Processing System **112** depicted in FIG. **2**. The baseband waveforms are combined in the Spatial Multiplexing/Demultiplexing module **114.1** using Cooperative-MIMO subspace processing to produce multiple pre-coded waveforms. The routing module **114.2** sends the pre-coded waveforms over the fronthaul **105** to multiple ones of the base transceiver stations' **101.1-101**.N antennas **102.1-102**.M_1, **106.1-106**.M_2, and **104.1-104**.M_N. The base transceiver stations **101.1-101**.N can be coordinated to concurrently transmit the pre-coded waveforms such that the transmitted waveforms propagate through the environment and constructively interfere with each other at the exact location of each UE **120.1-120**.K. The coherent combining of these waveforms at the location of each UE **120.1-120**.K results in the synthesis of the baseband waveform that had been output by the SDR instance **1151.1-1151.***i* and **1152.1-1152.***j* associated with that UE **120.1-120**.K. Thus, all of the UEs **120.1-120**.K receive their own respective waveforms within their own synthesized coherence zone concurrently and in the same spectrum.

In accordance with one aspect of the invention, each UE's corresponding synthesized coherence zone comprises a volume that is approximately a carrier wavelength or less in width and centered at or near each antenna on the UE. This can enable frequency reuse between nearby—even co-located—UEs. As disclosed in the '107 application, the Spatial Multiplexing/Demultiplexing module **114.1** can be configured to perform maximum ratio combining. Any of various algorithms for MIMO processing disclosed in the '107 application may be employed by methods and apparatus aspects disclosed herein. In some aspects, the module **114.1** can perform zero forcing, such as to produce one or more interference nulls, such as to reduce interference from transmissions at a UE that is not an intended recipient of the transmission. By way of example, but without limitation, zero forcing may be performed when there are a small number of actual transmitters (e.g., base transceiver station antennas) and/or effective transmitter sources (e.g., scatterers in the propagation environment).

By way of example, FIG. **12** is a block diagram that depicts a central processor **1100** communicatively coupled via a fronthaul network **1240** to multiple base transceiver stations, such as base transceiver stations **1271** and **1272**. Each base transceiver station **1271** and **1272** comprises a WWAN transceiver **1202** and **1203**, respectively, and baseband processor **1212** and **1213**, respectively. WWAN transceiver **1202** comprises a number N_1 of WWAN transceiver antennas **1204.1-1204**.N_1, and WWAN transceiver **1204** comprises a number N_M of WWAN transceiver antennas **1205.1-1205**.N_M. The baseband processor **1212** comprises a computer processor **1214** and a memory **1216**. The baseband processor **1213** comprises a computer processor **1215** and a memory **1217**. In accordance with some aspects of the disclosure, the baseband processors **1212** and **121** comprise Channel State Information processing logic **1218** and **1219**, respectively, and Channel State Information routing logic **1220** and **1221**, respectively. Each base transceiver station **1271** and **1272** comprises a fronthaul transceiver **1230** and **1231**, respectively, communicatively coupled via the fronthaul network to the central processor **1100**.

In accordance with some aspects of the disclosure, Channel State Information processing logic **1218** and **1219** can collect channel information uploaded by the UEs (not shown) and/or determine channel state information from measurements of training signals transmitted by the UEs (not shown). Channel State Information routing logic **1220** and **1221** can route channel state information to at least one central processor, such as the central processor **1100**.

In some aspects of the disclosure, the central processor **1100** comprises Channel State Information processing logic **1126**, Pre-coding logic **1136**, and Base Station Routing logic **1146**. In one aspect, computer software, such as logic **1126**, **1136**, and **1146**, comprises instructions stored on a non-transitory computer-readable medium (e.g., memory **1114**), that when executed on the processor **1112**, perform the steps of storing the WWAN channel state information received from the base transceiver stations (e.g., base transceiver stations **1271** and **1272**) based on the WWAN channel state information and/or at least one quality metric that characterizes each communication link between a base transceiver station and a UE; and selecting a plurality of antennas residing on multiple base transceiver stations to provide a set of distributed antennas. For example, a set of distributed antennas can be selected to serve each UE. Next, the processor **1112** calculates subspace processing weights from each UE's channel state information for the each UE's corresponding set of distributed antennas. The corresponding instructions can be in the Pre-coding logic **1136** and/or in subspace demultiplexing logic (not shown). The processor **1112** coordinates each UE's corresponding set of distributed antennas to communicate in the WWAN via the fronthaul network. For example, the corresponding instructions for coordinating the distributed antennas can be in the Base Station Routing logic **1146**. The central processor **1100** provides for performing at least one of subspace multiplexing of WWAN signals transmitted by each set of distributed antennas and subspace demultiplexing signals received by each set of distributed antennas.

The exemplary aspects of the disclosure may be implemented, at least in part, by computer software executable by the data processor **910** of the UEs (such as the UE shown in FIG. **9**), the data processor **1012** of the base transceiver stations (such as the base transceiver station shown in FIG. **10**), by the data processor **1112** of the central processor (such as the central processor shown in FIG. **11**A), by multiple data processors in a distributed computing system (not shown), and/or by hardware, or by a combination of software, hardware, and firmware.

In accordance with one aspect of the invention, subspace multiplexing is provided by the Pre-coding logic **1136** configured to produce pre-coded subspace (i.e., spatial multiplexing) weights and to encode data with the weights, and the Base Station Routing logic **1146** configured to route the encoded data to the base transceiver stations for transmission to the UEs. In accordance with another aspect of the invention, subspace demultiplexing is provided by the Base Station Routing logic **1146** configured to route UE uplink signals received by the base transceiver stations to the central processor **1100** and the subspace demultiplexing logic (not shown) configured to produce subspace demultiplexing weights based on the channel state information and

to de-multiplex (i.e., decode) the received signals. Thus, performing at least one of subspace multiplexing of WWAN signals transmitted by each set of distributed antennas and subspace demultiplexing signals received by each set of distributed antennas enables multiple UEs to employ simultaneous interference-free same-band communications.

In accordance with some aspects of the invention, certain features, such as pre-coding logic and subspace demultiplexing logic, can comprise an Application Programming Interface (API) or library that defines functionalities that are independent of their respective implementations, which allows definitions and implementations to vary without compromising each other. By way of example, and without limitation, APIs provided for base station network control can enable MIMO processing applications to operate on an abstraction of the network, such as by exploiting distributed antenna array systems and coordinated base station operations and capabilities, without being tied to the details of their implementation.

In accordance with some aspects of the disclosure, the steps of selecting antennas on multiple base transceiver stations for MIMO processing and coordinating the multiple base transceiver stations for cooperative-MIMO communications (which includes routing communication signals to and/or from the multiple base transceiver stations as part of a cooperative subspace processing operation) tie the mathematical operation (i.e., multi-user MIMO subspace processing) to specific and measurable operational benefits (i.e., based on measurable physical phenomena), such as the ability to improve WWAN performance (e.g., spectral efficiency, number of subspace channels, data rate per user, number of users supported, SNR, BER, etc.).

These steps add significantly more to MIMO processing than mere computer implementation. By employing steps, such as selecting multiple base transceiver stations to simultaneously serve each UE in a MIMO subspace processing operation, coordinating the selected multiple base transceiver stations to perform in a subspace multiplexing and/or demultiplexing process, and provisioning at least one central processor to perform subspace multiplexing and/or demultiplexing of signals transmitted by and/or received from the selected multiple base transceiver stations, the corresponding aspects of the invention go beyond the mere concept of simply retrieving and combining data using a computer.

In accordance with the disclosure, the various data processors, memories, programs, transceivers, and interfaces, such as depicted in FIGS. **9**, **10**, **11**, and **12**, can all be considered to represent means for performing operations and functions that implement the disclosed non-limiting aspects and embodiments.

The computer-readable memories (e.g., memories **920**, **1014**, **1114**, **1216**, and **1217**) may be of any type suitable to the local technical environment and may be implemented using any suitable data storage technology, such as semiconductor based memory devices, random access memory, read only memory, programmable read only memory, flash memory, magnetic memory devices and systems, optical memory devices and systems, fixed memory and removable memory. The computer processors (e.g., computer processors **910**, **1012**, **1112**, **1214**, and **1215**) may be of any type suitable to the local technical environment, and may include one or more of general purpose computers, special purpose computers, microprocessors, digital signal processors (DSPs) and processors based on multi-core processor architectures, as non-limiting examples.

In accordance with aspects of the invention depicted and described in the '163 application, FIG. **13**A illustrates a subspace processing method configured in accordance with some aspects of the invention. A data-sequence vector u having length Nis provided to a transmit filter **1301** before being coupled into a communication channel **99**. The channel **99** acts on a transmitted data vector x via an N×N non-singular matrix H and an additive noise vector n having a variance of $N_0/2$. A signal vector y received from the channel **99** is expressed by:

$$y=Hx+n$$

The received signal vector y is processed by a matched filter **1302** to generate an output signal vector z, which is expressed by:

$$z=R_f x+n'$$

where $R_f=H^*H$ and $n'=H^*n$. An estimate of x given z is expressed by:

$$\tilde{x}=R_b z+e$$

where $R_b^{-1}=R_f(N_0/2)R_{xx}^{-1}$, R_{xx} is the covariance of x, and e is the MMSE error. Additional processing, such as any of various adaptive feedback techniques, may be incorporated at the receiver end.

Although sub-space processing is commonly associated with array processing, the '163 application also discloses coding and decoding based on sub-space processing techniques. For example, as a signal is routed from one node to at least one other node in a network, algebraically unique linear codes are applied to the data for each "hop." In one set of embodiments, sub-space processing and CI methods can be combined. Sub-space processing can include frequency-diversity interferometry and/or interferometry between one or more sets of diversity-parameter values including, but not limited to, polarizations, codes, modes, phases, and delays.

As disclosed in the '163 application, FIG. **13**B illustrates a subspace processing method that employs decision feedback. In this case, Cholesky factorization provides:

$$R_f=G^*S_0G$$

where S_0 is a diagonal matrix and G is a monic, upper-diagonal matrix. A decision feedback equalizer includes a feed-forward filter **1303**, a decision system **1304**, and a feedback filter **1305**. An exemplary decision feedback equalization algorithm is represented by:

$$\tilde{z} := S_0^{-1}G^{-*}H^*y$$

for $k = 0, N-1$

$$\hat{x}_{N-k} := \text{decision}\left(\tilde{z}_{N-k} - \sum_{i=1}^{k} g_{N-k,N-k+i}\hat{x}_{N-k+i}\right)$$

end

where g_{ij} are elements of G, and $\hat{x}_i$ and $\hat{z}_i$ are elements of $\hat{x}$ and $\hat{z}$, respectively.

A decision feedback equalizer may reorder the received substreams by rearranging the rows and columns of H. For example, a layered processing approach may be employed. Symbols are detected sequentially and interference from previously detected symbols is subtracted. Received vector elements are weighted to null (or reduce) interference from undetected symbols.

Method and apparatus implementations of radio transceivers in accordance with aspects of the disclosure, such as radio transmission techniques and radio transmitters employed by UEs and/or base transceiver stations, are

depicted in the block diagram of FIG. **14**A. The blocks disclosed herein can be steps of a method, functional blocks of a transmitter and/or transmitter system, and/or components of a transmitter and/or transmitter system. In some aspects of the disclosure, such as disclosed in the '850 and '163 applications, a transmitter's components can reside on different devices, such as on different network devices communicatively coupled together via a network.

An exemplary aspect of the disclosure provides for OFDM signaling. An information signal s(t) is encoded and/or interleaved in block **1401**. Various types of coding that are known in the art can be employed. For example, in the uplink, it can be desirable to produce a transmission signal with low dynamic range (i.e., peak to average power). Thus, the UEs can employ CI coding on OFDM subcarriers to produce CI-OFDM (also known as a single-carrier OFDM) signals.

The coding/interleaving block **1401** can provide for generating or otherwise acquiring symbol values to be impressed onto the subcarriers. The information signal can be provided with predetermined training symbols in a training symbol injection block **1402**. Training symbols can be used for various purposes, including, but not limited to, channel estimation, signal-quality estimation, and synchronization.

An IFFT **1403** (or equivalent process) impresses the coded data symbols onto the subcarriers and adds a cyclic prefix. FIR filtering and interpolation **1404** is performed prior to preparing the resulting signal for transmission into a communication channel, typically via an RF front end (not shown).

Various methods and systems adapted to perform the blocks shown in FIG. **14**A can be provided by transmission systems and methods pertaining to the aspects and embodiments of the disclosure. Furthermore, various other signal-processing steps that are typically performed in radio transmitters may be included herein. For example, pre-equalization steps and/or systems may be included in the transmission methods and transmitters disclosed herein.

As described throughout the disclosure, array processing may be performed in transmitters and in transmission methods. Array processing (e.g., subspace multiplexing) can be performed after FIR filtering and interpolation **1404**. In some aspects, array processing can be integrated into the coding **1401**, IFFT **1403**, and/or FIR filtering **1404** blocks.

As used herein, RAN baseband processing is the Physical Layer processing of baseband signals, such as digital baseband signals that will be transmitted in the RAN (after DAC and up-conversion), and digitized baseband signals produced from received radio signals in the RAN. RAN baseband processing is distinguished from IP processing in that RAN baseband processing is particular to the RAN. By way of example, FIR filtering **1404**, modulation (e.g., IFFT **1403**), and training signal injection **1402** are RAN baseband processes. Coding **1401** can include Physical Layer and/or higher layers. For example, forward-error correction (FEC) is often employed by the data link layer or higher. It should be appreciated that RAN baseband processing includes RAN multiple access and RAN spread spectrum coding, but not transcoding. Interleaving **1401**, as it pertains to distributing data symbols over a physical resource (e.g., multiplexing data symbols on selected bins of a discrete Fourier transform) constitutes RAN baseband processing, whereas interleaving data bits in a data stream does not. Many base station network coordination processes, such as scheduling, handover, routing, power control, and control signaling, are not RAN baseband processing operations. While channel estimation is a RAN baseband processing operation, conveying channel estimates, SNRs, or BERs between base stations is not. While multiple access and multiplexing (i.e., generating the physical signals wherein data is partitioned by time interval, frequency, code space, etc.) constitutes RAN baseband processing, assigning network resources to UEs does not.

Method and apparatus implementations of radio transceivers in accordance with aspects of the disclosure, such as radio reception techniques and radio receivers employed by UEs and/or base transceiver stations, are depicted in the block diagram of FIG. **14**B. The blocks disclosed herein can be steps of a method, functional blocks of a receiver and/or receiver system, and/or components of a receiver and/or receiver system. In some aspects of the disclosure, such as disclosed in the '850 and '163 applications, a receiver's components can reside on different devices, such as on different network devices communicatively coupled together via a network.

Signals received from a communication channel are input to an FIR filtering and decimation block **1405**. Filtered signals may be processed in a synchronization step **1411** to control the timing of various reception processes, such as, but not limited to, a cyclic prefix removal and fast Fourier transform (FFT) step **1406** and array processing **1407**. Complex-amplitude measurements associated with individual subcarriers, such as estimates obtained via known training symbols and/or unknown data symbols, may be used in a channel-estimation step **1413**. The channel estimation step **1433** can facilitate the generation of weights (e.g., array-processing and/or CI combining weights).

Array processing **1407** is performed to achieve some preferred combination of system capacity (e.g., subspace demultiplexing) and signal quality (e.g., diversity combining). For example, array processing **1407** may include spatial interferometry multiplexing and/or any other form of array processing. In some aspects, array processing **1407** may be assisted by an interference-estimation step **1416**. CI combining **1418** may be performed in conjunction with the array-processing **1407** and/or a decoding and de-interleaving **1408**. Alternatively, either or both the array-processing **1407** and the decoding and de-interleaving **1408** may perform CI combining **1418**. The decoding and de-interleaving step **1408** performs any necessary de-interleaving of data symbols received from the array-processing **1407** prior to, or following decoding **1408**. Decoding **1408** can include channel, multiple access, spread spectrum, encryption, and/or other decoding processes.

FIG. **15** is a block diagram of a transceiver in accordance with some aspects of the disclosure. A receiver system **1501** is configured to couple a received signal from a communication channel. One or more typical receiver-side signal processing techniques (such as filtering, mixing, down conversion, amplification, A/D conversion, etc.) may be performed on the received signal. A filter bank, such as an FFT **1502**, separates the received signal into a plurality of frequency components. If the received signal is an OFDM signal, the FFT **1502** retrieves a symbol measurement for each OFDM subcarrier. The components are provided with weights in a receiver weighting system **1503**. The weights may include one or more types of weights, such as channel-compensation weights, decoding weights, spatial de-multiplexing weights, multi-user detection weights, array-processing weights, wavelet-processing weights, etc. The weighted components are combined in a combiner **1504**. The combined signals may be processed in a data processor **1505**. In some aspects, the data processor **1505** may be part

of a blind-adaptive processor **1506** that is adapted to generate and/or adapt weights relative to one or more performance parameters, such as channel estimates, confidence measures, data estimates, signal power, probability of error, BER, SNR, SNIR, etc.

In one aspect, the blind-adaptive processor **1506** processes information-bearing CI symbol measurements produced by the FFT **1502**. The processor **1506** may work in conjunction with the combiner **1504** to combine the measurements and estimate transmitted data. In some aspects, the combining process may include wavelet processing. The processor **1506** may work in conjunction with the data processor **1505** to provide a channel estimate based on data estimates. In some aspects, the processor **1506** can employ a time-varying channel-estimation filter. In some aspects, the processor **1506** provides channel compensation, which may be based on a statistical characterization of interference, such as a covariance matrix.

In some applications, the processor **1506** provides predistortion (i.e., pre-coding) weights to transmitted signals. A data stream is optionally processed by a transmit data processor **1507**. A transmitter weighting system **1508** is configured to weight data symbols provided to frequency bins of a frequency-domain-to-time-domain converter, such as an IFFT **1509**. Time-domain signals generated by the IFFT **1509** are provided to a transmission system configured to prepare the time-domain signals for transmission into a communication channel.

In accordance with aspects of the disclosure, transceiver operating characteristics can be adaptable, such as indicated in the block diagram depicted in FIG. **16**. In one aspect, a control circuit **1601** is configured to receive one or more system requirements **1611** and, optionally, one or more channel characteristics **1612**. The control circuit **1601** can adapt one or more signal parameters **1602** employed by a radio transceiver **1603**, such as radio transceivers employed by UEs, base transceiver stations, and/or central processors. Signal parameter adaptation and/or selection affect one or more transceiver operating parameters **1621**.

In one aspect, the control circuitry **1601** may scale a transmitted bit rate by scaling the symbol duration, the number of subcarriers, the subcarrier spacing, and/or the number of bits per symbol per subcarrier. This permits the transceiver **1603** to operate in different communications environments, which may require varying operating parameters and/or characteristics. By adapting the operating parameters and/or characteristics of the transceiver **1603**, the control circuitry **1601** can dynamically change the radio signals, thereby providing for compatibility or improving performance. For example, dynamically scaling the bit rate enables widely varying signal bandwidths, adjustment of delay-spread tolerances, and adaptability to different SNR requirements. An adaptable transceiver system can be particularly useful for mobile wireless communications, as well as other applications that support a variety of services in a variety of environments.

In accordance with some aspects of the disclosure, an OFDM system may be configured to select the number of subcarriers and a variable symbol duration. The control circuitry can dynamically select the number of subcarriers to decrease the signal bandwidth and the transmission rate while delay-spread tolerance remains the same. The control circuitry **1601** can also dynamically increase the symbol duration to decrease the transmission rate and the signal bandwidth and provide an increase in delay-spread tolerance. In some aspects, the control circuitry **1601** can be adapted to adjust the transmission rate by changing the type of modulation. In accordance with other aspects, variable transmission rates can be achieved by using adaptive coding wherein different coding schemes are selected to improve the link reliability and/or to decrease the peak-to-average power ratio.

In accordance with yet other aspects of the disclosure, adaptable transmission rates permit asymmetric data rates throughout the network. For example, individual UEs can be allocated varying sets of subcarriers depending on their data bandwidth needs. Additionally, during data downloading, for example, a mobile unit could have a larger downlink data rate than uplink data rate.

In accordance with some aspects of the disclosure, base transceiver stations employ adaptive antenna processing wherein UEs feedback their channel estimates via the uplink when uplink and downlink channel characteristics are not identical. In some aspects, power control can be performed on individual subcarriers or on groups of subcarriers. Alternatively, or in addition to power control, certain subcarriers may be selected to optimize one or more operational parameters, such as throughput, probability of error, received signal power, transmitter power efficiency, SNR, QOS, etc.

Sets of subcarriers may be selected with respect to the types of services being provided. For example, different qualities of service corresponding to different-priority links and/or different link services may be criteria for selecting subcarriers. In one case, subcarriers having little distortion and interference may be selected for services (such as data links) that do not tolerate high BER. In another case, a transmission may be divided into sections and sent on two or more groups of subcarriers (or channels). In some aspects, a more important section, such as addressing information, may be sent on higher-quality subchannels than subchannels on which payload data is sent. Addressing and other control information is typically less tolerant to errors than payload data. Thus, important parts of a transmission may be transmitted on higher-quality subspaces and/or on subcarriers having little distortion and fading.

In some aspects of the disclosure, various demand-assigned protocols govern the utilization of the bus medium. As used herein, the term bus medium, or bus, refers to a communication system or communication resources employed to communicatively couple together distributed transceiver components in a manner that resembles the functions of a computer bus. This expression covers all related hardware components (wire, optical fiber, etc.) and software, including communication protocols. By way of example, a bus can comprise a fronthaul network, a backhaul network, a local area network, and/or a wide area network. In one aspect, a bus communicatively couples together internal components residing in different networked devices, wherein the internal components are configured (such as by a central processor or via some distributed processing means) to function together as a single transceiver or transceiver system. In such aspects, a bus can comprise communication pathways, internal networks, etc. inside the networked devices.

As disclosed herein, software instructions configured to perform methods in accordance with aspects of the disclosure can provide various combinations of object-oriented design features. For example, a radio transceiver system comprising multiple components distributed across multiple networked devices may be provided with an abstraction interface wherein the multiple different constituent components are mapped to a single abstract device. Thus, the details of how the radio transceiver system is implemented (for example, whether the radio transceiver is a single

discrete device or comprised of multiple constituent components communicatively coupled together via a bus) can be hidden from systems and operations configured to employ the radio transceiver system. In one example, MIMO processing algorithms can be employed across the multiple constituent components in substantially the same manner as would be employed in a single device comprising multiple antennas. As described herein, MIMO processing algorithms can include various types of algorithms, including, but not limited to, MRC, MMSE, ZF, and/or successive interference cancellation. In some aspects, certain details of the radio transceiver system implementation are provided to the abstract device. For example, certain implementation details (or at least the effects of the implementation) can help a MIMO processor compensate for latencies in the bus communications between cooperating devices in a Cooperative-MIMO configuration.

In accordance with one aspect of the disclosure, each data communication device (DCD) of a set of DCDs in a network communicates with a central access point (AP). Multiple DCDs may request access from the AP in the same request access (RA) burst. In one aspect, each of the multiple DCDs transmits its access request to the AP within a frequency-domain subchannel in the RA burst that is orthogonal to the frequency domain subchannels used by the other DCDs requesting access. In another aspect, each of the multiple DCDs transmits its access request to the AP within a subspace channel in the RA burst that is orthogonal to the subspace channels used by the other DCDs requesting access. Alternatively, other orthogonal diversity-parameter values may be employed. In some aspects, each DCD provides channel training information in the RA burst to allow the AP and/or DCD to adapt to variations in channel characteristics.

FIG. **17** is a block diagram depicting a plurality K of UEs **120.1-120**.K (e.g., mobile or fixed subscriber units) in a wireless network comprising a plurality N of base transceiver stations (e.g., access points) **101.1-101**.N. At least one of the UEs **120.1-120**.K is configured to transmit a pilot signal or known training signal that is received at the base transceiver stations **101.1-101**.N. The propagation environment ensures that the set of pilot signals received by the base transceiver stations **101.1-101**.N is unique for each UE's **120.1-120**.K location. In some aspects of the disclosure, the uniqueness of the propagation environment can be exploited to provide or enhance coding. The base transceiver stations **101.1-101**.N are adapted to process the received pilot signals. Processing operations may depend on various characteristics of the received pilot signals, including absolute and/or relative signal power levels. For example, a predetermined set of the base transceiver stations **101.1-101**.N may be selected to process signals for a given UE based on the received pilot signal power.

In one aspect, at least one of the base transceiver stations **101.1-101**.N is configured to perform channel analysis to characterize the propagation environment of the transmissions between each UE **120.1-120**.K and the base transceiver station(s) **101.1-101**.N. Channel analysis may include delay-profile and/or flat-fading characterizations. In some aspects of the disclosure, the propagation environment is employed as a unique identifier for each UE **120.1-120**.K. In some aspects, weights calculated from channel estimates may be utilized in multiple-access codes, encryption codes, and/or authentication and verification procedures.

In some aspects of the disclosure, channel analysis is used to generate filter weights and/or array-processing weights at the base transceiver stations **101.1-101**.N to process received and/or transmitted signals. Such weights may be generated using various algorithms, such as MRC, MMSE, ZF, and/or successive interference cancellation, as well as others. The base transceiver stations **101.1-101**.N may comprise single-antenna systems or multi-antenna systems, such as antenna arrays. Received signals may be compared to some local or global timing reference, such as to analyze phase offsets and/or signal timing.

In another aspect of the disclosure, the base transceiver stations **101.1-101**.N are configured to transmit pre-coded signals to the UEs **120.1-120**.K. For example, the transmissions can be pre-coded to exploit the multipath environment between the access points **10011** to **10015** and the UEs **120.1-120**.K to constructively combine at the UEs **120.1-120**.K.

In one set of aspects, transmission (i.e., pre-coding) weights are generated from the reciprocal of a channel matrix that characterizes the propagation environment between a plurality of the base transceiver stations **101.1-101**.N and at least one of the UEs **120.1-120**.K. Channel (i.e., pre-coding) weights may be generated via any combination of deterministic (i.e., training) and blind-adaptive processing. Channel weights may be selected and/or adapted to optimize coherent combining of the base transceiver stations' **101.1-101**.N transmissions at one or more of the UEs **120.1-120**.K. Similarly, the channel weights may be selected and/or adapted to optimize coherent combining of signals received by the base transceiver stations' **101.1-101**.N from one or more of the UEs **120.1-120**.K. Any of various combining techniques may be employed.

In some aspects, channel weights are adapted to generate beam-pattern nulls at one or more of the UEs **120.1-120**.K or other transceivers. Channel weights may be adapted to provide time-varying channel compensation. Thus, beam steering, null steering, or any other time-dependent adaptive array processing may be performed. Appropriate combinations of carrier selection and carrier weighting may be provided to achieve simultaneous directionality (e.g., spatial multiplexing) and diversity benefits. In some applications, any of the base transceiver stations **101.1-101**.N may be replaced by UEs configured to function as routers, relays, and/or array elements of an adaptive transceiver array.

FIG. **18** is a block diagram of a RAN comprising base transceiver stations **101.1-101**.N configured in accordance with an aspect of the invention. The fronthaul network **105** can comprise a wireless, fiber optic, and/or wireline network that communicatively couples the base transceiver stations **101.1-101**.N to a central processor **110**. The central processor **110** is configured to process signals received from and transmitted by the base transceiver stations **101.1-101**.N.

In accordance with one aspect of the disclosure in the '163 application, the central processor **110** comprises a distributed computing system **111**. In accordance with another aspect of the disclosure in the '163 application, the central processor **110** is replaced by the distributed computing system **111**. In one aspect, the distributed computing system **111** comprises a plurality of processors, which may be geographically distributed. As used herein, the term "processor" can refer to a computer processor, a computer, a server, a central processing unit (CPU), a core, a microprocessor, and/or other terminology that indicates electronic circuitry configurable for carrying out instructions of a computer program.

The processors are communicatively coupled together via at least one network, such as a backhaul network **115**. The backhaul network **115** can comprise an optical fiber network, a wireline network (e.g., Ethernet or other cable

links), a wireless network, or any combination thereof. In one aspect, the processors are programmed to function as a plurality N of virtual base stations **111.1-111**.N. By way of example, each virtual base stations **111.1-111**.N may comprise one or more of the processors and perform base station processing operations that would ordinarily be performed by one or more of the corresponding base stations **101.1-101**.N. Specifically, virtual base stations can be implemented via software that programs general-purpose processors. For example, an SDR platform virtualizes baseband processing equipment, such as modulators, demodulators, multiplexers, demultiplexers, coders, decoders, etc., by replacing such electronic devices with one or more virtual devices, wherein computing tasks perform the functions of each electronic device. In computing, virtualization refers to the act of creating a virtual (rather than actual) version of something, including (but not limited to) a virtual computer hardware platform, operating system (OS), storage device, or computer network resources.

In accordance with the art of distributed computing, a virtual base station's functions can be implemented across multiple ones of the plurality of processors. For example, workloads may be distributed across multiple processor cores. In some aspects, functions for more than one base station are performed by one of the processors.

As used herein, distributed computing refers to the use of distributed systems to solve computational problems. In distributed computing, a problem is divided into multiple tasks, and the tasks are solved by multiple computers which communicate with each other via message passing. A computer program that runs in a distributed system is referred to as a distributed program. An algorithm that is processed by multiple constituent components of a distributed system is referred to as a distributed algorithm. In a distributed computing system, there are several autonomous computational entities, each of which has its own local memory.

In accordance with aspects of the disclosure, the computational entities (which are typically referred to as computers, processors, cores, CPUs, nodes, etc.) can be geographically distributed and communicate with each other via message passing. In some aspects, message passing is performed on a fronthaul or backhaul network. The distributed computing system can consist of different types of computers and network links, and the system (e.g., network topology, network latency, number of computers, etc.) may change during the execution of a distributed program. In one aspect, a distributed computing system is configured to solve a computational problem. In another aspect, a distributed computing system is configured to coordinate and schedule the use of shared communication resources between network devices.

A distributed computing system can comprise a grid computing system (e.g., a collection of computer resources from multiple locations configured to reach a common goal, which may be referred to as a super virtual computer). In some aspects, a distributed computing system comprises a computer cluster which relies on centralized management that makes the nodes available as orchestrated shared servers. In some aspects, a distributed computing system comprises a peer-to-peer computing system wherein computing and/or networking comprises a distributed application architecture that partitions tasks and/or workloads between peers. Such distributed peer-to-peer computing systems are disclosed in the '107 application. In some aspects, peers are equally privileged, equipotent participants in the application. They are said to form a peer-to-peer network of nodes. Peers make a portion of their resources, such as processing power, disk storage, network bandwidth, etc., available to other network participants without the need for central coordination by servers or stable hosts. Peers can be either or both suppliers and consumers of resources.

As disclosed in the patents and patent applications incorporated by reference herein, and particularly with respect to aspects of Cooperative-MIMO systems and methods, network nodes can function as either or both clients and servers. Furthermore, when wireless network nodes cooperate in subspace processing, they create network resources, such as subspace (i.e., spatial multiplexing) channels, performance gains, RAN coverage area, etc. Even when UEs cooperate as a client array (e.g., a UE cluster) in a Cooperative-MIMO implementation, each UE can improve the data bandwidth, quality of service, range, and power efficiency of the other UEs in the array, or cluster. Thus, in some aspects of a Cooperative-MIMO system, UEs can extend the network infrastructure, such as to increase per-client data bandwidth, the number of clients served, coverage area, and/or quality of service without requiring substantial capital outlays from network operator to upgrade the base station network.

In Cooperative-MIMO systems, mobile UEs can opportunistically join together via a peer-to-peer overlay network for client-side MIMO processing. In some aspects, UEs can join base transceiver arrays via an overlay network to assist in server-side MIMO processing. Due to random movement of UEs, aspects of the invention do not impose a particular structure on the overlay network. Because there is no structure globally imposed upon them, unstructured networks are easy to build and allow for localized optimizations to different regions of the overlay. Also, in some aspects, because the role of all peers in the network is the same, unstructured networks are highly robust in the face of high rates of churn (i.e., when peers are frequently joining and leaving the network).

In accordance with some aspects of the disclosure, the base transceiver stations **101.1-101**.N are "dumb terminals," wherein base station signal processing (for example, the baseband processing) is performed by the central processor **110** (which may include the distributed computing system **111**). Thus, in some aspects, the base transceiver stations **101.1-101**.N are simply radio remote units. For example, the base transceiver stations **101.1-101**.N might perform only basic signal-processing functions, such as RF processing (i.e., radio front-end processing), which can include frequency conversion and (optionally) ADC/DAC functions, while the central processor **110** (which may include the distributed computing system **111**) performs baseband processing, including channel analysis and generating base transceiver MIMO weights.

In one aspect, the central processor **110** coordinates or performs baseband signal processing corresponding to base station operations, whereas the base transceivers **101.1-101**.N provide only RF front end signal processing, including frequency conversion, and optionally, ADC/DAC. The central processor can perform waveform shaping, error detection, error correction, power control, channel selection, multiple access control, multiplexing, modulation, formatting, synchronization, coding, etc. for the plurality of base transceivers (i.e., access points) communicatively coupled to the central processor via the fronthaul network. In some aspects of the disclosure, the central processor **110** provides for base-station functionality, such as power control, code assignments, and synchronization. The central processor **110** may perform network load balancing, including providing for balancing transmission power, bandwidth, and/or processing requirements across the radio network. Centralizing

the processing resources (i.e., pooling those resources) facilitates management of the system, and implementing the processing by employing multiple processors configured to work together (such as disclosed in the '163 application) enables a scalable system of multiple independent computing devices, wherein idle computing resources can be allocated and used more efficiently.

Some aspects allow base station processing resources (e.g., the processors in the distributed computing system **111**) and the remote RF units (e.g., the base transceiver stations **101.1-101**.N) to be deployed separately. For example, RAN coverage, capacity, and/or data bandwidth per UE can be improved by adding base transceiver stations, and then the SDR platform dynamically adapts to the new RAN base station configuration. Similarly, the SDR platform can adapt to the loss of one or more of the base transceiver stations **101.1-101**.N. The distributed computing system (e.g., cloud network) **111** can adapt to varying processing loads by allocating computing resources as needed. Furthermore, system upgrades, such as new transmission protocols, can be easily implemented via software upgrades to the SDR platform.

In some aspects, base-station functionality is controlled by individual base transceiver stations and/or UEs assigned to act as base stations. Array processing may be performed in a distributed sense wherein channel estimation, weight calculation, and optionally, other network processing functions (such as load balancing) are computed by a plurality of spatially separated processors. In some aspects, access points and/or subscriber units are configured to work together to perform computational processing. A central processor (such as central processor **110**) may optionally control data flow and processing assignments throughout the network.

As disclosed in the '850 application, the system depicted in FIG. **18** provides system performance benefits by centralizing (e.g., pooling) much of the equipment (and/or signal processing) typically employed at the cell sites. Cost reduction is another motivation for centralizing the radio access network, as most of a cellular network's ownership costs comprise operating costs, including site rental, power, and support and maintenance expenses. Thus, instead of distributing baseband processing equipment at the edge of the network as in conventional cellular networks, centralizing the radio access network at the central processor **110** can greatly reduce capital expenditures to build out and upgrade the radio access network, as well as reduce operating expenditures.

As disclosed in the '163 application, providing for distributed computing at the central processor **110** provides network function virtualization to the radio access network. Benefits that can be realized with some aspects of the disclosure include cost reduction from pooling and virtualizing baseband processing. This can eliminate the need to provision for peak capacity on a per-site basis, thus reducing processing requirements. Furthermore, instead of requiring dedicated base station hardware, some of the disclosed aspects provide for the use of commercial (e.g., general purpose) servers running software.

As disclosed in the patents and applications incorporated by reference herein, other types of networks, including wireless networks, can connect the base transceiver stations **101.1-101**.N. One of the advantages of employing the optical fiber fronthaul **105** is that optical fiber can provide the high capacity and low latency required by many aspects of the invention. For example, when a large number of baseband processors are co-located at the central processor **110**, the amount of data bandwidth in the fronthaul and the synchronization requirements between base transceiver stations **101.1-101**.N can increase substantially when high RF bandwidth and MIMO are employed. Different aspects of the invention can provide for different functional splits between centralized and distributed functions.

Some aspects of the invention can reduce fronthaul requirements by implementing at least some of the Physical Layer processing at the base transceiver stations **101.1-101**.N while implementing other processing (e.g., higher layer processing, or the higher layer processing plus some of the Physical layer processing) at the central processor **110**. Thus, in some aspects of the invention, one or more of the base transceiver stations **101.1-101**.N depicted in the figures may be replaced by UEs adapted to perform as routers, repeaters, and/or elements of an antenna array.

In one aspect of the disclosure, the base station network comprising base transceiver stations **101.1-101**.N is adapted to operate as an antenna array. In such aspects, a portion of the network may be adapted to serve each particular UE. The central processor **110** and/or the base transceiver stations **101.1-101**.N may be configured to perform other signal-processing operations, such as, but not limited to, waveform shaping, error detection, error correction, power control, channel selection, multiple access control, multiplexing, modulation, formatting, synchronization, coding, etc. In some aspects of the disclosure, the central processor **110** is replaced by a distributed computing system. In some aspects, the distributed computing system may comprise a plurality of the UEs **120.1-120**.K, repeaters (not shown), and/or the base transceiver stations **101.1-101**.N.

FIG. **19** is a block diagram that depicts apparatus and method aspects of the disclosure. Access points (e.g., access point **1901**) and at least one access controller (e.g., central processor **1902**) are connected via a fronthaul network **1905**, which may comprise an optical fiber, wireless, and/or wireline network. In some aspects, the fronthaul network **1905** may comprise standard interfaces, such as Common Public Radio Interface (CPRI) or Open Base Station Architecture Initiative (OBSAI). The access point **1901** comprises radio processing equipment **1910**, and the central processor **1902** comprises baseband processing equipment **1920**.

In accordance with some aspects of the disclosure, the entire baseband processing is carried out in the central processor **1902** while there may be no baseband processing performed at the access points **1901**. For example, the radio processing equipment **1910** may comprise analog front end circuitry and digital front end circuitry, and the baseband processing equipment **1920** comprises circuitry for the layers L1 (i.e., the Physical Layer) and higher layers. In one aspect of the invention, the radio processing equipment **1910** may perform basic signal-processing tasks, such as amplification, RF filtering, frequency conversion, as well as other RF signal-processing functions. The baseband processing equipment **1920** may perform baseband processing, including modulation/demodulation, combining, channel characterization, power control, other system control functions, quality factor analysis, coding, array processing etc.

It should also be appreciated that in some aspects, such as supported by the disclosures of the patents and patent applications that are incorporated by reference, that either or both radio processing equipment **1910** and the baseband processing equipment **1920** may each be implemented with one or more processors and one or more memories including computer program code, the computer program code com-

prising instruction configured to cause the processor(s) to perform the corresponding radio processing and/or baseband processing functions.

In accordance with some aspects of the disclosure, physical-layer baseband processing is performed on an SDR platform, which can be implemented on a distributed (e.g., cloud) computing system. Physical-layer baseband processing can include multiplexing, de-multiplexing, modulation, de-modulation, and/or equalization.

In one aspect of the invention, the access point **1901** is a device that serves as the air interface to the user equipment and implements analog radio frequency functions of an eNodeB. The access point **1901** may include one or more antennas for communicating with one or more UEs, and may include support for a variety of antenna types and configurations including, but not limited to, single omni-directional antennas and MIMO arrays of directional antennas. Exemplary functions that may be performed by the access point **1901** include digital-to-analog (D/A) conversion, analog-to-digital (A/D) conversion, carrier multiplexing, power amplification, and RF filtering. The central processor **1902** may be an LTE network device configured to implement radio functions of the digital baseband domain. These functions may include, but are not limited to, radio base station control and management, MIMO processing, and channel coding and de-coding.

FIG. **20**A is a flow chart depicting methods in accordance with aspects of the disclosure. Each of a plurality of geographically distributed access points performs RF processing of signals received from UEs in a radio access network **2001**, such as a WWAN. The resulting RF-processed signals are communicated to a central processor via a fronthaul network **2002**, such as an optical fiber network. The central processor collects RF-processed signals from the plurality of geographically distributed access points **2003** and performs baseband processing of the collected signals **2004**. In one aspect of the disclosure, the baseband processing **2004** comprises distributed computing performed by a distributed computing system. For example, the central processor may configure a plurality of processors to perform baseband processing.

FIG. **20**B is a flow chart depicting methods in accordance with aspects of the disclosure. A central processor performs baseband processing of UE signals **2011** to be transmitted by a plurality of geographically distributed access points to UEs served by a radio access network. In one aspect of the disclosure, the baseband processing **2011** comprises distributed computing performed by a distributed computing system (e.g., a cloud). For example, the central processor may configure a plurality of processors to perform baseband processing.

The resulting baseband-processed signals are communicated to the plurality of geographically distributed access points via a fronthaul network **2012**. The central processor may coordinate the plurality of geographically distributed access points to transmit signals in the radio access network to the UEs **2013**. Each of the access points performs RF processing of the baseband-processed signals **2014** prior to transmitting the signals to the UEs.

In some aspects of the disclosure, the access point antennas are connected to the central processor via optical fiber. Various types of fronthaul networks may be employed, including optical fiber, wireline (e.g., cable), wireless (e.g., radio), and any combination thereof. In wireless backhaul networks, such as those disclosed in the '163 application, digitized RF signals from various nodes can be aggregated, which allows the building of networks in chain, tree, and ring topologies.

In some aspects, the access point antennas can be considered as radio remote units, and the central processor can be considered as a central hub unit. The baseband signals from multiple access points can be gathered and processed together in the central processor to provide distributed antenna system MIMO benefits, such as spatial multiplexing gain. Similar types of distributed antenna system MIMO processing (e.g., pre-coding) can be performed at the central processor for signals to be transmitted by the access points.

In one aspect of the disclosure, downlink data is transmitted via MRC spatial multiplexing with power control. It should be appreciated that different aspects can effect various types of combining via pre-coding configured with respect to signal propagation measurements in the RAN channel. Pre-coding may comprise MRC, ZF, MMSE, and/or any of a variety of adaptive techniques, including blind adaptive techniques disclosed in the '163 and '107 applications. Coding and power control can comprise open-loop and closed-loop methods. In some aspects, UEs may be selected by the central processor and scheduled for array processing based on quality metrics (e.g., channel conditions, power measurements, SNR, etc.).

In accordance with some aspects of the disclosure, a network topology is depicted in FIG. **21** comprising a source node **2100**, a destination node **2105**, and a plurality of intervening nodes **2102**.1-**2102**.P. The network nodes **2100**, **2105**, and **2102**.1-**2102**.P may comprise UEs and/or base transceiver stations. The network nodes **2102**.1-**2102**.P and any intervening nodes (not shown here, but depicted in the drawings of the '163 application) may be configured to function as routers and/or relays.

In accordance with some aspects of the disclosure, as the network evolves, the nodes adapt their routing tables. As network loads change, the nodes can perform load balancing, such as to ensure a predetermined range of bandwidth and transmit-power loads across the network. One or more paths to the destination node **2105** can be selected or modified to optimize loads across the network, minimize transmission power, and/or ensure received signal quality. In one aspect of the disclosure, multiple transmission paths to the destination node **2105** are employed to achieve one or more objectives, such as reducing the effects of fading, reducing transmission power in some of the relays, and/or distributing transmission power across the network.

Information intended for the destination node **2105** can be passed through the network along one or more intervening nodes **2102**.1-**2102**.P. One or more of the intervening nodes (e.g., nodes **2102**.1-**2102**.P) can provide a final radio link to the destination node **2105**. For the sake of simplicity, FIG. **21** depicts a plurality P of transmission paths **2101**.1-**2101**.P from the source node **2100** to the intervening nodes **2102**.1-**2102**.P. It should be appreciated that each transmission path can comprise multipath components. It should be appreciated that in some aspects, one or more intervening nodes (not shown) may be utilized between the source node **2100** and nodes **2102**.1-**2102**.P.

The source node **2100** comprises an antenna system **2110**, which may include one or more antennas. Similarly, each of the intervening nodes **2102**.1-**2102**.P comprises an antenna system (**2120**.1-**2120**.P, respectively) which may include one or more antennas. When multiple antennas are employed by a node (e.g., nodes **2100**, **2105**, and/or **2102**.1-

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2102.P), the node may perform any combination of diversity processing and spatial multiplexing with respect to its antenna system.

In accordance with one aspect of the invention, the source node **2100** selects a plurality P of the intervening nodes **2102.1-2102**.P to provide cooperative subspace processing, such as to increase the rank of the subspace pre-coding matrix and increase the number of linearly independent coded transmissions. In a first aspect of the disclosure, the transmission paths **2101.1-2101**.P comprise the radio access network. In a second aspect of the disclosure, the transmission paths **2101.1-2101**.P comprise a fronthaul network. In both the first and second aspects, the intervening nodes **2102.1-2102**.P comprise antennas of a Cooperative-MIMO antenna array.

As depicted in FIG. **21**, a plurality P of the intervening nodes **2102.1-2102**.P can be selected to provide a final RF link (e.g., transmission paths **2103.1-2103**.P) to the destination node **2105**. It should be appreciated that each transmission path can comprise multipath components. It should be appreciated that in some aspects, one or more intervening nodes (not shown) may be utilized between the source node **2100** and nodes **2102.1-2102**.P.

In one aspect, the destination node **2105** selects the plurality P of the intervening nodes **2102.1-2102**.P to increase the number of linearly independent coded transmissions it receives, effectively increasing the rank of the matrix that encodes the transmitted data. In one aspect of the disclosure, the transmission paths **2103.1-2103**.P comprise the radio access network, and the antenna system **2115** comprises a spatial multiplexing system configured to perform subspace processing. In another aspect of the disclosure, the transmission paths **2103.1-2103**.P comprise a fronthaul network, and the intervening nodes **2102.1-2102**.P comprise antennas of a Cooperative-MIMO antenna array.

In one aspect, the transmitted signals comprise multiple addresses corresponding to at least one path from the source node **2100** to the destination node **2105**. The transmission may include multiple addresses corresponding to a plurality P of devices (e.g., nodes **2102.1-2102**.P) that provide the final RF link to the destination node **2105**. Alternatively, the transmission may include only the destination address of the destination node **2105**. More than one destination address may be included for a particular transmission. A transmission may be duplicated when paths diverge. For example, a message with addresses to nodes **2102.1-2102**.P can be duplicated by node **2100**. In some aspects, a broadcast message includes a plurality of addresses, and the network is configured to propagate a single version of the message to all of the addresses.

In accordance with one aspect disclosed in the '163 application, a data message is provided that includes a plurality of destination addresses. Processing instructions, such as transmission weight values (e.g., a pre-coding matrix), are included with the data message. A single copy of the message is routed through nodes that form a path that is common to all of the destination addresses. The message is duplicated where the paths to the destination addresses diverge, but different linear coding is applied to the message for each of the paths. As disclosed in the '163 application, each router or relay can provide its own unique linear codes to the messages that pass through it.

The codes may include any combination of polyphase CI codes, CI-based codes, and channel-specific spatial interferometry codes (e.g., linear codes based on the random channel). For example, the channel characteristics for each transmission path (**2101.1-2101**.P and/or **2103.1-2103**.P) can be exploited to provide addressing and/or multiple-access coding. Coding may include space-time coding, space-frequency coding, polarization coding, etc.

Some aspects of the disclosure provide for CI codes that can be implemented across one or more diversity-parameter spaces. Similar to random linear codes, all CI codes of a given set of CI code words can be constructed from a combination of linearly independent code vectors that form the CI code generation matrix. A CI coder is configured to generate a plurality of algebraically unique linear combinations of a plurality of information signals.

FIG. **22**A depicts an aspect of the disclosure wherein at least the source node **2100** transmits a plurality P of transmit messages $t_1, t_2, \ldots, t_P$ on the plurality P of network paths **2101.1**, **2101.2**, . . . , **2101**.P, respectively to the plurality P of intervening nodes (e.g., nodes **2102.1**, **2102.2**, . . . , **2102**.P). In one aspect, each of the transmit messages $t_1, t_2, \ldots, t_P$ comprises a unique linear combination of P information messages (or symbols) $x_1, x_2, \ldots, x_P$. For example, a pth transmit message t_p may employ a vector of coefficients $[\alpha_{p,1}, \alpha_{p,2}, \ldots, \alpha_{p,P}]$ that is a row or column of a code matrix having rank P. In one aspect disclosed in the '163 application, the code matrix (e.g., channel-specific coding) comprises space-time or space frequency codes (e.g., pre-coding), such as derived from channel measurements. The characteristic randomness of the P terrestrial wireless transmission paths (e.g., **2101.1-2101**.P) can provide a code matrix of random values with rank P if the transmission paths **2101.1-2101**.P are sufficiently uncorrelated.

In one aspect, the source node **2100** selects the transmission paths **2101.1-2101**.P to build up the rank of the code matrix. For example, the source node **2100** selects a sufficient number of the intervening nodes **2102.1-2102**.P to ensure that the code matrix has sufficient rank to permit the destination node **2105** to decode the received data. The source node **2100** transmits the codes along with the encoded messages through the network via the intervening nodes **2102.1-2102**.P.

FIG. **22**B depicts an aspect of the disclosure wherein the intervening nodes **2102.1-2102**.P provide a plurality P of received messages $r_1, r_2, \ldots, r_P$ on the plurality P of network paths **2103.1**, **2103.2**, . . . , **2103**.P, respectively to the destination node **2105**. In one aspect, each of the received messages $r_1, r_2, \ldots, r_P$ comprises a unique linear combination of P information messages (or symbols) $x_1, x_2, \ldots, x_P$. For example, a pth received message r_P may comprise a vector of coefficients $[\beta_{p,1}, \beta_{p,2}, \ldots, \beta_{p,P}]$ that is a row or column of a code matrix having rank P. In one aspect disclosed in the '163 application, the code matrix (e.g., channel-specific coding) comprises space-time or space frequency codes (e.g., pre-coding), such as derived from channel measurements. The characteristic randomness terrestrial wireless transmission paths (e.g., paths **2101.1-2101**.P and/or paths **2103.1-2103**.P) can provide a code matrix of random values with rank P if the transmission paths (**2101.1-2101**.P and/or paths **2103.1-2103**.P) are sufficiently uncorrelated.

In one aspect of the disclosure, the destination node **2105** selects the intervening nodes **2102.1-2102**.P to build up the rank of the received coding matrix. For example, the destination node **2105** can select a sufficient number of the intervening nodes **2102.1-2102**.P to ensure that the code matrix has sufficient rank to permit the destination node **2105** to decode the received data.

In some aspects of the disclosure, the intervening nodes **2102.1-2102**.P function as a cooperative-MIMO antenna

array, which enables the destination node **2105** to receive a sufficient number of linearly independent combinations of transmitted signals to permit demultiplexing of the received signals. In one aspect, signals received by each of the intervening nodes **2102**.1-**2102**.P comprises a linear combination of transmitted data signals, and the linear combinations and corresponding code vectors received by the nodes **2102**.1-**2102**.P are communicatively coupled to the destination node **2105** via a fronthaul network comprising the paths **2103**.1-**2103**.P. In another aspect of the disclosure, the destination node **2105** comprises an antenna array (e.g., antenna system **2115**), and the transmission paths **2103**.1-**2103**.P comprise the radio access network. The nodes **2102**.1-**2102**.P transmit the codes along with the encoded messages to the destination node **2105**. In this aspect, the nodes **2102**.1-**2102**.P and/or the transmission paths **2103**.1-**2103**.P can provide additional coding to the signals received at the destination node **2105**. In some aspects, the code matrix may be determined by the destination node **2105** by deriving channel measurements from training (e.g., pilot) signals in the received signals. In other aspects, control signals (such as known training signals) can be encoded such that a receiver, upon correcting for channel distortions, can determine the code(s).

FIG. **23**A is a flow diagram that illustrates aspects of the disclosure pertaining to cooperative subspace multiplexing. In one aspect, a plurality of cooperating nodes is selected to build the dimension of a subspace spanned by coded transmissions **2301**. The plurality of cooperating nodes may comprise a source node. In some aspects, the source node communicates with cooperating transmitter nodes via a fronthaul network.

Linear codes are generated **2302**, for example, from channel estimates of a scattering-rich propagation environment. The natural randomness of terrestrial multipath channels can provide statistically random codes. In some aspects, linear coding is provided to transmissions via pre-coding based on channel measurements. In some aspects, linear coding may be provided to transmissions by multipath in the propagation environment. In such aspects, linear codes corresponding to different transmission channels will be algebraically unique if the channels from which the codes are derived are uncorrelated. This occurs when there is sufficient scattering. Thus, employing multipath scattering for encoding transmissions can be achieved by ensuring that transmitting antennas are sufficiently spatially separated to ensure uncorrelated subspace channels.

In some aspects of the invention, linear codes are generated **2302** and then the cooperating transmit nodes are selected **2301** to at least match the dimension of the set of linear codes (e.g., the rank of a resulting code matrix). In other aspects, the linear codes are generated **2302** to match the dimension of the subspace enabled by a pre-selected set of cooperating transmit nodes.

The cooperating transmit nodes transmit the coded messages and code matrix **2303**. In one aspect, the code vectors are transmitted along with the data payload. In some aspects, the code vectors may be included in control signals. For example, the code matrix may be conveyed by encoding known values, such as training signals. In some aspects, the natural randomness of the channel encodes transmitted messages and training signals. Thus, transmitting the coded messages and code matrix **2303** can comprise transmitting signals from cooperating transmit nodes that are sufficiently spatially separated to provide uncorrelated transmission channels.

FIG. **23**B is a flow diagram that illustrates aspects of the disclosure pertaining to cooperative subspace demultiplexing. In one aspect, a plurality of cooperating nodes is selected to build the dimension of a subspace spanned by received coded messages **2311**. The plurality of cooperating nodes may comprise a destination node.

A matrix of linear codes is determined from the received signals **2312**. For example, cooperating receiver nodes can communicatively couple their received messages to the destination node (or some other node(s) configured to perform MIMO subspace demultiplexing) via a fronthaul network. In some aspects, the code matrix accompanies the received messages in the data payload and/or as separate control information. In some aspects, the code matrix is determined from measurements of known training signals in the received messages.

In one aspect of the disclosure, determining the code matrix **2312** can indicate a required dimension that permits decoding. Thus, selecting cooperating nodes **2311** may be performed following step **2312**, such as to ensure that a sufficient number of linearly independent combinations of the original messages are collected to enable decoding. Once the destination node (or at least one other node configured to perform MIMO subspace demultiplexing) receives a sufficient number of linearly independent combinations, the received messages are decoded **2313**.

FIG. **24**A is a block diagram depicting a transceiver and transceiver method configured to perform routing in accordance with some aspects of the invention. In one aspect, each block comprises a step or set of steps, which can be performed by one or more circuits or machine components, such as a specialized computing device programmed with instructions to perform specific functions. In one aspect, each block comprises a circuit or a portion of a circuit in a transceiver apparatus. In another aspect, each block comprises a set of instructions that programs a specialized computing device to perform one or more steps disclosed herein. In another aspect, each block and/or a plurality of the blocks comprises at least one specialized computing device programmed with instructions to perform specific functions.

Transmitted signals are received by a receiver system **2401** that outputs a baseband signal. In a wireless network, the receiver system **2401** performs RF and, optionally, baseband processes typically performed to convert an RF signal to a baseband or intermediate frequency signal. For example, the receiver system **2401** may perform channel selection, filtering, amplification, frequency conversion, and A/D conversion.

In one aspect, each transmitted signal comprises a coded data payload and a preamble (or header) that comprises the code. The codes may comprise channel-specific coding. A decoder **2402** can be configured to decode the baseband signal relative to one or more codes in the header. A signal processor **2403** may process the decoded signals prior to producing an output data stream. Signal processing may include one or more signal-processing operations, including, but not limited to, quantization, channel decoding, multiple access decoding, demultiplexing, formatting, demodulation, channel estimation, channel compensation, synchronization, filtering, error detection, error correction, signal-quality analysis, multi-user detection, phase-jitter compensation, frequency-offset correction, time-offset correction, etc.

A control system **2404** is configured to select, adapt, or otherwise control the operation of one or more transceiver components. For example, channel estimates and/or signal-quality analysis performed by the signal processor **2403** may be processed in the control system **2404**, such as to adapt

decoding performed by the decoder **2402**. The control system **2404** may provide power control to a transmission system (e.g., transmission system **2406**) and/or otherwise provide network control. Similarly, coding may be adapted by the control system **2404**.

A pre-coder **2405** is configured to process input data bits to produce a coded signal that is coupled to the transmission system **2406**. The transmission system **2406** performs signal-processing operations typically performed to prepare a baseband signal for transmission into a communication channel. In a wireless network, the transmission system **2406** may perform one or more processes, including, but not limited to, D/A conversion, modulation, filtering, amplification, frequency conversion, beam forming, etc.

Signals from the receiver system **2401** can also be coupled through a routing system **2410**. In one aspect, signals from the receiver system **2401** are coupled to a decoder **2412**, which may include a bank of decoders. In one aspect of the disclosure, the decoder **2412** decodes received signals that are to be retransmitted. The decoded signals are processed in a signal processor **2413**, which may perform similar signal-processing operations as signal processor **2403**. Furthermore, the signal processor **2413** may perform pre-processing operations prior to coding in a pre-coder **2415**. The pre-coder **2415** may include a bank of pre-coders. A control system **2414** may be configured to select, adapt, or otherwise control the operation of one or more of the transceiver components **2412**, **2413**, and **2415**.

In one aspect, the control system **2414** and the coder **2415** may provide channel-compensation and/or beam-forming weights to the coded symbols. Such weights may be regarded as part of the routing process (e.g., the pre-coding). In some aspects, since routing decodes some signals that are not intended for the transceiver, the router components **2412**, **2413**, **2414**, and **2415** can be isolated from the rest of the transceiver by a fire wall **2410**.

In one aspect, the set of router components **2412**, **2413**, **2414**, and **2415** receives signals to be routed, decodes the signals **2412**, cleans up the decoded signals **2413**, and re-encodes the cleaned-up signals **2415** for retransmission **2406**. Additional pre-coded signals (e.g., from the pre-coder **2405**) can be combined with the pre-coded signals from the pre-coder **2415** prior to retransmission **2406**. As indicated by the junction that joins the pre-coder **2405** and the pre-coder **2415** prior to the transmitter **2406**, pre-coded signals to be routed may be summed with pre-coded "Data Input," which produces linear combinations of pre-coded signals.

As disclosed in the '850 and '163 applications, in some aspects, the decoder **2412** does not decode some or all of the input coded signals. Rather, the decoder **2412** maps the input coded signals to different code spaces. For example, when basic linear CI codes are employed, the code coefficients resemble Fourier Transform coefficients which are distributed uniformly on the unit circle in the complex plane. One advantage to using basic linear CI codes is that such codes are orthogonal, and some implementation do not require transmitting the decode vector(s) with the coded transmission. Orthogonal codes comprise different integer numbers of "rotations" on the unit circle in the complex plane. For non-zero rotations, a vector sum of the code coefficients produces a zero result. For a zero rotation, all the code values are mapped to the same point on the unit circle, so the code values sum coherently. Decoding **2412** can map an input code having a first number of rotations to an output code having a second number of rotations. If the second number of rotations is zero, then summing the result yields a solution for a code space in the set of linearly independent coded data values whose coefficients are basic linear CI code values. Thus decoding **2412** can solve for one or more unknowns (i.e., information signals) in the set of linear combinations and/or map at least one code space to at least another code space.

In one aspect of the disclosure, communication signals comprise coded sets of low-bandwidth subchannels. Thus, interference resulting from multipath and effective multipath resulting from retransmissions through the network can be reduced to flat fades. Sub-carrier bandwidths may be adapted to the multipath channel in one or more parts of the network. Coding may be adapted with respect to one or more parameters, including geographical distributions of subscriber units and access points, channel conditions, link priority, security, subscriber services, number of subscribers, etc.

In some aspects of the disclosure, each network node has access to the community's transmissions. The system can allow each node to dynamically select for reception only those transmissions that are relevant to that node. Individual transceivers may be equipped with adaptable or programmable decoders designed to select and decode one or more transmissions. The transceivers may be provided with a bank of decoders to decode and process multiple received signals simultaneously.

FIG. **24**B is a block diagram of a transceiver configured to perform routing in accordance with aspects of the invention. It should be appreciated that FIG. **24**B, as well as the other block diagrams of the disclosure, can indicate both apparatus and method implementations. For example, the blocks can indicate circuits, devices, systems, or other physical components of an apparatus or system. In some aspects, the blocks indicate functional components. The grouping of the functional components can take different physical forms. In some aspects, more than one block may be embodied by one particular physical component. In some aspects, a plurality of physical components can be employed as one of the blocks. In some aspects disclosed in the '850 and '163 applications, at least some of the disclosed signal processing operations can be performed by a computer processor and a computer-readable memory comprising processing instructions that instruct the processor to physically change input signals.

In the transceiver depicted in FIG. **24**B, signals from the receiver **2401** are coupled through a routing system **2420** and then retransmitted by the transmitter **2406**. The routing system **2420** can comprise a processor **2419** configured to process received signals to be routed, and then outputting processed signals to the transmitter **2406**. The received signals to be routed may comprise baseband and/or intermediate-frequency (IF) signals. The processor **2419** can be configured to perform one or more baseband or IF processes, including, but not limited to, signal shaping, filtering, re-quantization, error detection, error correction, interference mitigation, multi-user detection, amplification, up sampling, down sampling, frequency conversion, D/A conversion, AGC, symbol remapping, etc.

It should be appreciated that in some aspects, retransmitting (e.g., relaying, routing, and/or repeating) the received signal can effectively increase the rank of the channel matrix H from the perspective of the destination receiver(s), particularly if propagation channel is a scattering-rich environment. The rank of H is the sum of non-zero singular values λ_1 in which each λ_1 corresponds to an eigenmode of the channel (i.e., an eigen-channel, or subspace channel). Each non-zero eigenmode can support a data stream, thus the

MIMO channel can support k spatial sub-space channels, where k is the number of non-zero eigenvalues λ_i.

In accordance with some aspects of the disclosure, base-station responsibilities are assigned to (or assumed by) individual UEs. For example, base-station operations can be coordinated with simultaneous coded transmissions of a traffic channel and a control channel. Codes may include CI codes, CI-based coding, channel-specific coding, or any combination thereof. A time division duplexing method may be employed for transmit and receive operations to implement the necessary control functions for operation without a base station. At least one of the UEs can be assigned to be a network control station. By using time division duplexing for transmit and receive operations, the same frequency band(s) can be used for uplink and downlink, which can simplify channel estimation and MIMO processing.

A UE acting as a network control station can maintain power control and time synchronization normally performed by a base station. For example, power control can be maintained within predetermined time intervals by a feedback control loop using proportional integration and differentiation to smooth control such that power oscillations are maintained within desired limits. The network control functions may automatically be transferred if the connection with the transceiver is terminated or there is a predetermined degree of signal-quality degradation. The network control station can have channel control capabilities to assure transmission security. For example, the network control station may assign codes to other UEs to change the security or priority of individual communication links.

FIG. **25**A is a block diagram illustrating a network configuration that employs channel reuse between a plurality of networks. A signal **2500** having channel allocation C_1 in a first network is received by a transceiver **2510** (with antenna system **2520**). For example, the first network may comprise a WWAN, or "macro-cell." The channel C_1 is reused for communication in a second network (e.g., a micro-cell network) **2550** comprising transceivers **2510-2513**. For example, transmissions **2501-2503** employ the channel allocation C_1. As disclosed in the '163 application, the transmissions **2501-2503** can comprise array-processing pre-coding, which can permit reuse of the channel allocation C_1 by the second network via interference mitigation.

In one aspect of the disclosure, antenna systems **2520**, **2521**, **2522**, and **2523** may comprise multiple antennas, and each transceiver **2510**, **2511**, **2512**, and **2513** may be configured to perform array processing with its own antenna system. In another aspect of the invention, the transceivers **2510**, **2511**, **2512**, and **2513** can be configured to perform cooperative array processing, wherein array processing (such as subspace processing) operations are jointly processed by multiple ones of the transceivers **2510**, **2511**, **2512**, and **2513**. Combinations of local array processing (i.e., array processing on individual transceivers) and cooperative array processing (e.g., Cooperative MIMO) may be performed.

FIG. **25**B is a block diagram illustrating a network configuration that employs cooperative array processing and reuses channel C_1 allocated to a first link **2500**. In one aspect, a plurality of the transceivers (**2511**, **2512**, and **2513**) employs channel C_1 to communicate with transceiver **2520**. For example, the transceivers **2511**, **2512**, and **2513** transmit signals **2504**, **2505**, and **2506**, respectively, to transceiver **2510**. Pre-coding operations on the transmitted signals **2504**, **2505**, and **2506** can provide for beam forming (or equivalent array processing) operations. Various combining operations may be provided to produce any combination of interference rejection, diversity enhancement, and sub-space processing (i.e., capacity enhancement). The afore-mentioned operations can permit a micro-cell network (e.g., network **2550**) to employ the same macro-cell channels (e.g., channel C_1) without interfering with the macro-cell network.

Methods described with respect to FIGS. **25**A and **25**B and the related disclosures in the '163 application, the transceivers **2510**, **2511**, **2512**, and **2513** can be implemented, by way of example and without limitation, with apparatus embodiments depicted in and described with respect to FIGS. **24**A and/or **24**B.

FIG. **26** is a block diagram depicting systems and methods according to some aspects of the disclosure. In one aspect, a cooperative-MIMO network **2660** comprises multiple groups of separate geographically distributed transceivers, wherein at least a first group **2651** employs cooperative subspace processing (e.g., cooperative-MIMO) to communicate with at least a second group **2652**, such as disclosed in the '107 and '163 applications. In one aspect of the disclosure, the first transceiver group **2651** comprising transceivers **2610-2613** is configured to communicate subspace signals **2601-2603** employing a common channel C_1 to the second transceiver group **2652**, which comprises transceivers **2614-2616**. Since the transceivers **2610-2616** can be configured to operate in multiple networks (e.g., macro-cell and micro-cell networks), in one aspect, network **2660** can be a micro-cell network configured to reuse channel C_1, which is used for communication in the macro-cell.

The subspace signals **2601-2603** comprise a plurality of spatial subchannels that occupy a common frequency spectrum, time interval, and code space denoted by the common channel C_1, wherein subspace processing provides for non-interfering parallel subchannels. As disclosed herein, subspace processing can comprise any combination of transmitter-side and receiver side subspace processing. For example, subspace processing can comprise pre-coding (i.e., spatial multiplexing). In some aspects, subspace processing comprises subspace decoding (i.e., spatial demultiplexing).

The transceivers **2610-2616** each comprises an antenna system (e.g., antenna systems **2620-2626**, respectively), that includes one or more antennas. Thus, in some aspects, more than one antenna per transceiver can be available for cooperative-MIMO processing. In some aspects, one or more of the transceivers **2610-2616** can perform local antenna array processing (e.g., diversity combining and/or spatial multiplexing) in addition to participating in cooperative-subspace processing. As used herein, "spatial multiplexing" can denote the general practice of subspace processing, which can comprise pre-coding (also referred to as subspace coding or spatial multiplexing) and/or decoding (also referred to as subspace decoding or spatial demultiplexing). In some cases, "spatial multiplexing" specifically denotes subspace processing on the transmitter side of a communication link (which is distinguished from spatial demultiplexing performed on the receiver side of the link), and, thus, comprises subspace coding (also referred to as pre-coding). The intended scope of the terminology used in the disclosure is indicated by the context in which it is used.

With reference to FIGS. **25**A, **25**B, and **26**, and related disclosures in the '163 application, FIG. **27** is a flow diagram that depicts methods according to some aspects of the invention. In one aspect, a client transceiver (i.e., a client node) receives a channel allocation (e.g., channel C_1) for communicating in a first communication link **2701**. For example, the client transceiver may receive a signal in channel C_1. Alternatively, the client transceiver may be allocated channel C_1 for transmitting signals. The channel

allocation C_1 typically comprises a specified frequency band, time interval, and code space. When no multiple access codes are employed, the code space is simply a vector of ones (e.g., [1, 1, 1, . . . , 1]). By way of example, the channel C_1 may be allocated for communication between the client transceiver and at least one other transceiver in the first network, the channel C_1 being allocated so as not to interfere with other communication links in the first network.

A "client transceiver," as used herein, indicates a transceiver that is served by a first network via the first communication link. In some aspects of the disclosure, the client transceiver may perform additional network functions, and as such, may function as any of various network devices, such as a router, a relay, a repeater, or a gateway.

A transceiver group comprising multiple transceivers, including the client transceiver, is selected to communicate in a second communication link **2702**. In one aspect, selecting **2702** comprises provisioning a plurality of the transceivers to cooperatively transmit signals in the second link. In another aspect, selecting **2702** comprises provisioning a plurality of the transceivers to cooperatively receive signals in the second link. Pluralities of both transmitting and receiving transceivers may be selected, such as depicted in FIG. **26**.

In some aspects, the client transceiver functions as a router or relay, such as to forward communications it receives via the first link to a destination node or another intermediate node via at least a second link. The client may select **2702** the transceivers to which it forwards communications. In one aspect, communications forwarded by the client transceiver to a plurality of cooperating transceivers constitute the second link. In another aspect, transmissions from cooperating transceivers (which may or may not include the client transceiver) comprise the second link. In one aspect, the first link is part of a first network and the second link is part of a second network.

The channel C_1 is reused for communicating in the second link **2703**. Specifically, the second link simultaneously employs the same frequency band and code space as in the first link. Thus, some aspects of the invention are configured to mitigate co-channel interference between signals in the first and second links. Some aspects employ cooperative subspace processing **2704** between at least two transceivers communicating in the second link to mitigate interference between signals in the first and second links. For example, spatial multiplexing (i.e., pre-coding) performed by a plurality of cooperating transmitters can cancel transmissions in the second link that would otherwise interfere with the reception of transmissions in the first link. Spatial demultiplexing (i.e., subspace decoding) performed by cooperating transmitters can separate interfering first-link and second-link signals, such as to permit reception of either or both first-link and second-link signals by transceivers operating in the second link.

By way of example, if the first link channel C_1 is a downlink channel, then cooperative subspace multiplexing and/or demultiplexing can separate received second-link signals from received first-link signals within the transceiver group. By way of example, if the first-link channel C_1 is an uplink channel, then cooperative subspace multiplexing (e.g., pre-coding) can cancel co-channel interference due to second-link signals received by receivers communicating in the first link. Also, cooperative subspace multiplexing and/or demultiplexing can separate received second-link signals from received first-link signals within the transceiver group.

As will be appreciated to those skilled in the art, disclosures of the '850 and '163 applications can be employed in various types of communication networks, including LTE networks, which comprise a flat network architecture as opposed to hierarchical architectures of other cellular standards.

Thus, in accordance with some aspects of the disclosure, the UEs disclosed herein comprise LTE UEs. By way of example, a UE may comprise an RF transceiver for fixed and/or mobile clients receiving data streams over a downlink channel(s) in the radio access network and transmitting data via the uplink channel(s) in the radio access network.

A base transceiver station may comprise an eNodeB, which may handle radio resource management, user mobility, and scheduling. The base transceiver stations interface the fronthaul network with the radio access network. A base transceiver station of one aspect of the disclosure is an access point comprising an RF front-end configured to convert baseband signals to RF and RF signals to baseband. The base transceiver station may comprise a Digital-to-Analog Converter (DAC)/Analog-to-Digital Converter (ADC). In some aspects, the base transceiver station is a simple RF transceiver equipped with power amplifier/antenna(s), and RF signals are communicatively coupled between the base transceiver station and the central processor via the fronthaul network, which can include RF-over-fiber technology, such as described in related patents and applications that are incorporated by reference.

A controller employed in an LTE network may comprise a base transceiver station configured to perform certain specialized functions, such as transmitting training signals, receiving/transmitting control information from/to the UEs, receiving channel state information (CSI) or channel quality information from the UEs, etc. Coordinated multipoint systems disclosed herein may comprise multiple controllers. In an LTE network, the controller may comprise a mobility management entity.

A fronthaul network configured in an LTE system may comprise a combination of S1 and X2 interfaces. By way of example, but without limitation, the fronthaul may comprise S1-MME links between the mobility management entity and eNodeBs, S11-U links between the serving gateway and eNodeBs, and X2 links between multiple eNodeBs. In some aspects, the fronthaul network comprises the S1 interface. In other aspects, the fronthaul network comprises the X2 interface.

The LTE network typically comprises a gateway, which comprises a serving gateway (S-GW) that terminates the E-UTRAN interface, and a PDN gateway (P-GW), which interfaces with external networks. In accordance with aspects of the disclosure, the central processor can be implemented by the gateway, such as the S-GW component. In other aspects, one or more of the eNodeBs can be configured to operate as the central processor.

While aspects of the disclosure describe Cooperative-MIMO processing in which high channel selectivity (wherein selectivity refers to statistical variations of spatial gains of propagating signals) is achieved via rich multipath environments and/or geographically distributed transmitters (and/or receivers), alternative aspects may employ other diversity parameters (such as signal polarization) and/or various techniques (e.g., coherence multiplexing, frequency diversity interferometry, etc.), such as described in Applicant's patents and other applications, to achieve channel selectivity. By way of example, in U.S. Pat. No. 6,331,837, which is hereby incorporated by reference in its entirety, Applicant discloses that different antenna beam patterns can

provide for different spatial gains, thereby providing the selectivity necessary to achieve spatial multiplexing and/or de-multiplexing. Specifically, subspace processing can be achieved in the beamspace domain of a transmitting and/or receiving array, thus transferring the MIMO operation from the antenna elements to the beamspace. Data streams are mapped onto specific transmitted beam patterns, and beamspace multiplexed data streams are sent simultaneously. Similarly, specific radiation patterns are used to receive transmissions. Since beamspace multiplexing exploits aerial degrees of freedom, such techniques can be advantageous for arrays with closely spaced elements. In some aspects of the disclosure, one or more antenna elements in an array are parasitic elements.

One aspect of the '837 patent discloses outputs from multiple beamforming processes being input to a spatial de-multiplexing process. In the case wherein the number of active receiving antennas is less than the number of transmitting antennas, if the beamforming processes produce a number of linearly independent combinations of received transmissions at least equal to the number of transmit sources, then there is sufficient rank in the resulting channel matrix to separate the received signals. In one sense, the beamforming process can be implemented as a multiple-access coding process that maps M logical channels onto N physical subspace channels, where M>N. Although the total theoretical capacity of the channel (such as expressed by the corresponding Shannon-Hartley theorem for the corresponding MIMO implementation employed) does not increase, the capacity is partitioned across more subchannels. In one aspect, the M subchannels each have a lower SNR (and thus smaller capacity) than the corresponding N subchannels. This could be a result of more correlation between the elements of the channel matrix as its dimension increases. The reciprocal of any such process can be applied to spatial multiplexing. Various techniques, including coherence multiplexing, polarization subspace multiplexing, and frequency diversity interferometry are described, and these and the other disclosed techniques can be employed within the spatial multiplexing and de-multiplexing methods and systems disclosed herein.

The following references, which are part of the disclosure of the '850 application, are incorporated by reference in their entireties: U.S. patent application Ser. Nos. 09/718,851; 60/219,482; 60/194,633; 09/703,202 (now U.S. Pat. No. 7,076,168); Ser. No. 09/381,588 (now U.S. Pat. No. 7,010,048); Ser. No. 09/393,431 (now U.S. Pat. No. 6,888,887); Ser. Nos. 09/347,182; 09/324,206 (now U.S. Pat. No. 6,331,837);

B. Natarajan, C. R. Nassar and S. Shattil, "Exploiting Frequency Diversity in TDMA through Carrier Interferometry," Proceedings of Wireless 2000, 12th International Conference on Wireless Communications, Jul. 10-12, 2000, pp. 469-476;

B.Nataraj an, C. R. Nassar and S. Shattil, "Throughput Enhancement in TDMA through Carrier Interference Pulse Shaping," IEEE Vehicular technology Conference Proceedings, vol. 4, pp. 1799-1803, Fall 2000, Boston;

C. R. Nassar, B. Natarajan and S. Shattil, "Introduction of Carrier Interference to Spread Spectrum Multiple Access, "Proceedings of the IEEE Emerging Technologies Symposium on Wireless Communications and Systems, Dallas, Apr. 12-13, 1999;

S. Shattil, C. R. Nassar, "Array control systems for multicarrier protocols using a frequency-shifted feedback cavity," Radio and Wireless Conference, 1999. RAWCON 99. 1999 IEEE 1-4 August 1999 pp. 215-218;

Z. Wu and C. R. Nassar, "MMSE frequency combining for CI/DS-CDMA," IEEE Radio and Wireless Conference, Denver, Colo., Sep. 10-13, 2000, pp. 103-106;

S. A. Zekavat, C. R. Nassar and S. Shattil, "Smart antenna spatial sweeping for combined directionality and transmit diversity," *Journal of Communications and Networks* (*JCN*), *Special Issue on Adaptive Antennas for Wireless Communications*, vol. 2, no. 4, December 2000, pp. 325-330.

Some aspects of the disclosure can employ CI coding for spread-OFDM, spreading across subspaces, and/or other applications, such as described throughout the patents, applications, and non-patent literature cited herein, each of which is incorporated by reference in its entirety. In the following description, some of the variables used in the previous description are reused. However, the definition of each of those variables is intended to be interpreted with respect to the context in which they are currently defined, which takes precedence over any previous definition for the purpose of the following discussion only.

In OFDM, the transmission bandwidth is partitioned into a plurality N (which typically equals **2** raised to some integer power) of orthogonal subcarrier frequencies. Multicarrier spread-spectrum employs spreading across the subcarriers to produce a transmit signal expressed by $x=F^{-1}Sb$, where F^{-1} is an inverse discrete Fourier transform (IDFT), S is a spread-OFDM code matrix, and b is the transmitted symbol vector. The inverse DFT typically employs an over-sampling factor. In such instances, inverse DFT's dimension is M×N (where M>N is the number of time-domain samples per OFDM symbol block), whereas the dimension of the spread-OFDM code matrix is N×N.

At the receiver, the received spread-OFDM signal is expressed by $r=HF^{-1}Sb$, where H is a channel matrix for the transmission channel. A cyclic prefix in OFDM changes the Toeplitz-like channel matrix into a circulant matrix. The circulant channel matrix H is expressed by

$$H=F^{-1}\Lambda_H F,$$

wherein Λ_H is a diagonal matrix whose diagonal elements can correspond to the first column of the circulant channel matrix H.

Thus, neglecting noise for simplicity, the received signal is represented by

$$r=F'^{121}\Lambda_H FF^{-1}Sb,$$

which is

$$r=F^{-1}\Lambda_{HS}b.$$

The OFDM receiver processes r with a DFT to produce

$$y=\Lambda_H Sb.$$

In one aspect, in order to facilitate the estimation of b, it can be advantageous to employ a spreading code matrix S that commutes with Λ_H. For example, the matrix $S=\Lambda_C F$ may be employed, wherein Λ_C is the diagonal matrix of the circulant matrix C, which is defined by $C=F^{-1}\Lambda_C F$.

In this case, the received signal, r, is expressed as

$$r=F^{-1}\Lambda_H FF^{-1}(\Lambda_C F)b,$$

which can be written as

$$r = F^{-1}\Lambda_H\Lambda_C Fb$$
$$= F^{-1}\Lambda_C\Lambda_H Fb.$$

In the case of basic CI spreading, the spreading matrix $S=\Lambda_C F$ can be implemented with $\Lambda_C=I$, such that the spreading matrix S is just an N×N DFT matrix (e.g., an N×N matrix comprising DFT coefficients wherein N is an integer greater than two). While the use of fast Fourier transform techniques for DFT processing are well known, in the examples disclosed herein, a DFT matrix used for CI spreading (and a corresponding IDFT employed for CI de-spreading) can have matrix dimension N>2, but need not be constrained to powers of two.

In one aspect, the OFDM receiver performs DFT processing on the received signal, r, followed by equalization (e.g., Λ_H^{-1}, although other types of equalization can be performed, such as to compensate for noise and interference), and then CI despreading (e.g., F^{-1}) is performed. In some aspects, equalization and despreading can be performed as a combined and/or iterative process. Equalization (or equalization and despreading) can include multi-user detection techniques, such as successive interference cancellation, as well as other techniques.

In some aspects, the data symbols b can comprise symbols of a reference signal. Reference signals can comprise known training symbols, which can be used for channel estimation and/or channel quality determination. By way of example, demodulation reference signals transmitted in the uplink channel can be used for channel estimation, which can be part of a coherent demodulation process, such as may be performed at a base transceiver station and/or central processor. The channel estimates may be used to provide for spatial demultiplexing of signal transmissions from multiple UE antennas and/or multiple UEs. The channel estimates can be used to derive precoding weights (such as spatial precoding weights) for precoding transmissions in the downlink. In some aspects, sounding reference signals are used to determine channel quality, which may be employed to provide frequency-dependent scheduling on the uplink. In some aspects, the reference signals are time-multiplexed with user-data signals. In some aspects, the reference signals are frequency-multiplexed with user-data signals. In some aspects, the reference signals are code-division multiplexed with user-data signals.

By way of example, CI spreading (such as DFT spreading) can be performed to spread demodulation reference signals on LTE uplink channels, such as demodulation reference signals associated with transmissions of uplink data on the Physical Uplink Shared CHannel (PUSCH) and/or control signaling on the Physical Uplink Control CHannel (PUCCH). Similarly, CI spreading can be used to spread LTE's Sounding Reference Signal (SRS), which is used for channel quality determination to enable frequency-selective scheduling on the uplink. For example, the SRS may be transmitted on the last CI superposition pulse (i.e., SC-OFDMA symbol) in a sub frame. UEs transmitting their SRS in the same sub frame can be multiplexed via frequency or code division multiplexing.

If training signals (such as signals comprising known symbols) are employed, channel estimates can be derived from the received signal r, such as to provide channel state information used for precoding and/or decoding. In some aspects, the CI spreading matrix can comprise channel precoding. For example, the spreading matrix can be $S=\Lambda_H^{-1}F$, where A_H^{-1} is an estimated inverse channel matrix. The precoding can take various alternative forms and can employ any of the precoding techniques that are known in the art. For example, precoding can be configured to minimize bit error rates and/or improve any other link performance metric, such as may be measured by the receiver and/or determined by the transmitter. In accordance with aspects of the disclosure, precoding can comprise subspace MIMO precoding.

Since OFDM's over-sampled DFT is KxN, the basic CI spreading matrix S can resemble a sinc pulse-shaping filter, except that it maps each data symbol to a cyclically shifted (and orthogonally positioned) superposition of OFDM subcarriers in an OFDM symbol interval T_s. In some aspects, the CI spreading comprises pulse shaping, such as to produce raised-cosine, Gaussian, or other shaped pulses. For example, CI spreading can comprise a windowing function. Frequency-domain windowing can shape the frequency-domain signal such as to provide a predetermined time-domain pulse shape, as well as other time-domain features. Alternatively, other forms of pulse shaping can be performed.

In some aspects, CI spreading comprises a block transform wherein each superposition pulse is a cyclic shift of a pulse waveform within a fixed time interval, such as OFDM symbol interval T_s. In other aspects, CI spreading is implemented via a sliding window transform. While the pulse waveform is constrained within a given time interval, the time intervals of successive pulse waveforms can be shifted (e.g., incrementally shifted) in time, and the time intervals can overlap.

Since each CI-spread symbol comprises a linear combination of the data vector's b values, if a spread symbol is lost during transmission, that loss is mitigated due to the spreading. Thus, CI spreading can permit accurate estimation of a received signal despite substantial losses (such as due to flat fading, interference, etc.), even before error-correction processing is performed by the receiver. CI spreading can permit a receiver to accurately decode a transmission without requiring all of the spread symbols. For example, a receiver may accurately estimate N data values b by employing fewer than N spread symbols.

Since the CI-spread symbols employ predetermined linear relationships between the data symbols of b, techniques typically employed in multi-user detection (such as, but not limited to, successive interference cancellation and mixed-decision symbol estimation) can be used to enhance performance at the receiver. Thus, in some aspects of the invention, orthogonality of the spreading codes is not required if the spreading coefficients are known at the receiver. Rather, the code spaces processed by the receiver may simply need to be sufficiently de-correlated from each other to estimate the data symbols b. In this respect, despreading can be considered to comprise equalization. In other aspects, spatial precoding based on channel state information can be regarded as part of CI spreading, wherein the transmission channel effectively orthogonalizes the CI-spread transmissions received by the receiver(s). Thus, precoding is sometimes referred to as pre-equalization. In some aspects of the invention, the above-mentioned spreading matrix S comprises an invertible transform, which produce a sequence of coded data symbols x from an input data vector b: x=Sb. The inverse of the transform is then performed at the receiver to decode the received signals.

FIG. **28**A illustrates a method for providing CI-coded transmissions of information and control signals. In some aspects of the disclosure, such methods are performed by a UE. By way of example, a UE can comprise a processor and a memory coupled to the processor, the memory including a set of instructions stored therein and executable by the processor to perform the method depicted in FIG. **28**A. In some aspects, the UE can comprise circuits configured to perform one or more steps of the methods disclosed herein.

By way of example, a CI code generation process **2801** provides CI codes and/or CI-based codes for spreading at least one information signal and at least one control signal. A control signal can include one or more control-function signals, such as, but not limited to, power control signals, synchronization signals, code assignment signals, priority assignment signals, link assignment signals, channel assignment signals, duplexing control signals, training signals, signals indicating notice of transfer of control responsibilities, and request acknowledgement signals. Coding processes **2802** and **2803** can encode the information signal(s) and control signal(s), respectively. A transmission process **2804** provides for transmission of the coded signals, such as via any of the transmission protocols disclosed in the '163 application, the '850 application, and the other references mentioned in their disclosures.

In some aspects, one or more of the processes disclosed herein, such as processes **2801-2804**, can comprise a processor, a circuit, an apparatus component, and/or a functional block of a transmitter apparatus. In some aspects, a processor, circuit, and/or apparatus component can be configured to perform a plurality of the processes **2801-2804**. In some aspects, one or more of the processes **2801-2804** comprises a step in a method.

FIG. **28**B is a flow diagram depicting a method for managing network control in a CI network by one or more subscriber units according to some aspects of the disclosure. A CI transceiver can be configured to transmit CI-coded information and control signals **2810**. In a network identification and communication restriction step **2811**, CI spreading codes can be used, at least in part, to spread the communication and control channels. CI codes can be allocated to restrict communications between transceivers permitted to operate in the network, such as by providing for scheduling RAN resources in accordance with any of the multiple access protocols disclosed herein. CI codes can also be used to identify a radio network and each of the radio devices, as well as the type of communications being transmitted.

Duplexing **2812** provides for management of transmission and reception. Various types of duplexing can be employed, such as time-division duplexing, frequency-division duplexing, code-division duplexing, polarization-division duplexing, etc. A CI transceiver may include a plurality of CI decoders in parallel to enable simultaneous reception of more than one signal. Similarly, transmission of coded signals can be performed simultaneously with reception when the transmitted CI codes differ from the code of the received signal. Furthermore, different CI codes can be used to encode transmissions to differentiate types of transmitted signals. The use of CI spreading for multiplexing and multiple access are disclosed throughout the papers, patent applications, and patents incorporated by reference herein.

A network-control step **2813** can indicate that at least one of the subscriber units performs as a network control station. A network control station can initiate communications and maintain power control and time synchronization of the network. This can be an important function in a Cooperative-MIMO system, such as wherein a plurality of subscriber units cooperatively process RAN signals for uplink and/or downlink operations. Some aspects provide for transfer **2814** of network control from at least one subscriber to at least one other subscriber. The network control station can voluntarily transfer, or be commanded to transfer, power control and time synchronization of the network to any other radio in the network.

FIG. **28**C illustrates a network-control method that can be implemented in accordance with certain aspects of the disclosure. A CI coding step **2821** provides different CI codes (such as may be used to spread a signal) to information and control signals. In some aspects, a network control station can provide time-division duplexing **2822** to regulate transmission and reception. A network-control step **2823** can provide for network control by the network control station. Network control **2823** can include various operations, including, but not limited to, synchronization, power control, code assignment, channel assignments (i.e., scheduling), channel coding, transmission-path selection, load balancing, and spectrum management.

FIG. **28**D is a flow diagram that depicts a routing method in accordance with certain aspects of the disclosure. Coding **2831** can comprise providing a multi-address, CI-coded signal for transmission **2832**. The addresses may be provided via any combination of precoding and header addressing. Transmitted signals may be routed via one or more paths through a network. Duplication **2833** can be provided when transmission paths through a node diverge. Duplicated signals are transmitted along their respective paths.

FIG. **29**A is a flow diagram that depicts a CI signal generation method in accordance with some aspects of the disclosure. In some aspects, a UE can be configured to perform methods disclosed herein, such as the method in FIG. **29**A. By way of example, a UE can comprise a processor and a memory coupled to the processor, the memory including a set of instructions stored therein and executable by the processor to perform the method depicted in FIG. **29**A.

In one aspect, a DFT-spreader spreads a plurality of reference-signal symbols with Fourier coefficients to generate a DFT-spread reference signal **2901**. A symbol-to-subcarrier mapper maps DFT-spread symbols of the DFT-spread reference signal to a plurality of OFDM subcarriers **2902**. For example, mapping **2902** can be performed according to an OFDMA scheme, some other multiple-access scheme, and/or any other multiplexing scheme, such as disclosed herein. An OFDM modulator (such as an IFFT) modulates the DFT-spread reference symbols onto the plurality of OFDM subcarriers **2903** (according to their mapping **2902**) to produce a baseband OFDM transmission signal. In some aspects, the baseband OFDM transmission signal is processed **2904** prior to RF processing (not shown). For example, baseband processing **2904** may comprise appending a cyclic prefix, pulse shaping, digital-to-analog conversion, filtering, and/or other baseband processing.

In accordance with aspects disclosed herein, methods and functionality, such as depicted in the figures and described throughout the specification, can be implemented via one or more circuits, by a system of devices, by a digital processor programmed with instructions to perform the associated method(s) or function(s), and/or by any other apparatus. In accordance with some aspects of the disclosure, the aforementioned methods and/or functions are performed by a UE. In some aspects, at least one non-transitory computer-readable medium may comprise machine-readable instructions configured to program a general-purpose processor to perform one or more of the methods and functionalities disclosed herein.

In accordance with some aspects of the disclosure, the DFT spreader comprises an N-point DFT, and the OFDM modulator comprises an M-point inverse Fast Fourier Transform. In one aspect, the value of M is greater than N. The '163 application discloses that an N-point transform, such as a DFT, can be used to spread the information symbols to

produce coded symbols that are complex-weighted sums of the information symbols. Other transforms are also disclosed. CI can comprise a wide variety of complex spreading codes that are orthogonal (and/or nearly orthogonal), the variety employing DFT coefficients being among the simplest.

While in some aspects, the OFDM subcarriers are contiguous and within a single band, in other aspects, the OFDM subcarriers can comprise non-contiguous subcarriers. The non-contiguous subcarriers may be incrementally (i.e., equally) spaced and/or non-incrementally (i.e., unequally) spaced. Thus, the subcarriers can be distributed over noncontiguous bands. Different users may be assigned to different sets of subcarriers to provide for OFDMA. For example, the '163 application discloses that the OFDM subcarriers can be selected as a block of contiguous subcarriers, or the OFDM subcarriers can be non-contiguous. Interleaved spreading can comprise selecting non-contiguous OFDM subcarriers that are incrementally (i.e., equally) spaced throughout a given band. In some aspects, spreading can comprise selecting non-incremental (i.e., unequally) spaced OFDM subcarriers. In interleaved spreading, the IFFT can comprise a mapping function to provide the respective CI-OFDM symbols to their corresponding non-contiguous frequency bins of an IFFT.

In CI-OFDM, each information symbol can be spread over a set of subcarriers by using orthogonal CI spreading codes. In one aspect, the spreading code S(k) for a kth OFDM symbol is expressed as:

$$S(k)=\{e^{i0\cdot 2\pi k/N},\ e^{i1\cdot 2\pi k/N},\ \ldots,\ e^{i(N-1)\cdot 2\pi k/N}\},\quad k=0,\ 1,\ \ldots,\ N-1$$

where N is the spreading-code length (e.g., the number of subcarriers over which the information symbol is spread). In one aspect, a block of up to N information symbols can be spread into a block of N spread-OFDM symbols **2901**.

In one aspect, a jth OFDM symbol x(j) that is input to the IFFT in an OFDM transmitter can be expressed as:

$$x(j)=\Sigma_{k=0}^{N-1}b(k)\cdot e^{i2\pi jk/N}\ j,k=0,\ 1,\ \ldots,\ N-1.$$

where b(k) denotes the kth information symbol.

Blocks of CI-coded information symbols can be serial-to-parallel converted and input into an IFFT operation. The output of the IFFT is parallel-to-serial converted to produce a CI-OFDM signal having N frequency components. For a subcarrier separation $f_s=1/T_S$, where T_S is the OFDM symbol duration, the baseband CI-OFDM signal x(t) is:

$$x(t)=\sum_{k=0}^{N-1}\sum_{j=0}^{N-1}b(k)\cdot e^{i2\pi f_s t}\cdot e^{i2\pi kj/N}$$

For $N=2^m$ (i.e., m is an integer, so N is a power of 2), the spreading can be performed using an FFT, and de-spreading can comprise an IFFT.

At a receiver, time-domain samples of a received OFDM signal are serial-to-parallel converted and operated upon with an FFT before being de-spread by a corresponding CI despreading operation (such as an IFFT). The '163 application discloses some aspects in which equalization is performed by the receiver before de-spreading, and some aspects in which pre-coding performed at the transmitter provides for pre-equalization.

The '163 application discloses that reference signals (e.g., control signals, such as training signals, synchronization signals, etc.) are spread via CI spreading. This is different than in other spread-OFDM systems (such as MC-CDMA), which do not spread reference signals. In MC-CDMA, the receiver must perform channel equalization (and thus channel estimation) prior to despreading. Thus, in the case of pilot-based channel estimation, the transmitted pilots cannot benefit from the spreading sequence orthogonality properties and must be transmitted at different times or frequencies in order for a receiver to estimate the channel coefficients.

In some aspects of the disclosure, CI spreading of the reference signals can provide certain advantages, such as producing a signal with low PAPR, providing a superposition signal that facilitates synchronization, facilitating time-domain channel measurements, producing a signal that can facilitates both time-domain and frequency-domain channel measurements, as well as other advantages. For example, in one aspect, CI spreading can produce a superposition signal having predetermined amplitude characteristics in the time domain which facilitates time-domain channel analysis (and subsequent equalization) when advantageous. Since the superposition signal comprises OFDM as its basis, frequency-domain channel analysis (and subsequent equalization) can be performed when advantageous. Time-domain equalization typically has poorer performance than frequency-domain equalization, but frequency-domain equalization can be more computationally complex and consume more power. In one aspect, computational processing and power consumption can be reduced with little or no performance sacrifice in a poor scattering environment, such as may be characterized by a small delay spread, whereas frequency-domain equalization may be performed when the delay spread is above a predetermined threshold.

The '163 application discloses that in some aspects, CI spreading **2901** can comprise precoding, such as MIMO subspace precoding. The '163 application also discloses that selection (i.e., scheduling) of OFDM subcarriers (e.g., mapping **2902**) can be based on some quality metric associated with the channel quality of each subcarrier.

The method depicted in FIG. **29**A can be referred to as CI signal synthesis. FIG. **29**B is a flow diagram that depicts a CI signal analysis method in accordance with some aspects of the disclosure. After RF processing (not shown), a baseband signal derived from a received transmission can be processed **2911**, which can include analog-to-digital conversion (ADC), removal of any cyclic prefix (or guard interval), filtering (such as pulse-shape matched filtering), and/or other baseband signal processing. The resulting digital baseband signal is demodulated **2912** via a process (such as an IFFT) that provides time-domain to frequency-domain conversion of the baseband OFDM signal to provide data symbols that are received on each subcarrier. The data symbols can include DFT-spread reference symbols. Demapping **2913** can be performed to select a particular set (or sets) of the data symbols with respect to an OFDMA scheme and/or some other multiple access and/or multiplexing scheme, such as disclosed herein.

FIG. **30**A is a block diagram of a transmitter according to an aspect of the disclosure. Reference signals and, optionally, user data signals are processed by a CI coder **3021**, such as an N-point DFT, which provides DFT spreading to the reference signals. In some aspects, the N-point DFT **3021** can spread both the reference symbols and the user data symbols. The coding performed by the CI coder **3021** can be referred to as linear precoded OFDMA.

In one aspect, a UE comprises the transmitter shown in the diagram. In another aspect, a base transceiver terminal comprises the transmitter. In other aspects, such as described throughout the '163 application, any type of network node

(such as a node in a network mesh) can comprise the transmitter. By way of example, each node can represent an interconnect router and may comprise a computer processor. The node can comprise a network controller, which can be configured to perform network control functions. In some aspects, the network controller can be distributed among the nodes of the mesh network.

As disclosed in the '163 application, TDD can be performed. For example, TDD enables channel reciprocity which can permit uplink reference signals, such as training signals (e.g., pilot tones) to be used to estimate the downlink channel. The '163 application also discloses that frequency-division duplexing (FDD) can be employed. In one aspect, the UE measures its downlink channel and then provides feedback of the channel measurements on the uplink. In other aspects of FDD, a base transceiver station may calculate downlink channel state information from uplink training signals. The '163 application discloses other types of duplexing that can be employed, including code division duplexing, cancellation division duplexing, polarization division duplexing, and spatial division duplexing.

Various techniques for multiplexing are disclosed in the '163 application. For example, in orthogonal frequency division multiplexing, different subcarrier sets can be assigned to different devices. The assignment of a device's subcarriers can be performed by a mapping module **3022**. For example, a subcarrier interleaver **3022** can assign non-contiguous equally spaced subcarriers across a given frequency range to a UE as part of a scheduling process in OFDMA. In some aspects, the DFT spreader's **3021** outputs are mapped **3022** to a contiguous block of subcarriers. In such aspects, since a subset of the total number of subcarriers is assigned to each device, an M-point IFFT **3023** performs the OFDM modulation wherein M>N. The '163 application also discloses time-division multiplexing, code-division multiplexing, and space-division multiplexing.

In one aspect, a set of reference symbols can be transmitted across all the assigned subcarriers of a set. Multiple devices can be assigned to the same subcarrier set. Thus, in one aspect, each of multiple devices assigned to the same subcarriers can transmit its reference symbols in a different time slot. In some aspects, each device can be assigned different DFT spreading codes. In some aspects, DFT spreading codes can be employed to separate reference signals from user data signals. By way of example, U.S. patent application Ser. No. 09/324,206 (now, U.S. Pat. No. 6,331,837), which is incorporated by reference in its entirety, discloses encoding a reference signal using CI spreading. In some aspects of the disclosure, the DFT spreader **3021** can implement spatial precoding. In some aspects, the reference symbols can be interleaved between user data symbols.

OFDM modulation **3023** can comprise providing for pulse shaping. Pulse-shape selection can be based on various parameters, including spectral characteristics, time-domain signal features, feasibility of synchronization, interference and noise immunity, and implementation costs and complexities. Various pulse shapes can be provided by appropriately weighting the subcarriers, such as via a windowing function. Roll-off factors can be controlled by selecting and/or adjusting subcarrier weights. Various filtering techniques may be used to generate subcarrier superposition signals having predetermined time-domain characteristics. In one aspect, cyclic prefix insertion **3024** can include pulse shape filtering (not shown). The resulting digital baseband signal is processed by a radio front-end transmitter **3025**, which can provide for various radio front-end processing operations, such as digital-to-analog conversion, frequency up-conversion, amplification, filtering, and coupling into the radio channel.

FIG. **30**B is a block diagram of a CI-OFDM receiver configured in accordance with some aspects of the disclosure. The CI-OFDM receiver provides for a signal processing path that includes an RF radio and analog-to-digital converter **3026**, a cyclic prefix remover **3027**, an M-point FFT (time-domain to frequency-domain converter) **3028**, a subcarrier de-mapper/equalizer (de-interleaver) **3029**, and an N-point IDFT (De-spreader) **3030**.

The CI-OFDM receiver receives transmitted signals comprising DFT-spread reference symbols (and optionally, user data symbols) via at least one receive antenna (not shown), down-converts the received signals and converts them from analog to digital with the RF/ADC **3026**, and removes the cyclic prefix via the cyclic prefix remover **3027**. The FFT **3028** performs an M-point DFT once the CP has been removed, and the frequency-domain components produced therefrom are de-mapped (and in some cases equalized) by the subcarrier de-mapper **3029**. An N-point IDFT **3030** de-spreads the de-mapped frequency-domain components to produce a complex time-domain signal, which is processed by subsequent baseband processing (not shown).

In some cases, the cyclic prefix is a copy of the last part of the block, which provides a guard time between successive blocks and converts a discrete time linear convolution into a discrete time circular convolution. Thus, transmitted data propagating through the channel can be modeled as a circular convolution between the channel impulse response and the transmitted data block, which in the frequency domain is a pointwise multiplication of the DFT frequency samples. Then, to remove the channel distortion, the DFT of the received signal can simply be divided by the DFT of the channel impulse response point-wise, or frequency domain equalization may be used.

Some aspects of the disclosure provide for an apparatus comprising a processor and a memory coupled to the processor, wherein the memory includes a set of instructions stored therein and executable by the processor to perform methods disclosed herein. In one aspect, for a group of N data symbols of a reference signal, the processor performs N-point DFT spreading on the N data symbols to generate a set of N DFT-spread components of the N data symbols. The processor then maps the N DFT-spread components of the N data symbols to N subcarriers of a set of M subcarriers (M>N) to generate a set of complex subcarrier amplitudes. The processor performs an M-point inverse discrete Fourier transform, such as an inverse fast Fourier transform (IFFT), on the set of complex subcarrier amplitudes to generate a reference-signal sequence comprising M discrete time-domain values.

In accordance with certain aspects of the disclosure, CI-OFDM can be configured as a DFT pre-coded OFDMA scheme. CI-OFDM is distinctly different from prior-art OFDMA, for example, because of the DFT pre-coding (e.g., spreading) of the symbols in the transmitter, and the corresponding IDFT of the demodulated symbols in the receiver. Because of this pre-coding, the CI-OFDM subcarriers are not independently modulated, as in the case of the OFDMA subcarriers. CI-OFDM distinguishes itself from other spread-OFDM techniques in that its PAPR is lower than the PAPR of a conventional OFDMA signal. The use of CI-OFDM transmission techniques by UEs is described herein because lower PAPR greatly benefits mobile terminals in terms of transmit power efficiency. Thus, such CI-OFDM coding can be employed for UE uplink transmissions.

FIG. **31** is a block diagram that depicts a non-transient computer-readable memory **3100** comprising a set of instructions stored therein and executable by a processor to perform methods in accordance with aspects of the disclosure. In some aspects, the computer-readable memory **3100** can reside on at least one UE and be configured for processing uplink transmissions.

In one aspect, the instructions can comprise a software interface such as to provide for access to resources (e.g., functions, variables, etc.) inside a program or source code segment. Interfaces between software components can provide constants, data types, types of procedures, exception specifications, and/or method signatures. Sometimes public variables are defined as part of an interface. A software interface may provide access to computer resources, such as memory, CPU, storage, etc.). In some aspects, a software module comprises an interface and an implementation, wherein the implementation can contain code configured to perform procedures and methods described in the interface, as well as comprising private variable, procedures, and/or other structures and/or capabilities.

In one aspect, data bits corresponding to a reference signal (and, optionally, user data) is input to a baseband modulator source-code segment **3101** configured to transform the binary input to a multi-level sequence of complex numbers b in one of several possible modulation formats, including binary phase shift keying (BPSK), quaternary PSK (QPSK), **16** level quadrature amplitude modulation (16-QAM), 64-QAM, as well as others. The system may adapt the modulation format, and thus the transmission bit rate, to match the current channel conditions the terminal. In some aspects, source-code segment **3101** is referred to as a bit-to-symbol mapper that converts each set of bits to a symbol in a modulation constellation.

The input of a Spread-DFT source code segment **3102** comprises the data symbols b, which the source code segment **3102** groups into blocks, each containing N symbols. Serial-to-parallel conversion may be performed. The Spread-DFT source code segment **3102** can be configured to perform an N-point DFT to produce frequency-domain symbols which are the DFT-spread input symbols b. In one aspect of the invention, the above-mentioned spreading matrix S is employed as an invertible transform to produce a sequence of coded data symbols x from an input data vector b: x=Sb.

By way of example, FIG. **32** illustrates an invertible transform matrix S that may be employed in some aspects of the invention. In one aspect, the invertible transform matrix S is an NxN DFT matrix. Each row (e.g., row **3201**) of the matrix S multiplies original data vector b (which comprises N values) to produce a coded data symbol x_i. Specifically, each coded data symbol x_i comprises a linear combination of the original data symbols b, wherein the coefficients of the linear combination are values of the invertible transform matrix S, which is the DFT matrix.

In some aspects, such as described in the references disclosed herein, the Spread-DFT source code segment **3102** can be called a CI coder, a time-domain-to-frequency-domain converter, or an OFDMA precoder. In some aspects, source-code segment **3102** comprises a filter (which may include various filter types, including windowing filters), such as may be used for pulse shaping, shaping the spectrum of the transmitted signal, imparting predetermined time-domain features to the transmitted signal, and/or other filter functions. As described in the incorporated references and disclosed herein, source-code segment **3102** can further comprise spatial precoding functionality and/or other types of precoding.

A symbol-to-subcarrier mapping source code segment **3103** maps each of the N DFT outputs of x to one of M (M>N) orthogonal subcarriers. As in conventional OFDMA, a typical value of M might be 256 subcarriers and N=M/Q is an integer submultiple of M. Q is a bandwidth expansion factor of the symbol sequence. If all terminals (e.g., UEs) transmit N symbols per block, the system can potentially handle Q simultaneous transmissions without co-channel interference. When spatial multiplexing (e.g., spatial multiplexing or spatial demultiplexing) is employed, the number of concurrent non-interfering channels can be substantially higher. The result of the subcarrier mapping is a set of complex subcarrier amplitudes, where N of the amplitudes are non-zero.

As in conventional OFDMA, an M-point inverse DFT source code segment **3104** transforms the subcarrier amplitudes to a complex time-domain signal. In some aspects, this is referred to as frequency-domain-to-time-domain conversion. In accordance with certain aspects of the invention, such as disclosed in the incorporated references, the spread data symbols can be distributed over other diversity parameters. For example, each of a plurality of subcarrier sets can be transmitted by a different antenna. Thus, the source-code segment **3104** and/or circuitry coupled to the processor can be configured to distribute each set of OFDM subcarriers to a different set of antennas for transmission. For example, such aspects are disclosed in U.S. Pat. No. 7,839,941, which is a national stage of PCT/US99/02838, which are incorporated by reference in their entireties.

A cyclic-prefix appending source code segment **3105** appends a set of symbols (e.g., a cyclic prefix, a postfix, and/or a guard interval) to the sequence of complex time-domain symbols in order to prevent inter-block interference (MI) due to multipath delay.

The time-domain signal may be provided with additional baseband processing **3106**, which can include pulse shaping and/or other baseband processing, to produce a digital baseband transmission signal. The digital baseband transmission signal is typically provided to radio front-end circuitry (not shown), where processing circuitry can provide for DAC, filtering, frequency up-conversion, amplification, and/or other RF front-end processing prior to transmission. However, other types of radio front-end processing may be performed. By way of example, and without limitation, direct conversion of the baseband signal to RF may be performed via digital processing.

FIG. **33** is a block diagram that depicts a non-transient computer-readable memory **3300** comprising a set of instructions stored therein and executable by a processor to perform methods in accordance with aspects of the disclosure. In some aspects, the computer-readable memory **3300** can reside on at least one base transceiver station, at least one central processor, or a combination thereof, and be configured for processing received uplink transmissions.

Received signals are processed by a radio front-end (not shown), which can provide for amplification, filtering, frequency down-conversion, ADC, and/or other radio front-end processes typically performed in the art. In some aspects, a radio front-end can perform direct digital down-conversion of the received radio signal to a digital baseband signal.

An optional front-end digital processing source-code segment **3301** can be provided for direct down-conversion, ADC, filtering, synchronization, and/or other digital pro-

cessing of a received radio signal, an intermediate signal, an analog baseband signal, and/or a digital baseband signal.

An optional cyclic prefix removal source-code segment **3302** can be provided for removing a cyclic prefix, a postfix, a guard interval, or any combination thereof from a baseband digital signal.

An M-point DFT source-code segment **3303**, which may be configured to perform an M-point FFT, converts the baseband digital signal, which comprises a time-domain sequence of symbols, into a set of frequency-domain components, which represent complex amplitudes of the OFDM subcarriers. These complex-valued subcarrier symbols include DFT-spread signals, which comprise DFT-spread reference symbols.

A demapping source-code segment **3304** separates the subcarrier symbols by subcarrier sets, which can correspond to multiplexing and/or multiple-access schemes employed in the OFDM system.

The de-mapped symbols, which include spread reference symbols, are processed by an N-point IDFT source-code segment **3305**, which may be configured to perform an N-point IFFT, to despread the spread reference symbols. The de-spread reference symbols may undergo additional baseband processing **3006**, which may include channel estimation, equalization, spatial demultiplexing, decoding, filtering, error correction, data-symbol estimation, multi-user detection, and/or other baseband processing operations. In some aspects of the disclosure, channel estimation, equalization, spatial demultiplexing, multi-user detection, and/or other baseband processing can be performed prior to IDFT processing, such as directly following the DFT **3303** and/or the de-mapping **3304**.

Cyclic delay diversity (CDD) has been contemplated as a transmit diversity technique for OFDMA, such as presented in S. A. Zekevat, C. R. Nassar, and S. Shattil, "Smart antenna spatial sweeping for combined directionality and transmit diversity," *Journal of Communications and Networks* (*JCN*), *Special Issue on Adaptive Antennas for Wireless Communications*, vol. 2, no. 4, pp. 325-330, December 2000; S. A. Zekevat, C. R. Nassar, and S. Shattil, "Combined directionality and transmit diversity via smart antenna spatial sweeping," 38th Annual Allerton Conference on Communications, Control, and Computing, Champaign-Urbana, Ill., Oct. 4-6, 2000; and in S. Shattil and C. R. Nassar, "Array Control Systems For Multicarrier Protocols Using a Frequency-Shifted Feedback Cavity," IEEE Radio and Wireless Conference, Denver, Colo., Aug. 1-4, 1999, all of which are incorporated by reference in their entireties.

In CDD, a phase angle change in the frequency domain (such as may be provided as a cyclic shift delay in the time domain) can be applied to a signal prior to transmission. In OFDMA systems, CDD can be implemented after OFDM modulation. For example, after the IDFT, the transmit signal is split into N_T antenna branches. The cyclic shift of the first antenna is set to zero, while in the other branches, the signal is cyclically shifted by an antenna-specific cyclic shift δ_n, $n=1, \ldots, N_T-1$. The equivalent representation in the frequency domain is provides phase diversity.

In accordance with the disclosure of PCT/US99/02838, such as claimed in U.S. Pat. No. 7,839,941, a method and apparatus for enhancing transmit diversity provides for modulating each of at least one data symbol onto a plurality of subcarriers to be transmitted from a plurality of antennas, thereby producing a transmitted signal; and periodically changing the relative phase between the subcarriers. CI coding, such as DFT spreading disclosed herein provides for modulating each reference data symbol onto a plurality of OFDM subcarriers. Aspects disclosed therein provide for producing a periodically scanning beam pattern, which can be achieved via any of a variety of mechanisms that cause a phase shift in the transmitted signals.

Also disclosed in PCT/US99/02838, a type of CDD diversity scheme is referred to herein as sub-band based transmit diversity (SBTD). In SBTD, the contiguous bandwidth of a device (which may be a UE) having N_T transmit antennas ($N_T \geq 2$) is divided into N_T sub-bands, with each of the N_T transmit antennas being assigned to a respective one of the N_T sub-bands, wherein each transmit antenna transmits $1/N_T$ of data symbols for the device in its respective sub-band. A method and apparatus for enhancing transmit diversity provides for modulating each of at least one data symbol onto a plurality of subcarriers to be transmitted from a plurality of antennas, thereby producing a transmitted signal; and providing for a frequency offset between subcarriers transmitted from different antennas.

Because CI-OFDM signals are still being transmitted within contiguous sub-bands of contiguous sub-carriers in SBTD, SBTD preserves the low PAPR property of CI-OFDM and does not introduce frequency selectivity into CI-OFDM processing. Furthermore, dividing the transmitted data between separate sub-bands and on separate antennas can potentially reduce the complexity of the transmitter circuitry, as the size of the DFT (per antenna) may be reduced compared to the DFT required in non-SBTD diversity schemes. These aspects may be employed in the apparatus and method implementations disclosed herein. By way of example, such CDD techniques can be employed across distributed terminals in a Cooperative-MIMO system.

The various blocks shown in the figures may be viewed as method steps, and/or as operations that result from operation of computer program code, and/or as a plurality of coupled logic circuit elements constructed to carry out the associated function(s).

In general, the various exemplary aspects may be implemented in hardware or special purpose circuits, software, logic or any combination thereof. For example, some aspects may be implemented in hardware, while other aspects may be implemented in firmware or software which may be executed by a controller, microprocessor or other computing device, although the invention is not limited thereto. While various aspects of the exemplary embodiments of this invention may be illustrated and described as block diagrams, flow charts, or using some other pictorial representation, it is well understood that these blocks, apparatus, systems, techniques or methods described herein may be implemented in, as non-limiting examples, hardware, software, firmware, special purpose circuits or logic, general purpose hardware or controller or other computing devices, or some combination thereof.

It should thus be appreciated that at least some aspects of the exemplary aspects of the invention may be practiced in various components such as integrated circuit chips and modules, and that the exemplary aspects of this invention may be realized in an apparatus that is embodied as an integrated circuit. The integrated circuit, or circuits, may comprise circuitry (as well as possibly firmware) for embodying at least one or more of a data processor or data processors, a digital signal processor or processors, baseband circuitry and radio frequency circuitry that are configurable so as to operate in accordance with the exemplary aspects of this invention.

Various modifications and adaptations to the foregoing exemplary aspects of this invention may become apparent to those skilled in the relevant arts in view of the foregoing

description, when read in conjunction with the accompanying drawings. However, any and all modifications will still fall within the scope of the non-limiting and exemplary aspects of this invention.

The invention claimed is:

1. A non-transitory computer-readable medium including computer-readable program code stored thereon, the computer-readable program code configured to be executed by at least one processor to implement a method for generating an Orthogonal Frequency Division Multiplexing (OFDM) transmission signal, the method comprising:

employing an invertible transform to spread a plurality of data symbols with complex-valued coefficients to generate a plurality of spread data symbols;

mapping the spread data symbols to a plurality of OFDM subcarriers; and

responsive to the mapping, modulating the spread data symbols onto the plurality of OFDM subcarriers to produce the OFDM transmission signal comprising a superposition of the OFDM subcarriers, wherein employing the invertible transform is configured to provide the superposition with a reduced peak-to-average power ratio.

2. The non-transitory computer-readable medium recited in claim **1**, wherein the invertible transform comprises an N-point discrete Fourier Transform (DFT), and the modulating comprises performing an M-point inverse-DFT, wherein M>N.

3. The non-transitory computer-readable medium recited in claim **1**, wherein the modulating comprises performing an inverse fast Fourier transform.

4. The non-transitory computer-readable medium recited in claim **1**, wherein the data symbols comprise reference-signal symbols, which comprise at least one of known training symbols and synchronization symbols.

5. The non-transitory computer-readable medium recited in claim **1**, wherein the plurality of OFDM subcarriers comprise at least one of contiguous OFDM subcarriers and equally spaced non-contiguous OFDM subcarriers.

6. The non-transitory computer-readable medium recited in claim **1**, further comprising computer-readable program code configured to perform pulse-shaping module to provide the OFDM transmission signal with a predetermined pulse shape.

7. The non-transitory computer-readable medium recited in claim **1**, further comprising computer-readable program code configured to append at least one of a cyclic prefix, a postfix, and a guard interval to the OFDM transmission signal.

8. The non-transitory computer-readable medium recited in claim **1**, further comprising computer-readable program code to provide channel precoding.

9. The non-transitory computer-readable medium recited in claim **1**, wherein the plurality of data symbols are at least one of time-multiplexed with reference-signal symbols, frequency-multiplexed with reference-signal symbols, and code-multiplexed with reference-signal symbols.

10. The non-transitory computer-readable medium recited in claim **1**, further comprising computer-readable program code to provide Cyclic Delay Diversity (CDD) to the OFDM transmission signal.

11. A method, comprising:

performing an invertible transform, comprising multiplying a plurality of data symbols by a complex-valued spreading matrix to produce a plurality of spread symbols;

mapping the plurality of spread symbols to a plurality of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers; and

modulating the plurality of spread symbols onto the plurality of OFDM subcarriers to produce a spread OFDM signal to be transmitted into a wireless channel, wherein the spread OFDM signal comprises a superposition of the OFDM subcarriers, and wherein the complex-valued spreading matrix is configured to provide the superposition with a reduced peak-to-average power ratio (PAPR).

12. The method recited in claim **11**, wherein the plurality of OFDM subcarriers is a subset of subcarriers, the subset comprising at least one of a block of contiguous subcarriers, and a set of non-contiguous subcarriers.

13. The method recited in claim **11**, wherein the plurality of OFDM subcarriers is selected based on measured channel quality of the subcarriers.

14. The method recited in claim **11**, wherein the mapping is configured to provide the spread OFDM signal with reduced PAPR.

15. The method recited in claim **11**, wherein at least one of the spreading matrix and the mapping is configured to provide a spread reference signal comprising a coherent superposition of reference symbol components on different subcarriers.

16. The method recited in claim **11**, wherein the plurality of data symbols comprises at least one reference-signal symbol employed for at least one of synchronization and channel estimation.

17. The method recited in claim **11**, further comprising appending at least one of a cyclic prefix, a postfix, and a guard interval onto the spread OFDM signal.

18. The method recited in claim **11**, wherein the spreading matrix comprises an N-point Discrete Fourier Transform (DFT), and the modulating comprises employing an M-point inverse-DFT, and wherein N<M.

19. The method recited in claim **11**, further comprising providing Cyclic Delay Diversity to the spread OFDM signal.

20. The method recited in claim **11**, further comprising pulse shaping to provide the OFDM transmission signal with a predetermined pulse shape.

21. A User Equipment configured to perform the method recited in claim **11**.

22. An apparatus comprising:

a processor; and

a non-transitory memory coupled to the processor, the non-transitory memory including a set of instructions stored therein and executable by the processor to:

perform an invertible transform on a set of data symbols to generate a plurality N of spread data symbols, the invertible transform comprising complex-valued spreading codes;

map the N spread data symbols to at least N subcarriers of a plurality M of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers to generate a set of complex subcarrier amplitudes; and

perform an M-point inverse discrete Fourier transform (IDFT) on the set of complex subcarrier amplitudes to generate a time-domain sequence to be transmitted into a wireless channel, the time-domain sequence comprising a superposition of the OFDM subcarriers, wherein the invertible transform is configured to provide the superposition with a reduced peak-to-average power ratio.

23. The apparatus recited in claim 22, wherein the N subcarriers comprise at least one of contiguous OFDM subcarriers and non-contiguous OFDM subcarriers.

24. The apparatus recited in claim 22, configured to reside on a User Equipment.

25. The apparatus recited in claim 22, wherein M>N.

26. The apparatus recited in claim 22, wherein the IDFT comprises an inverse fast Fourier transform.

27. The apparatus recited in claim 22, wherein the non-transitory memory further comprises instructions to perform pulse-shaping on at least one of a set of signals, the set comprising the plurality of spread data symbols and the time-domain sequence, in order to provide the superposition with a predetermined pulse shape.

28. The apparatus recited in claim 22, wherein the non-transitory memory further comprises instructions to append at least one of a cyclic prefix, a postfix, and a guard interval to the time-domain sequence.

29. The apparatus recited in claim 22, wherein the at least N subcarriers is selected based on a measured channel quality.

* * * * *

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(12) **United States Patent**
Shattil

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(54) **SINGLE CARRIER FREQUENCY DIVISION MULTIPLE ACCESS BASEBAND SIGNAL GENERATION**

(71) Applicant: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

(72) Inventor: **Steve Shattil**, Cheyenne, WY (US)

(73) Assignee: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

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None
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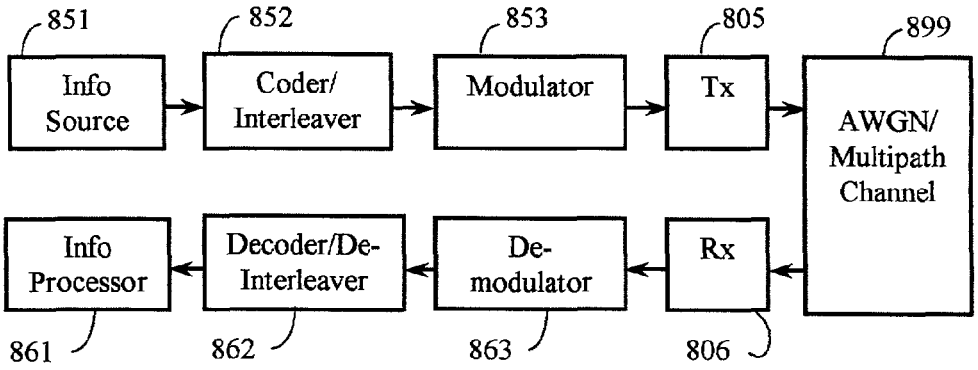
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Primary Examiner — Diane L Lo
(74) *Attorney, Agent, or Firm* — Steven J Shattil

(57) **ABSTRACT**

Applications of CI processing to ad-hoc and peer-to-peer networking significantly improve throughput, network capacity, range, power efficiency, and spectral efficiency. CI-based subscriber units perform network-control functions to optimize network performance relative to channel conditions, network loads, and subscriber services. CI codes are used to identify and address network transmissions. Channel characteristics of communication links are employed to encode, address, and authenticate network transmissions. CI transceivers used as relays and routers employ unique characteristics of transmission paths to code and decode network transmissions. A central processor is adapted to perform array processing with signals received from, and transmitted by, a plurality of subscriber units in a wireless network.

47 Claims, 17 Drawing Sheets



Related U.S. Application Data

continuation of application No. 15/149,382, filed on May 9, 2016, now Pat. No. 9,628,231, which is a continuation-in-part of application No. 14/727,769, filed on Jun. 1, 2015, which is a continuation of application No. 14/276,309, filed on May 13, 2014, now Pat. No. 9,048,897, which is a continuation of application No. 12/545,572, filed on Aug. 21, 2009, now Pat. No. 8,750,264, which is a division of application No. 11/187,107, filed on Jul. 22, 2005, now Pat. No. 8,670,390, and a continuation-in-part of application No. 10/145,854, filed on May 14, 2002, now abandoned.

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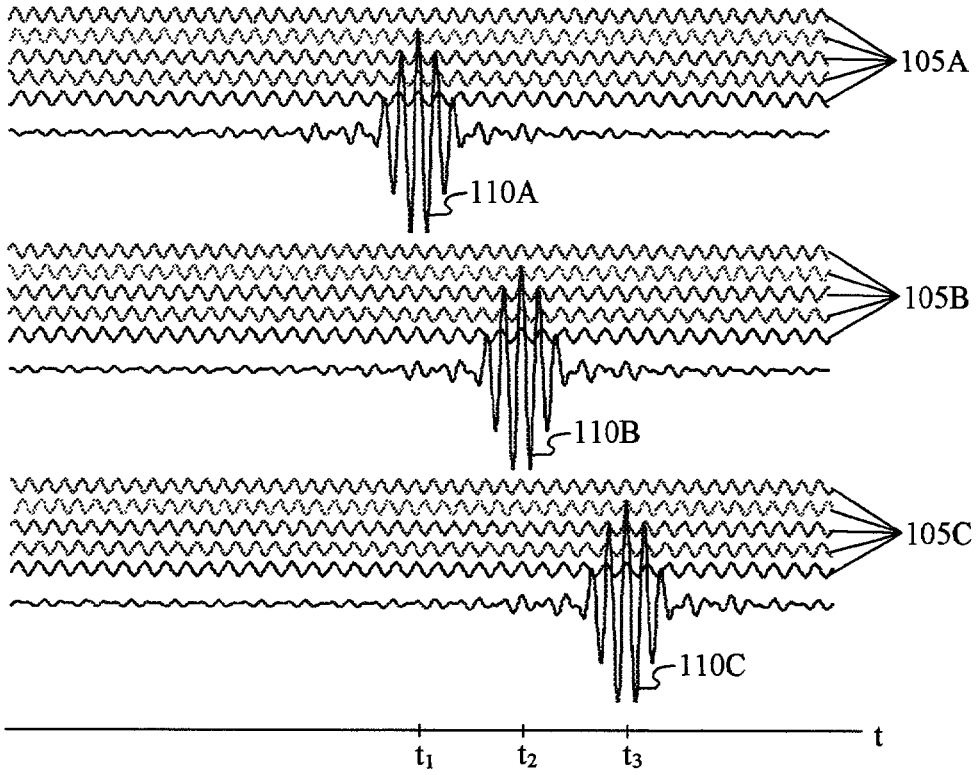


FIG. 1A

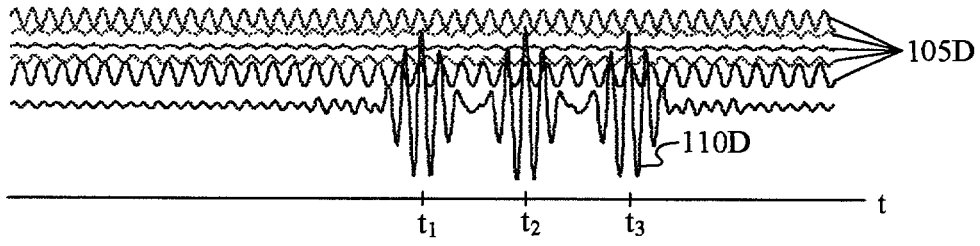


FIG. 1B

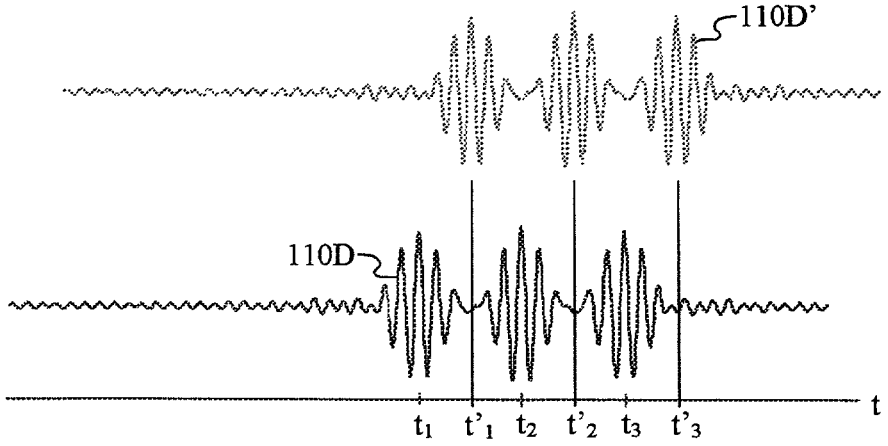


FIG. 1C

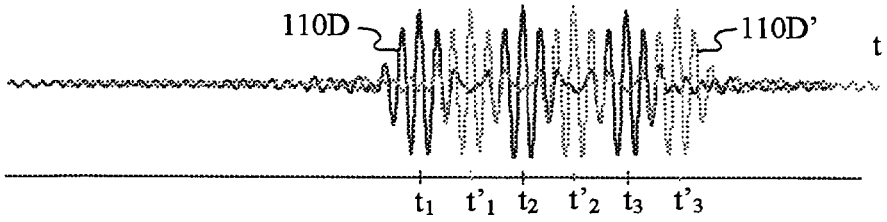


FIG. 1D

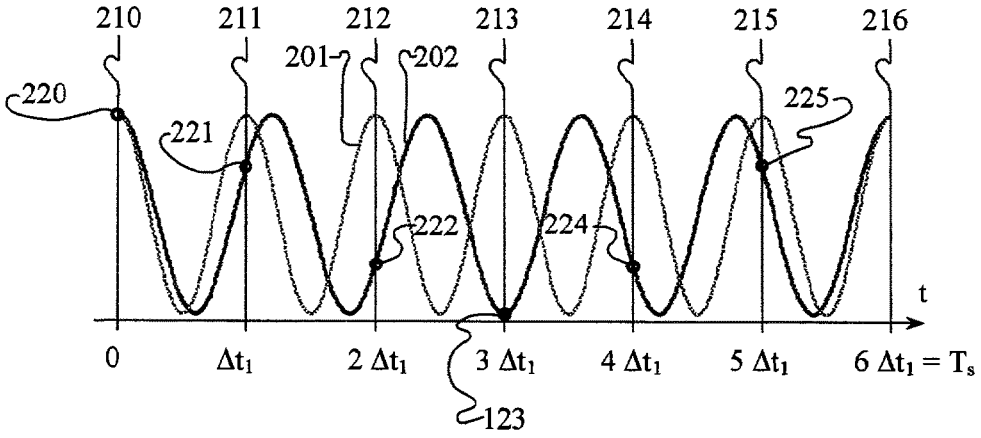


FIG. 2A

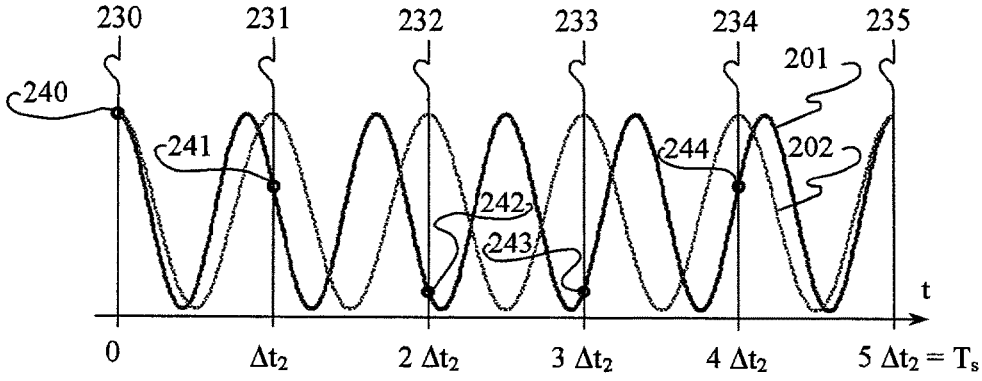
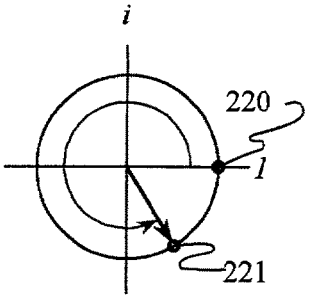
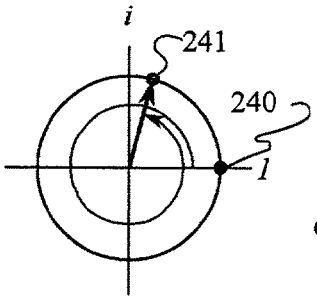


FIG. 2B



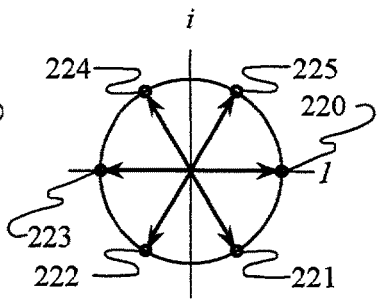
$f_{n-1} : f_n$

FIG. 3A



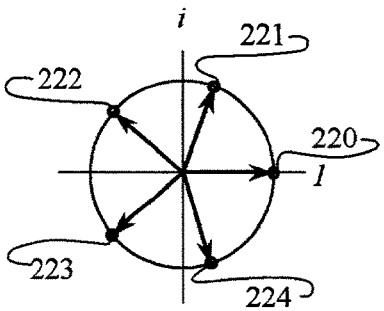
$f_{n+1} : f_n$

FIG. 3B



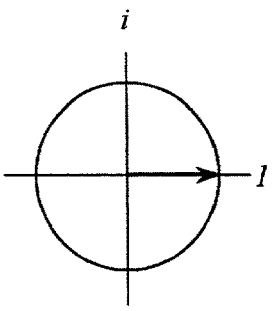
$f_{n-1} : f_n$

FIG. 4A



$f_{n+1} : f_n$

FIG. 4B



$f_n : f_n$

FIG. 4C

C(1) = [1 (1+i)/√2 i (-1+i)/ √2 -1 (-1-i)/ √2 -i (1-i)/ √2];

C(1)*= [1 (1-i)/ √2 -i (-1-i)/√2 -1 (-1+i)/√2 i (1+i)/√2];

C(2) = [1 (-1+i)/√2 -i (1+i)/√2 -1 (1-i)/√2 i (-1-i)/√2];

C(2)*= [1 (-1-i)/√2 i (1-i)/√2 -1 (1+i)/√2 -i (-1+i)/√2];

C(3) = [1 (1+i)/√2 i (-1+i)/√2 1 (1+i)/√2 i (-1+i)/√2];

C(3)*= [1 (1-i)/√2 -i (-1-i)/√2 1 (1-i)/√2 -i (-1-i)/√2];

C(4) = [1 (-1+i)/√2 i (-1-i)/√2 1 (-1+i)/√2 i (-1-i)/√2];

C(4)*= [1 (-1-i)/√2 -i (-1+i)/√2 1 (-1-i)/√2 -i (-1+i)/√2];

C(5) = [1 (-1-i)/√2 -i (-1+i)/√2 -1 (1+i)/√2 i (1-i)/√2];

C(5)*= [1 (-1+i)/√2 i (-1-i)/√2 -1 (1-i)/√2 -i (1+i)/√2];

C(6) = [1 (1-i)/√2 i (1+i)/√2 -1 (-1+i)/√2 -i (-1-i)/√2];

C(6)*= [1 (1+i)/√2 -i (1-i)/√2 -1 (-1-i)/√2 i (-1+i)/√2];

C(7) = [1 (1+i)/√2 -i (1-i)/√2 1 (1+i)/√2 -i (1-i)/√2];

C(7)*= [1 (1-i)/√2 i (1+i)/√2 1 (1-i)/√2 i (1+i)/√2];

C(8) = [1 (-1+i)/√2 -i (1+i)/√2 1 (-1+i)/√2 -i (1+i)/√2];

C(8)*= [1 (-1-i)/√2 i (1-i)/√2 1 (-1-i)/√2 i (1-i)/√2];

FIG. 5A

	C(1)	C(1)*	C(2)	C(2)*	C(3)	C(3)*	C(4)	C(4)*	C(5)	C(5)*	C(6)	C(6)*	C(7)	C(7)*	C(8)	C(8)*
CI(1)	0	8	0	0	0	0	0	0	4-4i	0	0	4+4i	0	0	0	0
CI(1)*	8	0	0	0	0	0	0	0	0	4+4i	4-4i	0	0	0	0	0
CI(2)	0	0	0	8	0	0	0	0	0	4-4i	4+4i	0	0	0	0	0
CI(2)*	0	0	8	0	0	0	0	0	4+4i	0	0	4-4i	0	0	0	0
CI(3)	0	0	0	0	0	8	0	4-4i	0	0	0	0	4+4i	0	0	0
CI(3)*	0	0	0	0	8	0	4+4i	0	0	0	0	0	0	4-4i	0	0
CI(4)	0	0	0	0	0	4+4i	0	8	0	0	0	0	0	0	4-4i	0
CI(4)*	0	0	0	0	4-4i	0	8	0	0	0	0	0	0	0	0	4+4i
CI(5)	4-4i	0	0	4+4i	0	0	0	0	0	8	0	0	0	0	0	0
CI(5)*	0	4+4i	4-4i	0	0	0	0	0	8	0	0	0	0	0	0	0
CI(6)	0	4-4i	4+4i	0	0	0	0	0	0	0	0	8	0	0	0	0
CI(6)*	4+4i	0	0	4-4i	0	0	0	0	0	0	8	0	0	0	0	0
CI(7)	0	0	0	0	4+4i	0	0	0	0	0	0	0	0	8	0	4-4i
CI(7)*	0	0	0	0	0	4-4i	0	0	0	0	0	0	8	0	4+4i	0
CI(8)	0	0	0	0	0	0	4-4i	0	0	0	0	0	0	4+4i	0	8
CI(8)*	0	0	0	0	0	0	0	4+4i	0	0	0	0	4-4i	0	8	0

FIG. 5B

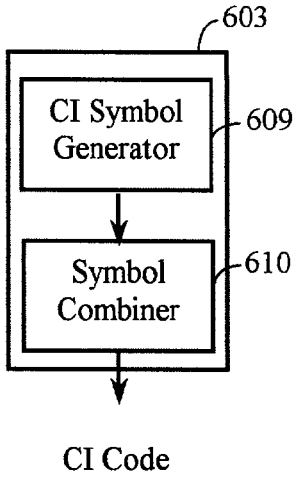


FIG. 6A

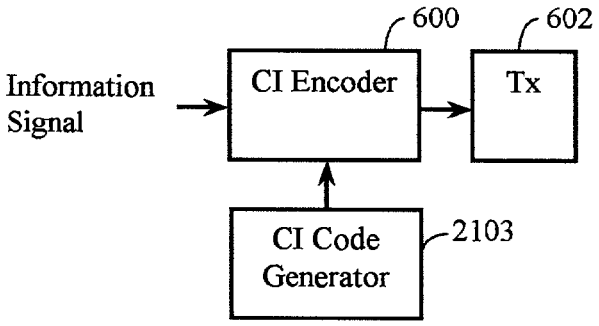


FIG. 6B

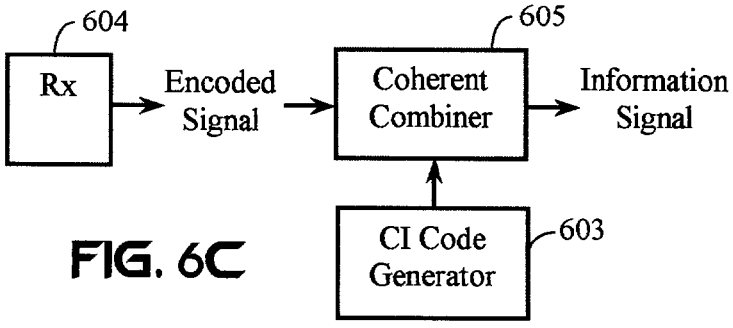


FIG. 6C

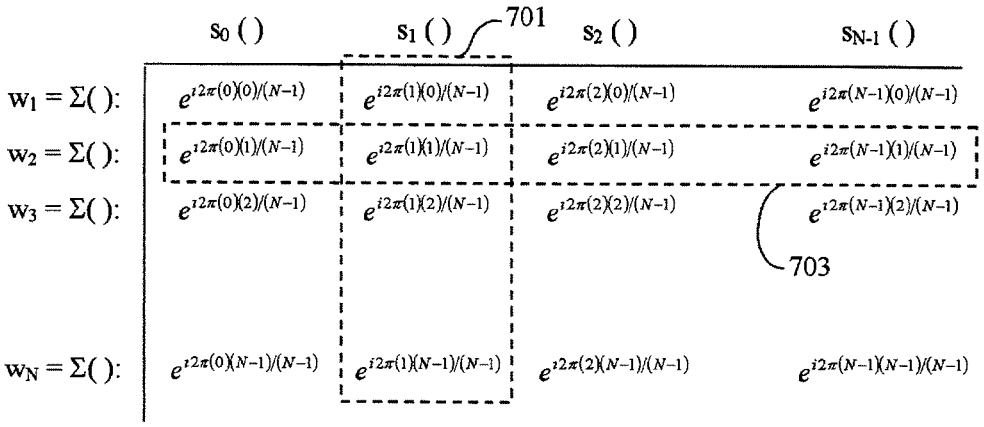

s_0 ( )
s_1 ( )
701
s_2 ( )
s_{N-1} ( )
$w_1 = \Sigma( )$:
$w_2 = \Sigma( )$:
$w_3 = \Sigma( )$:
$w_N = \Sigma( )$:
$e^{i2\pi(0)(0)/(N-1)}$
$e^{i2\pi(1)(0)/(N-1)}$
$e^{i2\pi(2)(0)/(N-1)}$
$e^{i2\pi(N-1)(0)/(N-1)}$
$e^{i2\pi(0)(1)/(N-1)}$
$e^{i2\pi(1)(1)/(N-1)}$
$e^{i2\pi(2)(1)/(N-1)}$
$e^{i2\pi(N-1)(1)/(N-1)}$
$e^{i2\pi(0)(2)/(N-1)}$
$e^{i2\pi(1)(2)/(N-1)}$
$e^{i2\pi(2)(2)/(N-1)}$
$e^{i2\pi(N-1)(2)/(N-1)}$
703
$e^{i2\pi(0)(N-1)/(N-1)}$
$e^{i2\pi(1)(N-1)/(N-1)}$
$e^{i2\pi(2)(N-1)/(N-1)}$
$e^{i2\pi(N-1)(N-1)/(N-1)}$

FIG. 7

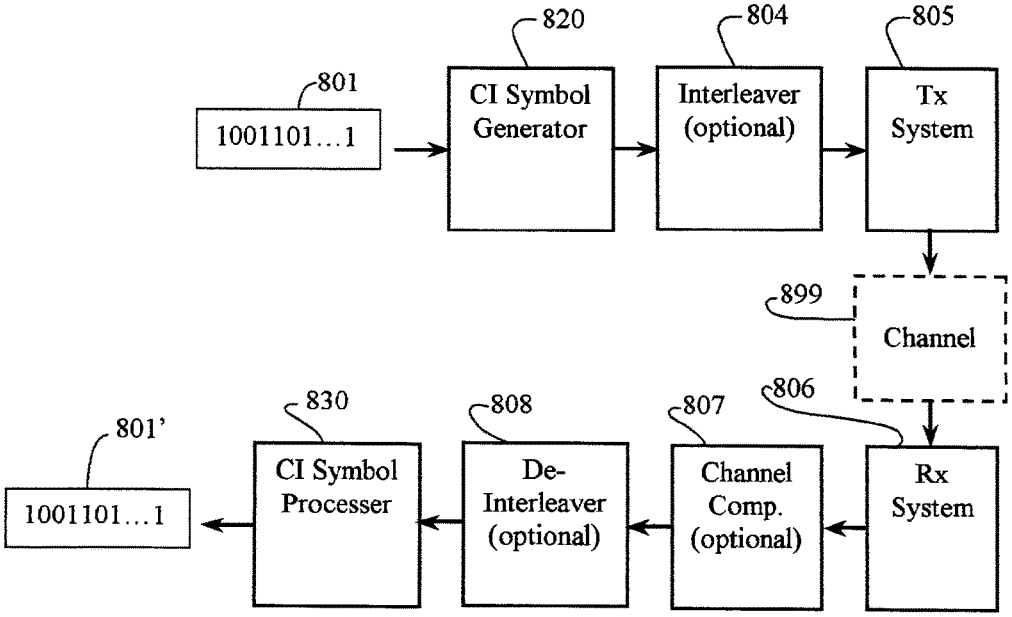

820
804
805
801
1001101…1
CI Symbol Generator
Interleaver (optional)
Tx System
899
Channel
806
830
808
807
801'
1001101…1
CI Symbol Processer
De-Interleaver (optional)
Channel Comp. (optional)
Rx System

FIG. 8A

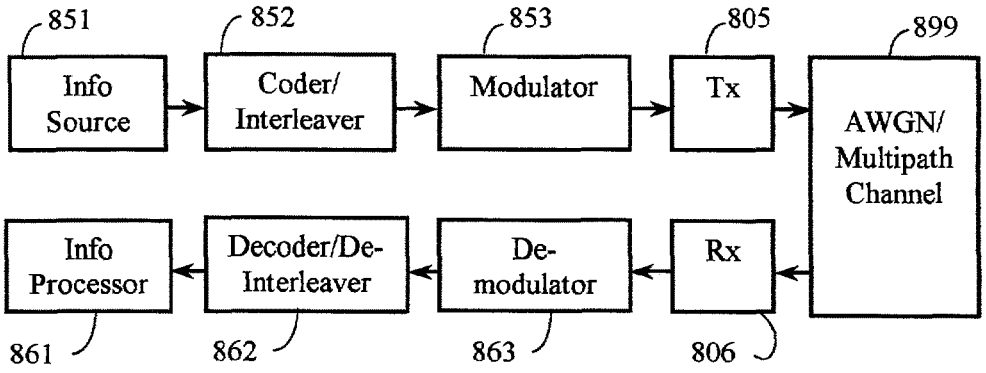

851
852
853
805
899
Info Source
Coder/ Interleaver
Modulator
Tx
AWGN/ Multipath Channel
Info Processor
Decoder/De-Interleaver
De-modulator
Rx
861
862
863
806

FIG. 8B

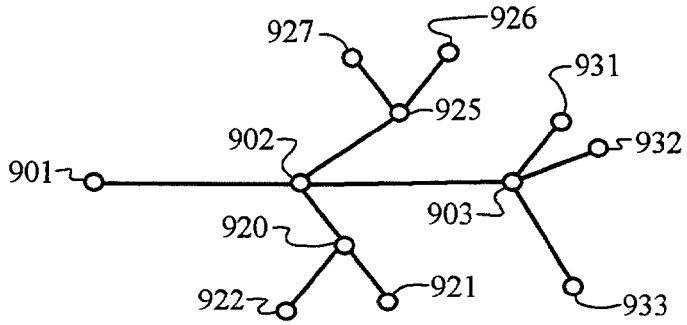


FIG. 9A

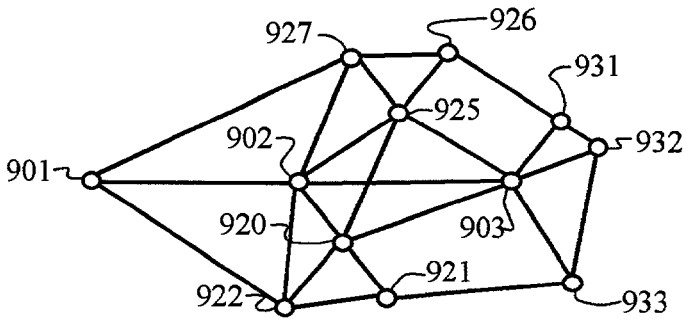


FIG. 9B

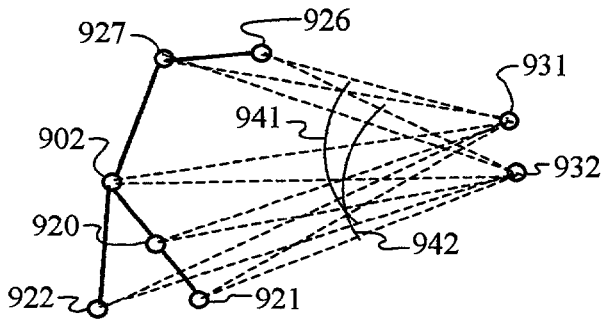


FIG. 9C

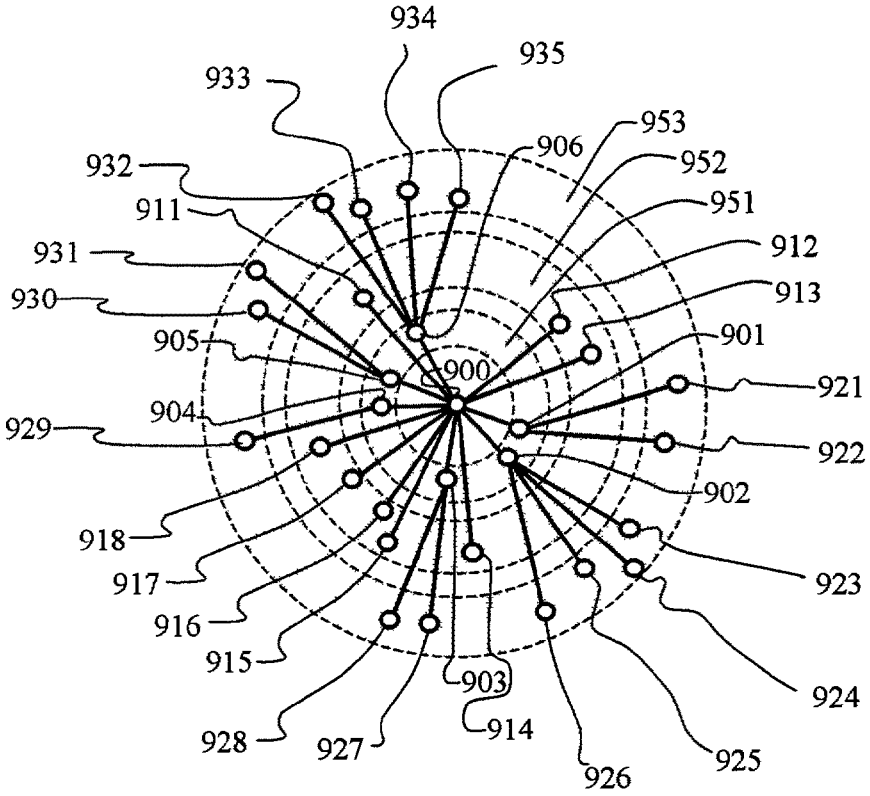

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FIG. 9D

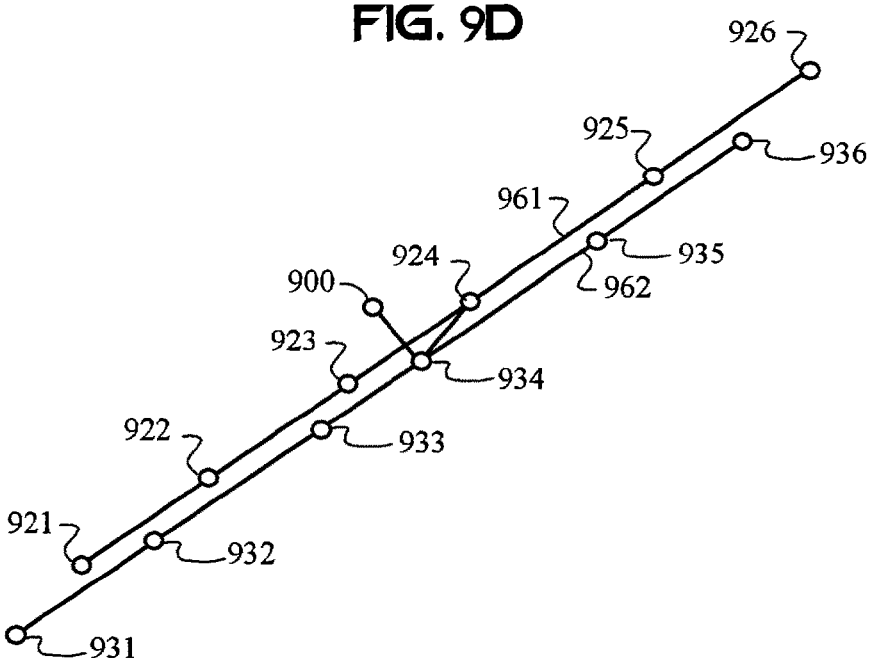

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933
921
932
931

FIG. 9E

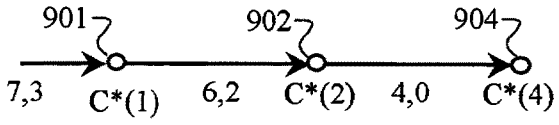


FIG. 9F

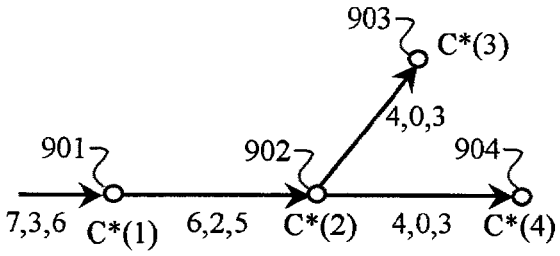


FIG. 9G

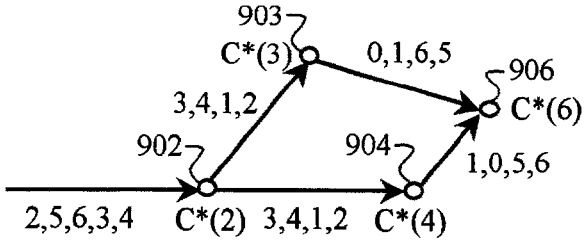


FIG. 9H

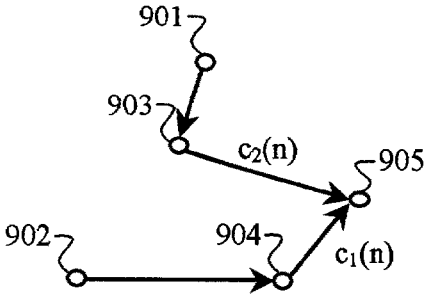


FIG. 9I

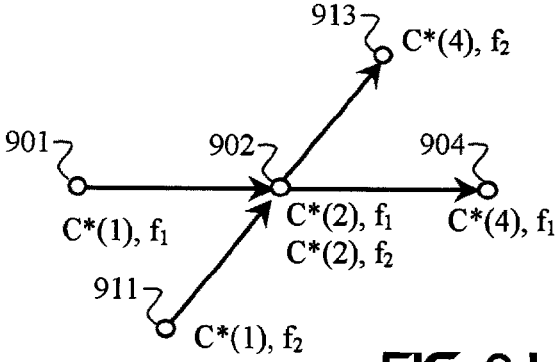


FIG. 9J

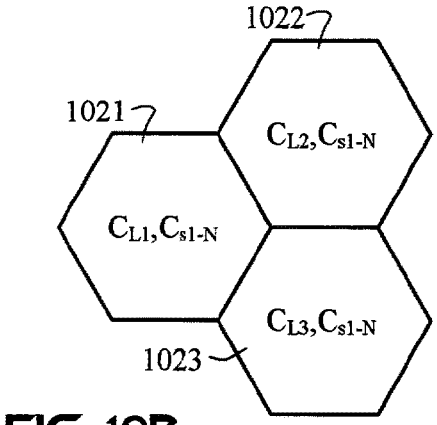


FIG. 10B

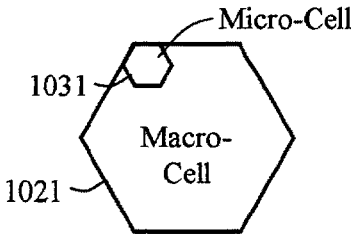


FIG. 10A

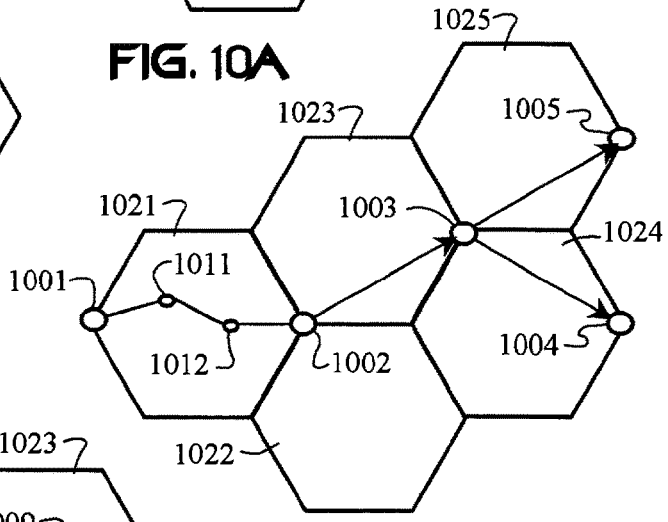


FIG. 10C

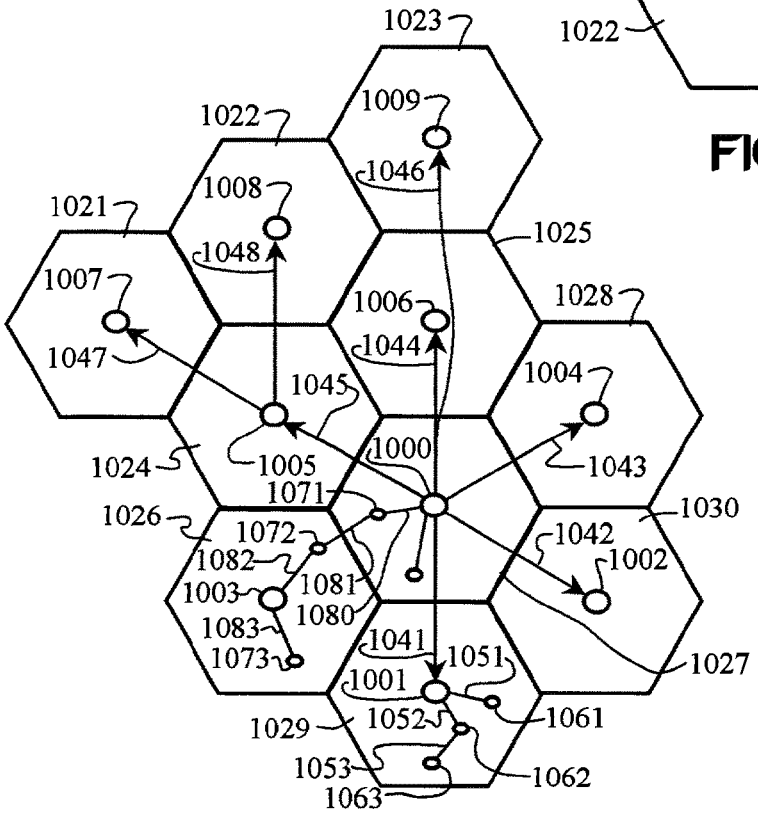


FIG. 10D

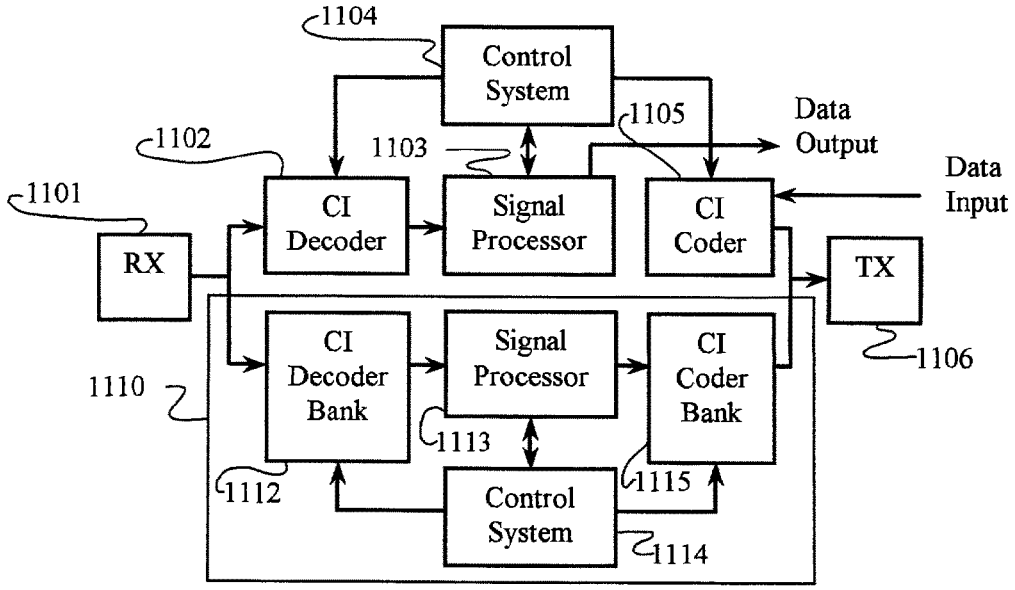


FIG. 11A

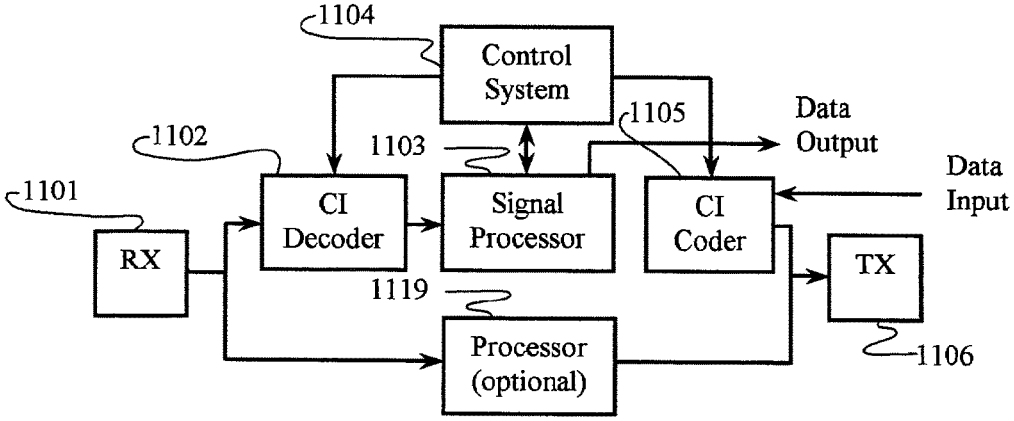


FIG. 11B

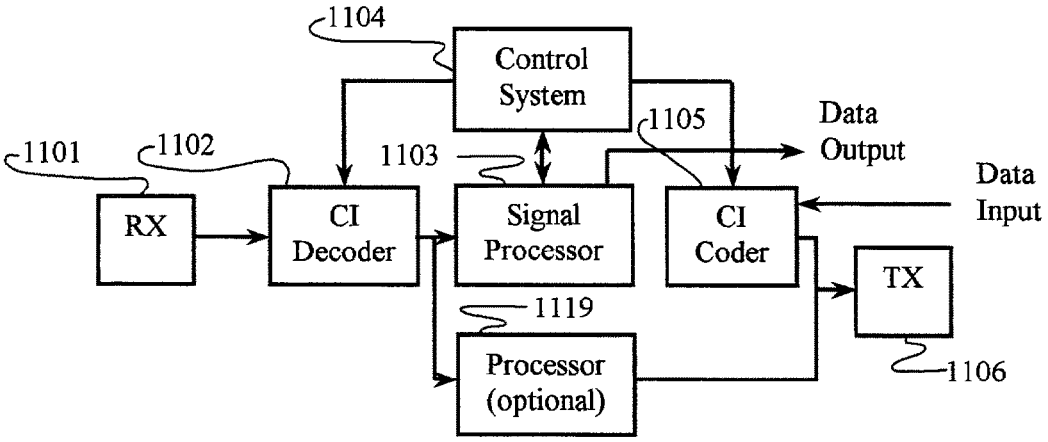


FIG. 11C

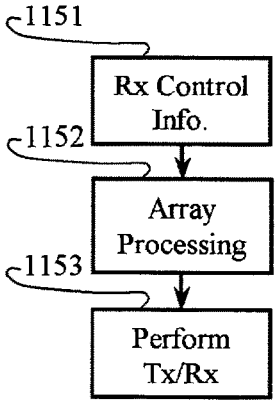


FIG. 11D

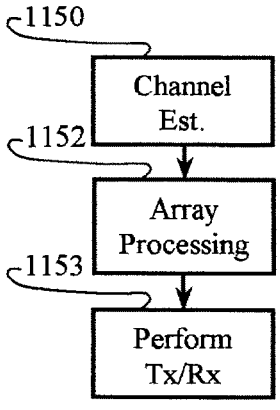


FIG. 11E

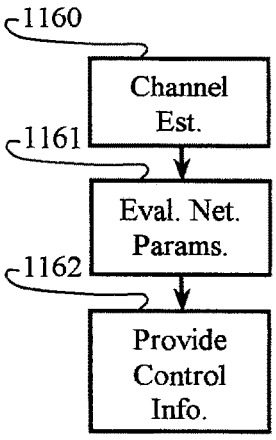


FIG. 11F

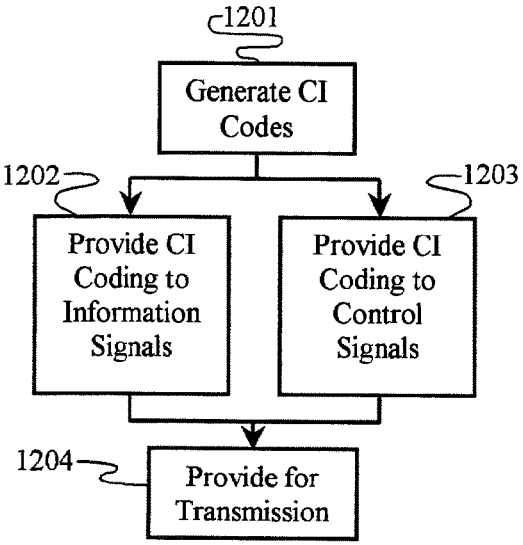


FIG. 12A

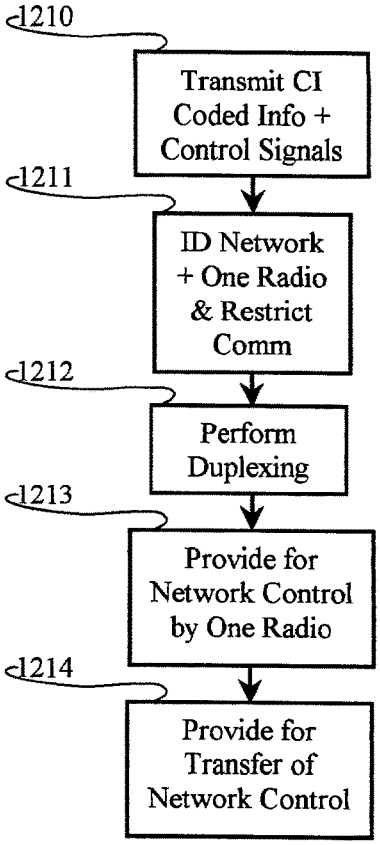


FIG. 12B

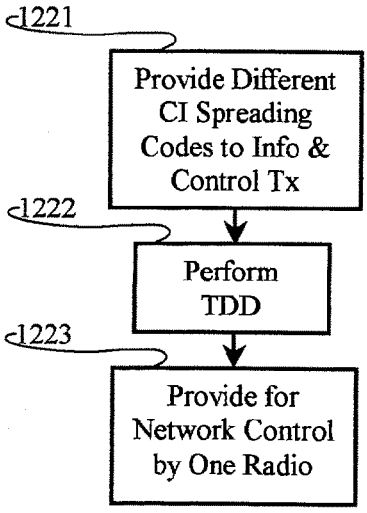


FIG. 12C

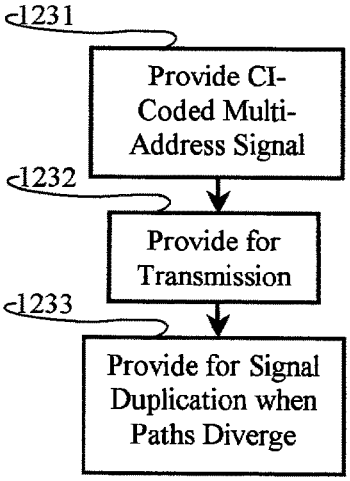


FIG. 12D

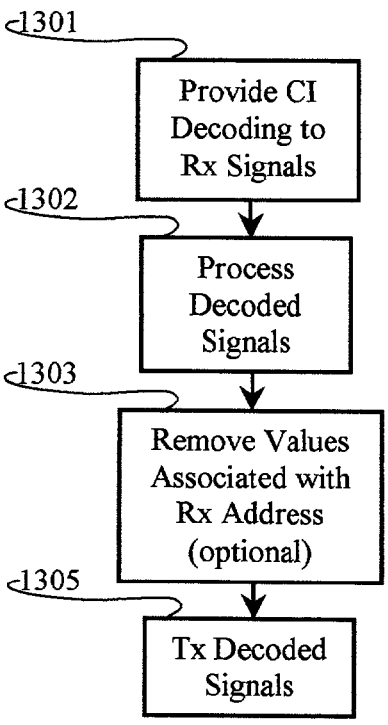


FIG. 13A

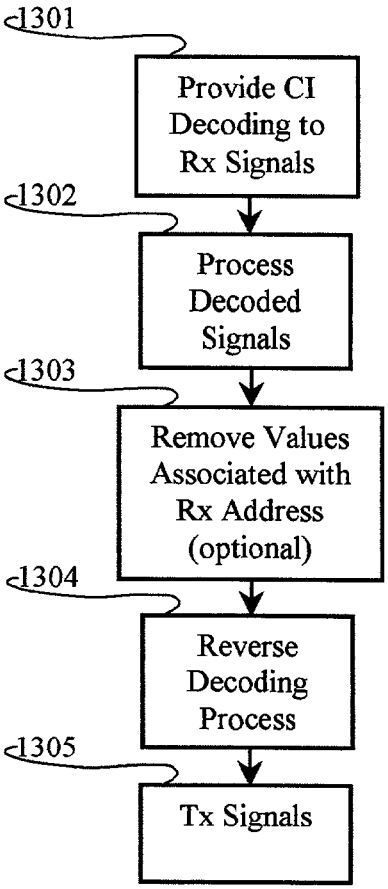


FIG. 13B

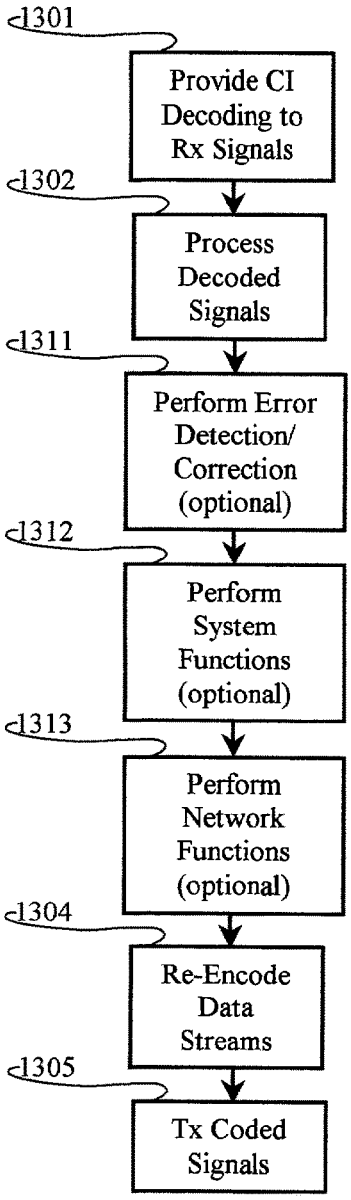


FIG. 13C

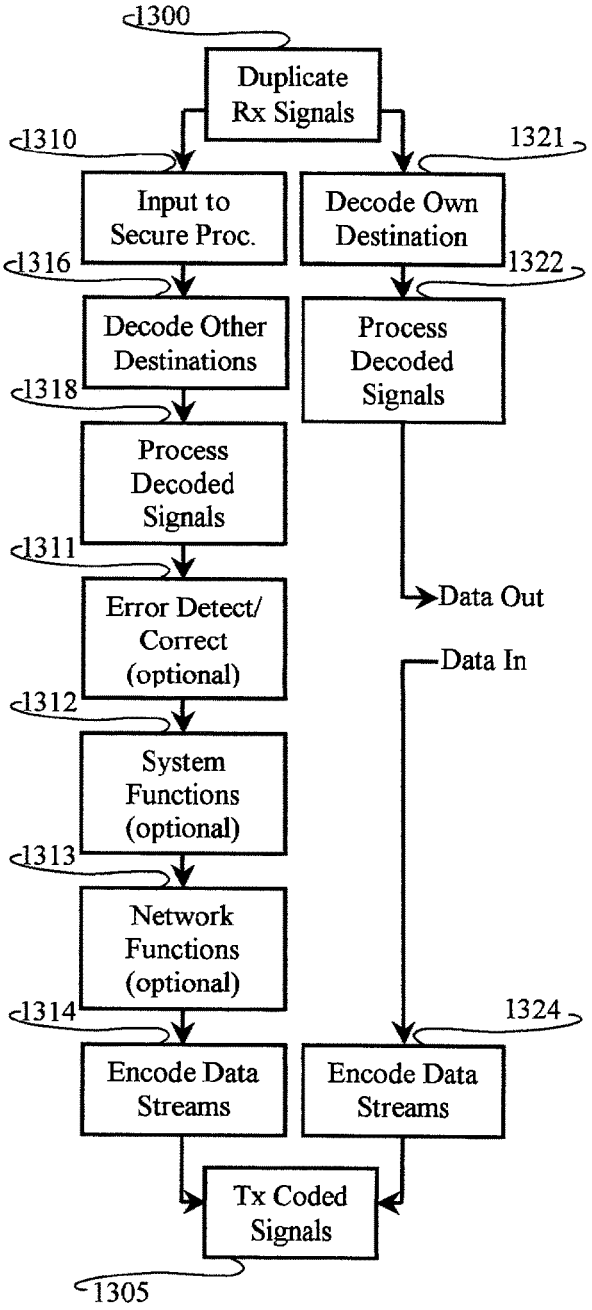


FIG. 13D

SINGLE CARRIER FREQUENCY DIVISION MULTIPLE ACCESS BASEBAND SIGNAL GENERATION

This application is a continuation of U.S. patent application Ser. No. 15/489,664 filed on Apr. 17, 2017, which is a continuation of U.S. patent application Ser. No. 15/149,382, filed on May 9, 2016, now U.S. Pat. No. 9,628,231, which is a continuation in part of U.S. patent application Ser. No. 14/727,769 filed Jun. 1, 2015, which is a continuation of U.S. patent application Ser. No. 14/276,309 filed May 13, 2014, now U.S. Pat. No. 9,048,897, which is a continuation U.S. patent application Ser. No. 12/545,572, filed Aug. 21, 2009, now U.S. Pat. No. 9,042,333, which is a division of U.S. patent application Ser. No. 11/187,107 filed on Jul. 22, 2005, now U.S. Pat. No. 8,670,390, which claims priority to U.S. Provisional Patent Application No. 60/598,187 filed Aug. 2, 2004 and is a continuation in part of U.S. patent application Ser. No. 10/145,854 filed on May 14, 2002, all of which are hereby incorporated by reference in their entireties and all of which this application claims priority under at least 60 U.S.C. 120 and/or any other applicable provision in Title 60 of the United States Code.

BACKGROUND OF THE INVENTION

I. Field of the Invention

The present invention relates to networks of wireless transceivers that implement Carrier Interferometry (CI) and/or CI-based coding.

II. Description of the Related Art

A wideband signal, such as a direct-sequence CDMA (DS-CDMA) signal, transmitted in a multipath environment experiences a frequency-selective fade. If the duration of the data bits is smaller than the multipath delay, the received signal experiences inter-symbol interference resulting from delayed replicas of earlier bits arriving at the receiver.

Improved DS-CDMA systems use interference cancellation to increase capacity; however, the required signal-processing effort is proportional to at least the cube of the bandwidth. Furthermore, DS-CDMA is susceptible to near-far interference, and its long pseudo-noise (PN) codes require long acquisition times. For these reasons, Orthogonal Frequency Division Multiplexing (OFDM) has been merged with DS-CDMA.

In multicarrier CDMA (MC-CDMA), a spreading sequence is converted from serial to parallel. Each chip in the sequence modulates a different carrier frequency. Thus, the resulting signal has a PN–coded structure in the frequency domain, and the processing gain is equal to the number of carriers.

In multi-tone CDMA, or multicarrier DS-CDMA, the available spectrum is divided into a number of equal-width frequency bands used to transmit a narrowband direct-sequence waveform. In U.S. Pat. No. 5,504,775, binary CDMA code symbols are applied to individual carriers in an OFDM system. U.S. Pat. Nos. 5,521,937, 5,960,032, and 6,097,712 describe multicarrier DSSS systems having direct-sequence coding on each subcarrier.

U.S. Pat. No. 5,955,992, PCT Pat. Appl. No. PCT/US99/02838, and U.S. Pat. Pub. No. 2002034191 describe CI, which is a multicarrier protocol implemented with polyphase codes. These polyphase codes may be used for multiple access, spread spectrum, channel coding, or encryption, as described in U.S. Provisional Appl. 60/259,433, filed Dec. 31, 2000. Multiple carriers are redundantly modulated with data streams that are orthogonalized by virtue of different sets of phases encoding each data stream. Interferometry of the carriers provides the means to orthogonalize the data streams, whether the carriers are combined or processed separately. Weights applied to the carriers shape the carrier superpositions, thus, allowing CI signals to appear as single-carrier waveforms, such as Time Division Multiple Access (TDMA) or DS-CDMA signals.

Adaptive antenna arrays may be implemented with DS-CDMA communications to provide significant improvements in range extension, interference reduction, and system capacity. To identify a particular user, a DS-CDMA system demodulates Walsh codes after converting the received signal from analog radio frequency (RF) to digital. Therefore, an adaptive antenna array requires information about the user codes, or it needs to demodulate many different incoming RF signals to track mobile users. These methods are complex processes that are more difficult to implement than tracking users in non-CDMA systems. Furthermore, the wideband nature of DS-CDMA signals restricts the effectiveness of beam forming, interference nulling, spatial interferometry multiplexing, and other techniques employed by adaptive antenna arrays.

U.S. Patent Application entitled "CI Multiple Input, Multiple Output," filed on Nov. 22, 2000, describes applications of multiple-input, multiple-output processing (such as antenna-array processing) to CI signals. CI processing allows wideband single-carrier signals, such as DS-CDMA transmissions, to be processed as a plurality of narrowband components. This simplifies array processing by facilitating beam forming, null steering, space-frequency processing, as well as other adaptive array processing techniques.

U.S. Pat. No. 4,901,307 introduces the concept of marginal isolation, which is another method of exploiting spatial division multiplexing in communication networks. Since cellular implementations of DS-CDMA are typically interference limited, even small reductions in the overall power level of the system allow for increased system capacity.

Ad-hoc networks allow subscriber units to perform base station functions. This allows micro-cell subnetworks, which lowers overall system power levels and improves spectral efficiency. U.S. Pat. No. 5,943,322 describes an adaptable DS-CDMA network that uses a control-signal channel to assign base-station functions (e.g., power control and synchronization) to a subscriber unit. U.S. Pat. No. 6,233,248 provides for multi-address transmissions to be sent on common paths between nodes until the paths diverge. U.S. Pat. No. 5,422,952 allows signals for a particular user to be transmitted throughout the entire network. Different transmissions are provided with unique PN codes.

None of the prior-art references describe the use of CI, CI-based protocols, or CI coding in ad-hoc networks. Thus, none of the prior-art references can provide the improved bandwidth efficiency, enhanced power efficiency, increased range, increased throughput, and superior immunity to multipath, jamming, and co-channel interference enabled by the combination of CI and adaptable networks.

SUMMARY OF THE INVENTION

Applications of CI to ad-hoc networking provide substantial performance improvements that can be used for any combination of range extension, transmission-power reduction, increased throughput, and improved bit-error rates. Performance improvements resulting from frequency-do-

main processing are particularly useful in ad-hoc networks (as well as in micro-cell networks and networks that employ relays) where interference and multipath typically impede performance. CI pulse shaping also increases throughput (typically characterized as a doubling of throughput), which can be used to increase the number of users, generate higher data rates, and/or provide channel coding.

Adaptations of CI to conventional multicarrier protocols (such as OFDM and MC-CDMA) eliminate the high peak-to-average-power ratios (PAPR) associated with conventional multicarrier protocols. Low PAPR allows low-dynamic-range amplifiers to be used, resulting in substantial cost and power savings.

Conventional codes, such as multiple-access codes, channel codes, spreading codes, etc., may be implemented with CI chip shapes. Alternatively, polyphase codes based on mathematical relationships between CI sub-carriers may be provided.

Applications of CI coding are extended to identifying and addressing network transmissions. CI transceivers are adapted to perform network-control functions. CI coding facilitates routing in ad-hoc and peer-to-peer networks. Networks are adapted to perform array processing with signals received from, and transmitted by, groups of subscriber units. Other applications and embodiments of the invention are apparent from the description of preferred embodiments and the claims that follow.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A illustrates a plurality of CI carriers having phase fronts that are aligned at a specific time. The CI carriers combine to generate a plurality of superposition signals that are orthogonal to each other in time.

FIG. **1**B illustrates an in-phase superposition of CI carriers of a carrier set that produces a superposition signal corresponding to a sum of the superposition signals shown in FIG. **1**A

FIG. **1**C illustrates two sets of orthogonal superposition signals. The signals in each set are orthogonal to each other. The signals in a first set are substantially orthogonal to signals in a second set.

FIG. **1**D shows a summation of two orthogonal sets of CI signals wherein signals in a first set are quasi-orthogonal to signals in a second set.

FIG. **2**A illustrates phase relationships between two orthogonal sinusoidal waveforms that demonstrate a mathematical basis of CI processing.

FIG. **2**B illustrates relationships between two orthogonal sinusoidal waveforms.

FIG. **3**A illustrates a phase offset of adjacent samples shown in FIG. **2**A.

FIG. **3**B illustrates a phase offset of adjacent samples shown in FIG. **2**B.

FIG. **4**A shows samples distributed uniformly around a unit circle in the complex plane.

FIG. **4**B shows samples distributed uniformly around a unit circle in the complex plane.

FIG. **4**C is a normalized complex-plane representation of samples of a signal having a particular frequency collected at a sampling rate that equals, or is some sub-harmonic frequency of, the signal frequency. Each sample corresponds to an integer number of full rotations in the complex plane.

FIG. **5**A shows a set of 16 octonary CI code vectors of length **8**.

FIG. **5**B shows correlations of the 16 octonary codes shown in FIG. **5**A.

FIG. **6**A illustrates basic components of a CI-code generator.

FIG. **6**B illustrates basic components of a CI transmitter.

FIG. **6**C illustrates basic components of a CI decoder.

FIG. **7** illustrates the relationship between basic CI symbol values w_n and data symbols s_n processed with CI code chips to produce the CI symbol values w_n.

FIG. **8**A illustrates basic components of a CI coding system and a CI decoding system.

FIG. **8**B shows a system diagram of a CI transceiver.

FIG. **9**A illustrates a tree network that may be implemented in some aspects of the present invention.

FIG. **9**B illustrates a network design that permits a plurality of communication paths to each node.

FIG. **9**C illustrates a network design adapted to provide array processing performance advantages.

FIG. **9**D illustrates a concentric ring network configuration.

FIG. **9**E illustrates a network configuration adapted to the geographic distribution of a plurality of subscribers located along a roadway.

FIG. **9**F illustrates a plurality of nodes adapted to route CI code-addressed signals.

FIG. **9**G illustrates a simple tree-style CI-based network of the present invention.

FIG. **9**H illustrates a simple CI-based network wherein each node can be reached by a plurality of paths.

FIG. **9**I illustrates a network characterized by two communication paths to a common destination node.

FIG. **9**J illustrates a network having a plurality of crossing communication paths.

FIG. **10**A illustrates a multi-level cellular architecture that may be employed by systems and methods of the present invention.

FIG. **10**B illustrates three adjacent cells in a cellular network of the present invention.

FIG. **10**C shows a cellular architecture of the present invention that includes a plurality of cells and a plurality of base stations located on cell boundaries.

FIG. **10**D illustrates a cellular network of the invention including a plurality of cells, a plurality of base stations, and a plurality of subscriber units.

FIG. **11**A illustrates a CI transceiver adapted to perform routing.

FIG. **11**B illustrates an alternative embodiment of a CI transceiver adapted to perform routing.

FIG. **11**C illustrates an alternative embodiment of a CI transceiver adapted to perform routing.

FIG. **11**D illustrates a method in which a transceiver in a network is provided with control information that includes information used to generate one or more array-processing weights.

FIG. **11**E illustrates a method in which an individual network transceiver is adapted to perform array processing relative to local conditions. The transceiver can be adapted to optimize transmit/receive operations relative to signal quality measured at the transceiver.

FIG. **11**F illustrates an array-processing method that employs at least one central processor to provide beamforming operations across a plurality of spatially distributed network transceivers. The central processor may direct the network transceivers to apply weights to transmitted and/or received signals. Alternatively, the central processor may perform array processing by providing weights to signals it transmits to, and receives from, network transceivers. The central processor may be adapted to perform various combining operations, including CI combining.

FIG. **12**A illustrates a method for providing CI-coded transmissions of information and control signals.

FIG. **12**B illustrates a method for managing network control in a CI network by one or more subscriber units adapted to function as base stations.

FIG. **12**C illustrates a network-control method of the present invention.

FIG. **12**D shows a routing method of the present invention.

FIG. **13**A shows a relay method of the present invention.

FIG. **13**B illustrates an alternative embodiment of a relay method of the invention.

FIG. **13**C illustrates a transceiver processing and routing method of the invention.

FIG. **13**D illustrates an alternative transceiver processing and routing method of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The description of the preferred embodiments assumes that the reader has a familiarity with CI described in the following publications, which are incorporated by reference:

1. B. Natarajan, C. R. Nassar, S. Shattil, M. Michelini, "Application of interferometry to MC-CDMA", accepted for publication in IEEE Transactions on Vehicular Technology.
2. C. R Nassar, B. Natarajan, and S. Shattil, "Introduction of carrier interference to spread spectrum multiple access," IEEE Emerging Technologies Symposium, Dallas, Tex., 12-13 Apr. 1999.
3. B. Natarajan and C. R. Nassar, "Introducing novel FDD and FDM in MC-CDMA to enhance performance," IEEE Radio and Wireless Conference, Denver, Colo., Sep. 10-13, 2000, pp. 29-32.
4. Z. Wu, C. R. Nassar, A. Alagar, and S. Shattil, "Wireless communication system architecture and physical layer design for airport surface management," 2000 IEEE Vehicular Technology Conference, Boston, Mass., Sep. 24-28, 2000, pp. 1950-1955.
5. S. Shattil, A. Alagar, Z. Wu and C. R. Nassar, "Wireless communication system design for airport surface management—Part I: Airport ramp measurements at 5.8 GHz," 2000 IEEE International Conference on Communications, Jun. 18-22, 2000, New Orleans, pp. 1552-1556.
6. B. Natarajan, C. R. Nassar, and S. Shattil, "Carrier Interferometry TDMA for future generation wireless—Part I: Performance," accepted for publication in IEEE Communications Letters.
7. Z. Wu, C. R. Nassar, and S. Shattil, "Capacity enhanced DS-CDMA via carrier interferometry chip shaping," IEEE 3G Wireless Symposium, May 30-Jun. 2, 2001, San Francisco, Calif.
8. Z. Wu, C. R. Nassar, and S. Shattil, "Frequency diversity performance enhancement in DS-CDMA via carrier interference pulse shaping," The 13th Annual International Conference on Wireless Communications, Calgary, Alberta, Canada, Jul. 7-10, 2001.
9. C. R. Nassar and Z. Wu, "High performance broadband DS-CDMA via carrier interferometry chip shaping," 2000 International Symposium on Advanced Radio Technologies, Boulder, Colo., Sep. 6-8, 2000, proceeding available online at http://ntai.its.bldrdoc.gov/meetings/art/index.html.
10. Z. Wu and C. R. Nassar, "MMSE frequency combining for CI/DS-CDMA," IEEE Radio and Wireless Conference, Denver, Colo., Sep. 10-13, 2000, pp. 103-106.
11. D. Wiegand, C. R. Nassar, and S. Shattil, "High Performance OFDM for next generation wireless via the application of carrier interferometry," IEEE 3G Wireless Symposium, May 30-Jun. 2, 2001, San Francisco, Calif.
12. B. Natarajan, C. R. Nassar, and S. Shattil, "Exploiting frequency diversity in TDMA through carrier interferometry," Wireless 2000: The 12th Annual International Conference on Wireless Communications, Calgary, Alberta, Canada, Jul. 10-12, 2000, pp. 469-476.
13. B. Natarajan, C. R. Nassar, and S. Shattil, "Throughput enhancement in TDMA through carrier interferometry pulse shaping," 2000 IEEE Vehicular Technology Conference, Boston, Mass., Sep. 24-28, 2000, pp. 1799-1803.
14. S. A. Zekevat, C. R. Nassar, and S. Shattil, "Smart antenna spatial sweeping for combined directionality and transmit diversity," accepted for publication in Journal of Communication Networks: Special Issue on Adaptive Antennas for Wireless Communications.
15. S. A. Zekevat, C. R. Nassar, and S. Shattil, "Combined directionality and transmit diversity via smart antenna spatial sweeping," 38th Annual Allerton Conference on Communications, Control, and Computing, Champaign-Urbana, Ill., Oct. 4-6, 2000.
16. S. Shattil and C. R. Nassar, "Array Control Systems For Multicarrier Protocols Using a Frequency-Shifted Feedback Cavity" IEEE Radio and Wireless Conference, Denver, Colo., Aug. 1-4, 1999.
17. C. R. Nassar, et. al., MultiCarrier Technologies for Next Generation Multiple Access, Kluwer Academic Publishers: 2001.

Applications of CI, array processing, spatial interferometry, and related systems and methods are cited in the following patents and patent applications, which are hereby incorporated by reference:

1. U.S. Pat. No. 5,955,992
2. U.S. Pat. No. 6,008,760
3. U.S. Pat. No. 6,211,671
4. U.S. Pat. No. 6,331,837
5. U.S. Pat. No. 6,348,791
6. PCT Appl. No. PCT/US99/02838
7. PCT Appl. No. PCT/US00/18113
8. U.S. patent application Ser. No. 09/347,182
9. U.S. patent application Ser. No. 09/472,300
10. U.S. patent application Ser. No. 09/433,196
11. U.S. patent application Ser. No. 09/393,431
12. U.S. patent application Ser. No. 09/718,851
13. U.S. patent application Ser. No. 09/703,202
14. U.S. patent application Ser. No. 10/034,386
15. U.S. patent application Ser. No. 10/078,774
16. U.S. patent application Ser. No. 10/131,163
17. U.S. Provisional Pat. Appl. No. 60/163,141
18. U.S. Provisional Pat. Appl. No. 60/219,482
19. U.S. provisional Pat. Appl. No. 60/259,433
20. U.S. provisional Pat. Appl. No. 60/286,850

1. Definitions

Various terms used in the descriptions of CI methods and systems are generally described in this section. The descriptions in this section are provided for illustrative purposes only, and are not limiting. The meaning of these terms will be apparent to persons skilled in the relevant art(s) based on the entirety of the teachings provided herein. These terms may be discussed throughout the specification and the cited references with additional detail.

An address, or network address, as used herein, describes any set of symbols used to identify a particular network node

or transceiver. An address may include symbols in a header or other part of a data transmission. An address may correspond to a code used to encode a transmission. In some applications of the invention, an address may specify one or more routes through a network. For example, multiple addresses may indicate one or more preferred paths through the network. Alternatively, a message address may be constructed via some mathematical relationship of node addresses that indicate one or more paths to at least one destination node. In some aspects of the invention, the message address may be changed as the message propagates through the network.

The term carrier signal, or carrier, when used herein, refers to at least one electromagnetic wave having at least one characteristic that may be varied by modulation. Subcarriers may be referred to as carriers. Other wave phenomena, such as acoustic waves, may be used as carriers. Carrier signals may include any type of periodic signal. Carrier signals may include sinusoids, square waves, triangle waves, wavelets, and/or arbitrary waveforms. A carrier signal is capable of carrying information via modulation. A carrier signal may be modulated or unmodulated. Multicarrier signals may include multi-frequency signals, multi-spatial signals, multi-directional signals, multi-polarization signals, multiple coded signals, multiple sub-space signals, multi-phase-space signals, time-domain (discreet-time) signals, and/or any other set of electromagnetic signals having different orthogonal or quasi-orthogonal values of at least one diversity parameter. A code sequence can be regarded as a carrier signal. A subcarrier may include more than one signal and more than one type of signal.

Channel compensation describes signal processing performed on at least one transmitted and/or received signal according to measured and/or calculated channel fluctuations. Channel compensation may include any of various blind adaptive techniques. Alternatively, channel compensation may employ at least one pilot or training signal to probe the channel. Known signals can be used to compensate for various multipath effects (such as fading and/or inter-symbol interference), mitigate multi-user interference, and/or remove jamming signals. Channel compensation may employ a combination of adaptive and reference-signal processing. Channel compensation may include adaptive channel equalization. Channel compensation in a CI and/or antenna-array system may employ some type of combining.

Channel estimation describes any combination of blind adaptive techniques and reference-signal processing to determine signal distortion resulting from the effects of at least one communication channel. In one example, a pilot symbol is transmitted periodically from a remote transmitter. A local receiver exploits the known transmission time, frequency, polarization, and/or any other diversity-parameter value of at least one pilot symbol to process the transmitted pilot symbol and estimate the distortion caused by the channel environment. On the basis of an estimated value, distortion in the received data symbols is compensated. In some aspects of the invention, a pilot tone may be employed.

CI codes, as used herein, may include basic CI codes or advanced CI codes. CI codes are based on mathematical relationships between CI carriers and phase spaces. CI codes can be used as direct-sequence codes, multicarrier codes (e.g., MC-CDMA), etc. Applications of CI codes can be extended to any application of conventional binary direct sequences, including but not limited to, spread spectrum, multiple access, channel coding, encryption, anti-jamming, etc. CI codes may be applied across any set of orthogonal or quasi-orthogonal diversity-parameter values or subspaces. Although CI codes can be represented with respect to phase relationships generated by vector precession in the complex plane, the implementation of CI coding can be extended to circular, elliptical, and linear polarizations.

A coder, as used herein, describes any system, device, or algorithm adapted to generate spread-spectrum codes, multiple-access codes, channel codes, encryption codes, multilevel codes, compression codes, hybrid codes, and CI codes. A coder may interleave coded data symbols in one or more diversity-parameter spaces. The coder may provide channel coding to the data symbols. A CI coder, includes any algorithm, device, or system adapted to combine, merge, or otherwise impress at least one data symbol onto a plurality of CI code chips or carriers. The CI encoder may impress each CI code chip onto one or more diversity-parameter values prior to, or after, impressing data symbols onto the CI code. A CI code may be impressed onto at least one intermediate-frequency (IF) carrier. The CI encoder may perform multiplexing. For example, the CI encoder may encode data streams onto different CI codes. The CI encoder may employ other diversity parameters on which to multiplex multiple data streams.

A combiner, as used herein, describes any system, device, and/or algorithm adapted to combine a plurality of signals, samples, or symbol values. A combiner may combine multiple carriers or signal values to generate a superposition signal. A combiner may provide weights to carriers or signal values to generate one or more superposition signals having predetermined characteristics, such as time domain, frequency domain, spatial domain, sub-space domain, and/or other physical characteristics. A combiner may compensate for noise, interference, and/or distortion.

Combining often involves generating weights based on channel estimates. The weights may be adapted relative to some performance measurement, such as probability of error, bit-error rate (BER), signal-to-noise ratio (SNR), signal-to-noise-plus-interference ratio (SNIR), and/or any other signal-quality parameter. Possible combining techniques include equal-gain combining (EGC), orthogonal restoring combining (ORC), and minimum mean squared error combining (MMSEC). Performance measurements may include any combination of instantaneous and averaged performance measurements. Averaging may be performed over one or more diversity parameters.

A combiner may perform combining in more than one diversity-parameter space. For example, MMSE combining may be performed in the frequency domain to generate a plurality of combined signals that may be processed via EGC in the time domain. Other types of combining, as well as combining in different dimensions, may be performed. Combining may also be performed as a receive-side array-processing technique. Array processing (e.g., spatial combining) may be integrated into other combining operations, such as CI subcarrier combining.

A communication channel, as described herein, typically comprises an RF channel. A communication channel may include any propagation medium and/or path between at least one transmitter and at least one receiver. A communication channel may be natural and/or man-made, including, but not limited to, air, space, wire, cable, waveguide, microstrip, strip-line, optical fiber, and liquid.

A control channel is a communication channel in which control information is transmitted.

Control information, as used herein, includes any information used to set, monitor, identify, adapt, or change communications and/or transceiver operations in a network.

Control information may be provided for power control, synchronization, routing, channel assignments, code assignments, addressing, identification, acknowledgment, transfer of network control, etc. Control information may include pilot signals, training symbols, addresses, tags, codes, parity symbols, reference (e.g., timing, phase, power, frequency) signals, and/or transceiver-control signals.

A decoder, as used herein, describes any system, device, or algorithm capable of decoding an encoded information (e.g., data) signal. A decoder typically decodes an encoded signal with respect to one or more reference signals (e.g., codes, decode sequences, code keys, etc.). Decoding may take the form of a correlation process, matched filtering, or any kind of processing (e.g., complementary processing) that extracts at least one desired information signal from the coded signal. In a preferred embodiment, collected samples are phase shifted with respect to at least one code prior to being summed. In some multicarrier systems, it is impractical to perform matched filtering or correlation. Rather, data symbols are obtained from the output bins of a Fourier transform process. Similarly, other types of transforms or inverse transforms may be performed in a decoder.

A destination node, as used herein, describes a network transceiver selected to receive at least one communication signal. A destination node may describe a local destination node within a particular network. Alternatively, a destination node may describe the final destination(s) of at least one particular transmission.

The term diversity-parameter, as used herein, describes at least one signal characteristic that enables a signal to be distinguished from another signal. Examples of diversity parameters include, but are not limited to, amplitude, spatial gain distribution, directionality, energy, power, linear polarization direction, circular/elliptical polarization direction, circular/elliptical polarization rotation rate, mode, frequency, time, code, phase, coherence length, and phase space. Diversity parameters may include proportions of two or more diversity-parameter values. Diversity parameters may include any combination of unique signal characteristics. Diversity parameters may include diversity-parameter subspaces, such as spatial sub-spaces. A common diversity parameter, as used herein, is a range of at least one diversity-parameter value into which electromagnetic signals may be mapped.

Duplexing, as used herein, describes any processing technique adapted to separate transmitted and received signals. Various multiple-access techniques may be adapted to perform duplexing. Time-division duplexing (TDD) may be provided with respect to orthogonal time-domain slots. In CI-based protocols, TDD may be provided with respect to time-domain characteristics of multicarrier superposition signals and/or time-offset coding applied to CI. Frequency-division duplexing (FDD) provides for separation of signals characterized by different frequency bands. The multicarrier structure of CI enables FDD. Even spread-spectrum protocols, such as DS-CDMA, may benefit from CI-enabled FDD without the reduced frequency-diversity benefits inherent in conventional FDD. Code division duplexing (CDD) may be provided.

CI phase-division duplexing (CI-PDD) describes the separation of multicarrier signals having different phase spaces. Transmitted and received CI signals may be separated due to the orthogonality (or quasi-orthogonality) of the phase spaces. One application of CI-PDD involves applying a matched filter to desired received components to remove the effects of transmitted signals (as well as undesired received signals). Cancellation may be used to electromagnetically isolate receivers from transmitters that use the same time and frequency bands for transmission. Some of these cancellation techniques are described in U.S. Pat. No. 6,348,791, which is incorporated by reference. Polarization division duplexing includes orthogonal polarization duplexing (OPDD) and quasi-orthogonal polarization duplexing (QPDD). OPDD is a well-known method of using orthogonal polarizations to double channel capacity. For example, linear polarized antennas may be oriented perpendicular to each other to provide isolation. OPDD involves using known ratios of co-channel interference to cancel the interfering signals. Circular polarization duplexing (CPD) may employ opposite polarization spins. CPD may employ orthogonal polarization frequencies. OPDD, QPDD, and CPD may employ three-dimensional (i.e., x-y-z axis) polarizations

Coherence time division duplexing (CTDD) may be used to remove interfering signals having different time offsets. In CTDD, an information signal modulated onto a wideband signal is transmitted along with a decode signal. A predetermined time offset between the modulated and decode signals allows a receiver to extract the information signal without any knowledge of the wideband signal. In CI-based signals, a time offset corresponds to a vector of phase offsets corresponding to the CI sub-carriers. Wideband signals, such as additive white Gaussian noise, chaotic signals, pseudo-random signals, etc., may be provided (or closely approximated) by a predetermined weighted set of CI sub-carriers. Orthogonal CTDD pertains to time-offset differences between transmitted and received signals that exceed the inverse of the coherence bandwidth of the signals. Quasi-orthogonal CTDD occurs when the time-offset differences between desired receive signals and interfering transmissions do not exceed the inverse coherence bandwidth of the signals. This causes overlap interference in the matched-filter output. The overlap interference may be removed via cancellation.

An information signal, as used herein, describes one or more signals that convey some form of useful information via magnitude, phase, frequency, polarization, mode, direction, and/or some signal property derived therefrom. CI-based information signals may include any type of communication signal, such as, but not limited to, voice, data, and text. Information signals may include any of various types of remote-sensing signals, such as radar signals, Lidar signals, spectroscopy signals of various types (e.g., absorption, scatter, luminescence, resonant, emission, harmonic, intermodulation, etc.), probing signals, and imaging signals (e.g., X-ray, gamma-ray, ultrasound, seismic survey, acoustic, sonar, optical, pulse radio, spread spectrum, etc.). Any information signal may be considered to be a CI-based signal if it is processed via CI signal-processing techniques. Thus, a received non-CI signal may be converted into a CI signal by decomposing the received signal into orthogonal sub-carrier components.

The term modulation, as used herein, refers to any method of impressing a signal (such as an information signal, a code signal, and/or a sub-carrier) onto an electromagnetic signal. Modulation describes the adjustment of one or more physical signal characteristics with respect to an information signal. Modulation may be combined with spreading. Signals, such as analog and/or digital information signals, may be impressed onto one or more carrier signals via any combination of modulation techniques, including, but not limited to, amplitude modulation, phase modulation, frequency modulation, pulse modulation, and/or polarization modulation. Pulse modulation (such as CI-pulse modula-

tion) may include Pulse-Amplitude Modulation (PAM), pulse-code modulation, pulse-frequency modulation, pulse-position modulation, and/or pulse-width modulation.

CI signal generation sometimes includes modulation, PAM, Frequency Shift Keying (FSK), Phase Shift Keying (PSK), and Quadrature Amplitude Modulation (QAM). Coded modulation, such as trellis-code modulation, may be performed. Data symbols may be modulated onto a code sequence, such as a multiple-access code, a spreading code, an encryption code, a channel code, etc. A code sequence may include digital and/or analog signals. Examples of code sequences include direct-sequence codes, MC-CDMA codes, CI codes, CI/DS-CDMA codes, frequency-hopping codes, chirp codes, coherence-multiplexing codes, sub-channel codes, and code length division multiplexing codes. Some types of modulation can include the formation of code-chip values, continuous-code values, and/or code-chip sequences based on data-symbol values. Data symbols may be input to a code-generation process.

A network control station (also referred to as a base station) is any network transceiver adapted to perform network control operations, such as communication control, power control, synchronization, assignment of operating parameters to other network transceivers, spectrum management, load balancing, network configuration, code assignment, channel selection, performance monitoring, performance optimization, routing, authentication, verification, channel estimation, etc.

A network transceiver is any transceiver adapted to operate in a network. A network transceiver may include a base station, access point, relay, router, and/or subscriber unit.

A receiver, as used herein, includes any system, device, or process that employs any combination of detection and estimation. Detection is the task of determining if a predetermined signal is present in an observation. Estimation is the task of obtaining or determining values of one or more signal parameters. A receiver may perform various signal-processing operations, including, but not limited to, filtering, channel selection, A/D conversion, AGC, timing recovery, carrier acquisition, carrier recovery, bandwidth adjustment, sample-rate adjustment, matched filtering, soft-decision quantization, array processing, error detection, error correction, amplification, decoding, DC-signal removal, equalization, combining, spectral shaping, noise-bandwidth control, spectral translation, amplifier linearization, de-interleaving, in-phase/quadrature-phase gain and phase balancing, etc.

An RF front end describes any device or system adapted to convert baseband or IF signals to RF for transmission. An RF front end may be adapted to receive and convert RF signals to baseband or IF. An RF front end may be adapted to perform RF, IF, and/or baseband signal processing to prepare a received RF signal for IF or baseband processing. Similarly, RF, IF, and/or baseband processing may be provided to prepare a baseband or IF signal for coupling into an RF communication channel. An RF front end may perform array processing.

A source node is a transceiver in a network from which a transmission originates. A source node may be defined relative to a given network. For example, although a base station may receive a transmission and retransmit the information into a given network, the base station may be regarded as the source node relative to the given network. Alternatively, the source of the information may be identified as the source node.

A subscriber, or subscriber unit, as used herein, is a transceiver that is capable of acting as an information source and/or an information sink in a network. A subscriber is typically provided with communication services from at least one network. A subscriber typically communicates communication information with other subscribers. However, this communication information may be routed through other subscribers or non-subscriber devices. Thus, a subscriber is typically provided with at least one communication link to at least one other transceiver, such as a base station, access point, relay, router, and/or another subscriber.

A subspace, as used herein, describes a signal space that can include a plurality of signals having at least one common diversity parameter value (or range of values) and, preferably, is characterized by some means to separate at least one of the signals from at least one other of the signals. For example, each of a plurality of signals sharing the same frequency band, but transmitted by a different transmitter element characterized by some unique physical property (i.e., diversity-parameter value), may be characterized as a sub-space signal. Preferably, a plurality of receiving antennas are adapted to produce a plurality of algebraically unique combinations of the transmitted signals. Accordingly, algorithms and/or processors are provided to separate at least one desired signal from at least one interfering signal.

A transmitter, as used herein, includes any system, device, or process adapted to couple one or more signals into at least one communication channel. A transmitter may perform one or more signal-processing operations to prepare the signal for propagation in a channel. For example, transmitter-side signal processing may include D/A conversion, frequency up-conversion, filtering, spreading, predistortion, and/or array processing.

A CI transmitter may be implemented via any of many different techniques. The present invention anticipates design variations of CI-based transmitters. A CI/DS-CDMA transmitter, as well as any other CI transmitter, is characterized by the signals generated. In particular, a CI/DS-CDMA transmitter is any device, system, or algorithm capable of impressing information onto a plurality of carriers and adjusting (e.g., weighting) the carriers to provide a superposition signal having predetermined time-domain characteristics. Such time-domain characteristics may include a signal resembling a direct-sequence code.

An unlicensed frequency band refers to any frequency band that is allocated for unlicensed use by the Federal Communications Commission or an equivalent national or international regulatory organization. For example, unlicensed frequency bands for wireless LAN are specified in the IEEE 802.11 standards.

2. Introduction to Carrier Interferometry

Various aspects of the present invention are based on CI. Other aspects of the invention are particularly applicable to CI methods and systems. There are too many variations, permutations, and specific implementations of CI to describe in this introduction. Accordingly, the descriptions and examples of CI described herein are not intended to limit the scope of how CI is defined, but rather to illustrate a few of the many ways that the present invention may be implemented. Descriptions of CI are also intended to clarify some of the aspects and embodiments of the present invention.

Inter-symbol interference occurs when a reflected signal travels a distance sufficiently greater than the distance traversed by a line-of-sight signal so as to cause a delay greater than the duration of a data symbol. CI avoids inter-symbol interference by transmitting data symbols on narrowband carriers. Multipath fading occurs when a narrowband signal

traverses two paths having a half-cycle phase difference. CI avoids the problem of multipath fading by transmitting each data symbol on multiple carriers that are adequately separated with respect to frequency or some other diversity parameter. Redundant modulation typically reduces bandwidth efficiency. CI avoids the problem of reduced bandwidth efficiency by modulating up to 2N data symbols on each of N carriers. Increased interference on one or more carriers typically increases probability of error. CI avoids the problem of increased interference and probability of error by exploiting interferometry to orthogonalize data symbols modulated on the same carriers. Thus, CI achieves higher throughput with better signal quality than any other multiple-access protocol.

FIG. **1**A illustrates a basic form of CI in which a plurality of CI carrier sets **105**A, **105**B, and **105**C each have phase fronts aligned at a specific time t_1, t_2, and t_3, respectively. A plurality of superposition signals **110**A, **110**B, and **110**C result from a summation of each carrier set **105**A, **105**B, and **105**C, respectively. The superposition signal **110**A illustrates a pulse envelope centered at time t_1. All of the carriers **105**A are in-phase at time t_1 and thus, combine constructively. The superposition signal **110**A has a maximum magnitude at time t_1. At other times (e.g., times t_2 and t_3), the carriers in carrier set **105**A combine destructively, resulting in low or undetectable signal levels.

In CI, the individual signal components **105**A, **105**B, and **105**C contributing to a CI pulse **110**A, **110**B, and **110**C, respectively, or information symbol s_n have an extended duration T_s relative to the pulse width T_{pulse}. The extended symbol duration T_s (i.e., the duration of component waveforms corresponding to a symbol s_n) reduces spectral sidelobes associated with the transmitted information symbol s_n. The extended waveform shape can be overlapped with extended waveforms associated with other symbols $s_{n'}$ ($n' \neq n$). Naturally, interference will occur between the waveforms associated with different data symbols. However, CI coding can be employed to provide orthogonality (or quasi-orthogonality) between the composite waveforms (i.e., the data symbols s_n).

Although multicarrier-based CI signals (such as signals **110**A, **110**B, and **110**C) can resemble sin c-shaped pulses, which are orthogonalized by time-domain pulse positioning, it is important to note that multicarrier-based CI signals are composed of multicarrier (e.g., multi-frequency) components and are typically processed (e.g., generated and/or decomposed) in the frequency domain.

The signal **110**A results from an addition of N carriers that have a uniform frequency separation f_s. FIG. **1**A illustrates a simple case of rectangular (i.e., non-tapered) windowing of the carrier amplitudes. The CI carriers are uniformly spaced in frequency $f_n=f_o+nf_s$, where f_o is some zero or non-zero offset frequency, f_s is a non-zero shift frequency, and n is some integer or set of integers. A superposition CI signal, such as signal **110**A, is expressed by:

$$e(t)=\sum_{n=1}^{N} e^{t[(\omega_c+n\omega_s)t+n\Delta\phi]},$$

and has a magnitude of:

$$|e(t)|=\left|\frac{\sin(N(\omega_s t+\Delta\phi)/2)}{\sin((\omega_s t+\Delta\phi)/2)}\right|.$$

The CI signals are periodic with period $1/f_s$ for an odd number of carriers N and with period $2/f_s$ for an even number of carriers N. The main lobe has a duration $2/Nf_s$ and each of the N−2 side lobes has a duration $1/Nf_s$. The amplitude A(l) of the lth side lobe with respect to the main lobe amplitude is:

$$A(l)=\frac{1}{N\sin(\pi(l+1/2)/N)}$$

Applying a phase shift of $n\Delta\phi_k$ to each nth carrier shifts the CI envelope in time by $\Delta t=\Delta\phi_k/2\pi f_s$. Therefore, N signals can be positioned orthogonally in time. The phase shifts can provide necessary phase relationships to create the desired timing of the information signal received by at least one receiver (not shown).

The cross correlation between users is:

$$R_{cc}(\tau)=\frac{1}{2f_s}\frac{\sin(N2\pi f_s\tau/2)}{\sin(2\pi f_s\tau/2)}\cos((N-1)2\pi f_s\tau/2),$$

where τ is the time shift between envelopes. Zeros occur at: k/Nf_s, k=1, 2, . . . , N−1 and at $(2k-1)/2(N-1)f_s$, k=1, 2, . . . , N−1. CI can support N orthogonal users (or channels). If additional users or signals need to be accommodated, CI provides N−1 additional positions to place signals.

A CI signal centered at time τ is orthogonal to the CI signal centered at time t_1 whenever the difference between τ and t_1 is $\Delta t=k/Nf_s$, k=1, 2, . . . , N−1. This enables CI waveforms to represent information symbols located sequentially in time without creating inter-symbol interference. The superposition signal **110**D shown in FIG. **1**B represents a sum of the orthogonally positioned superposition signals **110**A, **110**B, and **110**C.

An offset in the time domain corresponds to linearly increasing phase offsets in the frequency domain. A CI signal with a time offset $\tau=k/Nf_s$ is equivalent to a CI carrier set with carriers 1 to N having phase offsets:

$$\{\phi_1,\phi_2,\ldots,\phi_N\}=\{0,2\pi k/N,2\cdot 2\pi k/N,\ldots,(N-1)\cdot 2\pi k/N\}.$$

Orthogonality between CI signals can be understood as an appropriate time separation $\tau\in\{k/f_s, k=1, 2, \ldots, N-1\}$ between superposition signals, or as carriers of each carrier set coded with a different polyphase spreading sequence:

$$f(\phi)\{e^{j\theta 1},e^{j\theta 2},\ldots,e^{j\theta N}\}=\{e^{j0},e^{j2\pi k/N},\ldots,e^{j(N-1)\cdot 2\pi k/N}\}$$

with respect to values of k=0, 1, . . . , N−1.

A set of quasi-orthogonal signals can be determined from non-orthogonal time offsets that minimize the mean-squared value of the interference between the quasi-orthogonal signals. This criteria is satisfied by multiples of a time-offset value $\Delta t=1/(2Nf_s)$. FIG. **1**C shows a first set of N orthogonal signals **110**D represented in time by:

$$\{t_1,t_2,\ldots,t_{N-1}\}=\{1/f_s,2/f_s,\ldots,(N-1)/f_s\}.$$

A second set of N orthogonal signals **110**D' is represented in time by:

$$\{t_1,t_2,\ldots,t_{N-1}\}=\{1/f_s,2/f_s,\ldots,(N-1)//f_s\}.$$

The first set of signals **110**D is quasi-orthogonal to the second set **110**D' and results in a minimal amount of interference, as shown in FIG. **1**D.

This result can also be expressed in terms of carrier phase offsets using the equivalence between shifts in the time domain and phase offsets in the frequency domain. A first set of N orthogonal signals is represented in phase by N complex spreading codes:

$$f_1(\phi)\{e^{j\theta 1}, e^{j\theta 2}, \ldots, e^{j\theta N}\}=\{e^{j0}, e^{j2\pi k/N}, \ldots, e^{j(N-1)\cdot 2\pi k/N}\}$$

A second set of N orthogonal signals is represented in phase by N complex spreading codes:

$$f_2(\phi)\{e^{j\theta' 1}, e^{j\theta' 2}, \ldots, e^{j\theta' N}\}=\{e^{j(0+\Delta\phi)}, e^{j(2\pi k/N+\Delta\phi)}, \ldots, e^{j((N-1)\cdot 2\pi k/N+\Delta\phi)}\}$$

where $\Delta\phi=\pi/N$.

The superposition signal **110**D in FIG. **1**B can be thought of as a superposition of complex-weighted carriers in a carrier set **105**D or a sum of the superposition signals **110**A, **110**B, and **110**C. The carrier set **105**D represents a sum of the carrier sets **105**A, **105**B, and **105**C. The complex amplitudes of carrier set **105**D can be characterized by a complex-weight vector $w=[w_1, w_2, \ldots, w_N]$. Each value w_n of the weight vector w corresponds to a particular carrier frequency f_n. The values w_n can be derived from a complex addition of carriers in the carrier sets **105**A, **105**B, and **105**C. The values w_n can be derived from summing complex numbers representing the magnitude and phase of each carrier in the carrier sets **105**A, **105**B, and **105**C.

CI signals demonstrate both excellent frequency resolution and excellent time resolution. A CI signal is composed of multiple narrowband carriers that allow it to be resolved into its frequency components. When observed in the time domain, a basic CI signal is very narrow, enabling it to be easily separated from other CI signals and to resolve the channel's multipath profiles.

Because the period and width of the pulse envelope depends on the amplitudes, relative phases, and frequency separation of the CI carriers, the frequency of each carrier may be changed without affecting the pulse envelope as long as the amplitudes, relative phases, and frequency separation are preserved. Thus, frequency hopping and frequency shifting of the carriers does not affect the temporal characteristics of the superposition signal, such as superposition signal **110**A. Tapering the amplitude distribution of the CI carriers broadens the main-lobe width and reduces the amplitude of the side lobes.

A CI signal has a number of carrier signals that may each have a bandwidth that is less than the coherence bandwidth of the communication channel. The coherence bandwidth is the bandwidth limit in which correlated fading occurs. The total bandwidth of the CI signal preferably exceeds the coherence bandwidth.

CI carriers corresponding to any particular user, channel, or data symbol may be spaced in frequency by large amounts to achieve a large system bandwidth relative to the coherence bandwidth. In this case, CI uses frequency to achieve uncorrelated fading. However, any diversity parameter or combination of diversity parameters may be used to achieve uncorrelated fading over the system bandwidth, or even between individual carriers.

The system bandwidth of a group of CI carriers may be selected relative to the coherence bandwidth of one or more subchannels, such as spatial sub-channels. Carriers that are closely spaced in frequency may have uncorrelated fading if they are transmitted from different locations or have different degrees of directivity. CI carriers transmitted from different locations may have different fades over each spatial sub-channel and therefore, can benefit from diversity combining at a receiver (not shown).

Phase shifts applied to an nth carrier to separate a kth channel from adjacent channels are given by:

$$\phi_{kn}=\pi k n f_s(\Delta t)+\phi^0_{kn}=\pi kn/N+\phi^0_{kn}$$

where ϕ^0_{kn} is an initial phase-offset corresponding to the nth carrier and the kth channel. The values of Δt depend on whether the channel spacing is orthogonal or quasi-orthogonal.

Although FIG. **1**A and FIG. **1**B illustrate an in-phase superposition of carrier signals, this example can be extended to other superpositions of CI. For example, the time offset Δt (and the corresponding carrier phase shifts ϕ_{kn}) for adjacent channels may be applied to CI implementations that do not have in-phase superpositions. The time offsets Δt (and thus, the phase shifts ϕ_{kn}) derived in this case are also relevant to CI implementations that process the received carriers separately. When each carrier is processed separately, phase-offset coding (in addition to the phase offsets ϕ_k, used to separate channels) may be used to reduce or minimize the peak of the superposition signal.

The carrier sets **105**A, **105**B, and **105**C have phase offsets corresponding to a pulse-width duration. However, any type of orthogonal (e.g., non-overlapping) or quasi-orthogonal (e.g., overlapping) spacing may be provided. Carrier sets having quasi-orthogonal (or non-orthogonal) spacing may be processed with multi-user (or multi-channel) detection techniques or with any other type of interference-suppression technique.

FIG. **1**A and FIG. **1**B illustrate several levels of signal decomposition that reduce a complex time-domain signal into simple components. The time-domain pulses may be scaled and positioned to produce a predetermined time-domain signal indicative of an information signal, coding, and at least one transmission protocol. Multiple frequency components may be weighted to produce an information signal having predetermined time-domain characteristics. Similarly, multiple frequency components that comprise the pulses may be selected and weighted to impart predetermined characteristics to the pulses. The scale of the components selected for signal processing can be selected to provide a desired granularity for the information architecture.

Modulation of the pulses, the carriers, or both may be performed over the duration of the signals shown in FIG. **1**A and FIG. **1**B. Carrier modulation may be performed over a pulse-repetition period, a pulse duration, or any multiple or fraction of either. In some cases, guard intervals, guard bands, and/or cyclic prefixes may be provided to CI signals.

3. CI Codes

CI codes, as used herein, may include basic CI codes or advanced CI codes. CI codes are based on phase relationships between orthogonal carriers, such as illustrated by samples **220** to **225** shown in FIG. **2**A.

Basic CI codes of the present invention can be derived from phase relationships between orthogonal carrier frequencies. FIG. **2**A illustrates first and second orthogonal sinusoidal waveforms **201** and **202**. Each waveform **201** and **202** has an integer number of wavelengths over a particular symbol interval T_s. The first waveform **201** frequency f_1 is six cycles per symbol interval T_s. The second waveform **102** frequency f_2 is five cycles per symbol interval T_s.

The samples **220** to **225** of waveform **202** are selected at intervals of Δt_1 corresponding to periods **210** to **215** of waveform **201** over a symbol interval $T_s=6\Delta t_1$. In this case, the waveforms **201** and **202** are aligned in phase at times t=0

and $t=T_s$. At $t=\Delta t_1$, sample **221** occurs at 5/6 of waveform **202** period Δt_2. Each sample **220** to **225** can be represented by a value on a unit circle in the complex plane. For example, FIG. **3**A shows a complex-plane representation of samples **220** and **221**.

Since the sampling frequency f_1 exceeds the frequency f_2 of the sampled waveform **202**, the phase shift of each successive sample **220** to **225** falls short of a full cycle of waveform **202**. The waveforms **201** and **202** are orthogonal due to selection of an appropriate symbol interval T_s that causes the samples **220** to **225** to be distributed uniformly across the unit circle in the complex plane, as illustrated by FIG. **4**A. The sample values **220** to **225** cancel when they are summed.

FIG. **2**B illustrates a first waveform **201** sampled at intervals **230** to **235** relative to a sampling frequency f_2 of a second waveform **202**. A symbol interval is expressed by $T_s=5\Delta t_2$. Each sample **240** to **244** corresponds to a phase shift that is greater than a full cycle of waveform **201**, as illustrated by FIG. **3**B. The orthogonality of the waveforms **201** and **202** ensures that the samples **240** to **244** are distributed uniformly around the unit circle in the complex plane, as shown in FIG. **4**B. Samples **240** to **244** collected over a symbol interval T_s cancel when summed.

FIG. **4**C shows a normalized complex-plane representation of samples (collected at a sampling rate $f_{sample}=f_n$) of a desired waveform having a frequency f_n. Since $f_{sample}=f_n$, the samples always occur on the same part of the unit circle in the complex plane. Thus, the samples sum constructively. In this example, the samples occur at the peaks of the desired waveform and thus, occur on the real axis in the complex plane. The number of samples N_s per symbol interval T_s is expressed by:

$$N_s=f_{sample}T_s=(f_o+nf_s)/f_s$$

The number of samples per waveform period (1/A) is 1.

Nearby waveform frequencies $f_{n\pm n'}$ can be expressed as: $f_{n\pm n'}=f_o+(n\pm n')f_s$. The number of samples per period of a nearby waveform can be expressed as:

$$N_{n\pm n'}=\frac{f_{n\pm n'}}{f_{sample}}=1\pm\frac{n'f_s}{(f_o+nf_s)}$$

In the complex plane, the sampled values shift by an amount:

$$\phi_{n\pm n'}=\pm\frac{n'f_s}{(f_o+nf_s)}2\pi \text{ radians}$$

N_s samples collected throughout the symbol interval T_s are distributed uniformly on a unit circle in the normalized complex plane unless $f_{n\pm n'}$ is an integer multiple of f_n. The case in which $f_{n\pm n'}=mf_n$ (where m is some integer) can be avoided by appropriately frequency converting the received signal(s) and/or the sampling rate to ensure that the vector sum of the samples is zero.

CI codes can be used as direct-sequence codes, multicarrier codes (e.g., MC-CDMA), etc. Applications of CI codes can be extended to any application of conventional binary direct sequence codes, including, but not limited to, spread spectrum, multiple access, channel coding, encryption, and interference mitigation. CI codes may be applied across any set of orthogonal or quasi-orthogonal diversity-parameter values or subspaces.

Basic CI codes can be generated from phase relationships indicated by vector precession in the complex plane, such as shown in FIG. **4**A. CI coding can be applied to circular, elliptical, and linear polarization. CI polarization codes may be based on vector precession in a two- or three-dimensional polarization plane. Advanced CI codes may be based on basic CI polarization codes. Similarly, vector rotation in a plane or a higher-dimension field of orthogonal bases may be used to generate basic and/or advanced CI codes. The basic family of CI codes is generated from an M×M matrix of elements having phases ϕ_{nm} described by:

$$\phi_{mn}=2\pi mn/M+2\pi f_o m/f_s M,$$

where m and n are row and column indices, respectively. M may have any positive integer value. The second term in ϕ_{mn} is an optional phase shift applied to all terms in a row. The phase-shift ϕ_{mn} may correspond to a carrier frequency offset f_o and a sub-carrier separation f_s. A basic CI code c_m of length N can include a row or column vector consisting of terms:

$$c_m=e^{im\phi'}\sum_{n=0}^{N-1}e^{imn\phi}\hat{n}$$

where $\phi=2\pi/M$ and $\phi'=2\phi f_o/f_s M$.

Some of the CI codes are complex-conjugate pairs. For example, correlations between CI codes are expressed by the following relationship:

$$\text{corr}_{m,m'}=\left(\frac{1}{M}\right)e^{i(m+m')\phi'}\sum_{n=0}^{M-1}e^{in(m+m')\phi}$$

The correlations are non-zero for (m+m')=M.

CI codes may have polyphase and/or multi-magnitude values. A CI code set may include one or more binary code vectors corresponding to at least one conventional binary-phase code. In the case where CI codes include complex-valued chips, the real and imaginary parts may be impressed upon different orthogonal parameters. For example, a magnitude corresponding to a real value may be modulated on an in-phase carrier component, whereas a corresponding imaginary value may be modulated on a quadrature-phase carrier component.

Orthogonal components may include, but are not limited to, perpendicular linear polarizations, left-hand and right-hand circular or elliptical polarizations, orthogonal polarization-spin frequencies, subspaces (e.g., spatial, directional, temporal, phase, polarization, etc.), orthogonal frequencies, orthogonal time intervals, direct-sequence codes, etc. Modulation may include phase modulation, amplitude modulation, frequency modulation, polarization modulation, time-offset modulation, or any combination thereof.

Phase shifts corresponding to CI code chips may be impressed upon a single carrier or onto multiple carriers. In one embodiment, phase shifts are impressed relative to a transmitted or locally generated reference phase. In another embodiment, differential phase modulation (DPM) is employed. In one embodiment, DPM is employed on a single carrier. In another embodiment, DPM is applied to a multicarrier transmission protocol. In one embodiment, each phase shift is conveyed as a phase differential between at least two carriers.

CI codes may be applied to ordinary direct-sequence (e.g., DSSS or DS-CDMA), MC-CDMA, OFDM, coded OFDM, Discreet Multitone, Wavelength Division Multiplexing (WDM), ultra-dense WDM, Multi-tone CDMA, Multi-code spread spectrum, or any of the CI protocols. In the case where CI codes are used in a multicarrier transmission protocol, phase-shift coding may be accomplished in any of several ways. Each carrier may be phase shifted with respect to each chip of a CI code chip sequence. Each carrier may be modulated with respect to any single-carrier modulation scheme. Each carrier may be modulated with one or more CI code chip encoded subcarriers. Each carrier may be provided with at least two diversity parameters that are modulated to convey real and imaginary parts of CI codes chips.

Multicarrier signals may be defined by any set of substantially orthogonal diversity-parameter values. These diversity parameters may include, without limitation, frequency, phase space, polarization (including linear, circular, elliptical) in two or three dimensions, mode, code (e.g., DS and/or CI), time, any type of subspace, and any combination thereof.

Advanced CI codes can involve one or more types of processing applied to basic CI codes. Some examples of advanced CI codes include matrices resulting from processing basic CI codes with a Hadamard-Walsh matrix, matrices derived from Hadamard-Walsh/CI matrices, and expanded CI matrices based on Hadamard-Walsh matrix expansion.

The basic CI codes can be combined (with each other or with other direct-sequence codes) to form other families of polyphase and/or poly-magnitude CI codes. In any set of CI codes, the chip sequences may be truncated, appended, rearranged, concatenated, etc., to generate orthogonal or quasi-orthogonal chip sequences. Codes of similar or different lengths may be concatenated. Different chip sequences may be combined in such a way that at least one chip sequence is interleaved with chips from at least one other code.

CI code vectors may be multiplied by other code vectors including, but not limited to, direct-sequence codes, complementary codes, and/or other CI codes. Groups of CI code chips may be modulated (scaled and/or shifted) with respect to other code chips. A CI code may be overlayed with a long code, a Hadamard-Walsh code, a Barker code, a Gold code, a Kasami code, a Golay code, a CI code, or some other code. CI coding may include multiple levels of coding wherein at least one set of code chips modulates at least one other set of code chips.

Basic CI codes form an orthonormal basis. New orthonormal bases can be generated by linearly combining CI codes of a particular length. More advanced permutations of CI codes may also be provided to form orthonormal bases. The orthonormal bases may be multiplied by code chips of other sequences, such as Hadamard-Walsh, Gold, CI, etc.

Data symbols may be mapped to CI codes to provide channel coding. For the purpose of mapping, bi-orthogonal CI codes may be generated by including a code set multiplied by the value −1. CI codes may be used to generate trans-orthogonal (e.g., simplex) codes. Quasi-orthogonal mapping may be performed by phase shifting or scaling the CI codes. A second set of orthogonal CI codes may be generated by rotating the phase of a first code set by $\pi/2$, thus providing in-phase and quadrature CI codes.

CI-coded symbols may be decoded by correlating a coded signal with a complex-conjugate code. A received signal may be processed with an FIR filter having coefficients set appropriately to decode a desired signal. The received signal may be sampled and summed. Optionally, samples of the received signal may be weighted prior to being summed to compensate for any of various effects, such as channel distortions, transmitter-side encoding (e.g., to reduce PAPR), jamming, etc. Weighting may be performed with respect to one or more optimization processes in which weights are adjusted with respect to at least one measurement, such as signal to noise, signal to noise plus interference, probability of error, BER, received signal power, etc.

The received signal may be phase shifted with respect to chip phases of a decoding signal. If a received signal includes multiple samples per chip interval, the chip samples may be time shifted with respect to the chip phases of the decoding signal. The samples corresponding to each chip may be cyclically shifted with respect to a decode chip sequence. Subsequent processing, such as sampling, adding, comparison, and/or decision making (hard and/or soft) may be performed to evaluate data symbols measured after the decoding process.

FIG. **5**A shows a set of 16 octonary code vectors C(n) resulting from multiplying an 8×8 basic CI code matrix $CI_{8\times8}$ by rows of an 8×8 Hadamard-Walsh matrix $HW_{8\times8}$. An 8×8 matrix resulting from a product of a matrix $CI_{8\times8}$ by a row of matrix $HW_{8\times8}$ includes two binary-phase 8-chip codes (which correspond to rows of matrix $HW_{8\times8}$), two quaternary-phase code vectors, and four octonary-phase code vectors including two complex-conjugate pairs. The 16 code vectors C(n) are selected from octonary-phase vectors in matrices resulting from products of vectors of $HW_{8\times8}$ with CI code matrix $CI_{8\times8}$.

FIG. **5**B shows auto correlations and cross correlations of the 16 octonary codes C(n) shown in FIG. **5**A. The correlation relationships may be used to choose orthogonal or quasi-orthogonal code sets from the codes C(n). For example, the codes C(1), C(1)*, C(2), C(2)*, C(4), C(4)*, C(7), and C(7)* form an orthogonal eight-code set. The code pair {C(1), C(1)*} has zero cross correlation with C(2), C(2)*, C(4), C(4)*, C(7), and C(7)* and thus, can be used with these codes to provide orthogonal code sets. Code C(1) has a non-zero cross correlation with codes C(1)*, C(5), and C(6)*. Thus, an orthogonal set may include codes C(1) and C(5), and exclude codes C(1)* and C(6)*. The codes C(3), C(3)*, C(5), C(5)*, C(6), C(6)*, C(7), and C(7)* form another orthogonal eight-code set. Codes C(7), C(3), C(8), C(4), C(1), C(5), C(2), and C(6) form yet another orthogonal eight-code set. Many other code sets, including quasi-orthogonal codes, are possible.

Orthogonal and quasi-orthogonal code sets may be implemented separately or simultaneously. Code sets may include combinations of different M-ary polyphase codes. An M-ary code set may include codes with a code length (i.e., number of code chips) that is less than or greater than M. Code sets may include numbers of codes that are less than or greater than the code lengths. Code sets may include same-length and/or different-length codes.

Although basic CI codes and one family of advanced CI codes are described herein, many other implementations of coding based on CI are clearly anticipated. CI code sets may be selected or manipulated to provide cross-correlation values that are shifted by $\pi/2$. CI codes may be used to generate bi-orthogonal and/or trans-orthogonal CI code sets. CI codes may include linear combinations of other CI codes. CI codes may be derived from Hadamard-Walsh matrix expansion, code concatenation, code interleaving, code superposition, and/or weighted code superposition wherein weights are applied to one or more code chips. A CI code may include at least one set of CI matrix elements, such as

a row, a column, a diagonal, and/or matrix elements selected with respect to some predetermined pattern.

CI code chips may be cyclically shifted, swapped, or otherwise re-ordered. CI codes may be implemented as multi-level codes with one or more codes that are not necessarily CI codes. Multiple codes including at least one CI code may be interleaved. CI codes may be interleaved with same length or different length codes. CI codes may be implemented in block coding, convolutional coding, turbo coding, any other form of channel coding, encryption, multiple-access coding, spread-spectrum coding, peak-power mitigation, etc. CI codes may be implemented with orthogonal coding, quasi-orthogonal coding, bi-orthogonal coding, trans-orthogonal coding, or any combination thereof.

CI codes may be generated by convolving at least one set of CI codes with at least one other set of codes, including one or more of the following: CI codes, binary direct-sequence codes, channel codes, spreading codes, multiple-access codes, etc. CI codes may be provided with one or more parity-check symbols formed from linear combinations of data symbols and/or code chips.

FIG. **6**A illustrates basic components of a CI-code generator **603**. A CI-symbol generator **609** generates a plurality of CI symbols that are coupled to a symbol combiner **610**. The symbol combiner **610** groups the CI symbols to generate one or more CI codes.

A CI-symbol generator, such as the CI-symbol generator **609**, includes any algorithm, system, or device adapted to generate a plurality of CI symbols. CI symbols may include basic CI symbols. CI symbols may be discreet-valued or continuous-valued numbers or functions. CI symbols may be values derived from at least one invertible transform function, such as a Fourier transform, a Laplace transform, a Walsh transform, a wavelet transform, etc. CI symbols may include linear combinations of other CI symbols, linear combinations of CI symbols with other code symbols, CI symbols modulated with code sequences from a predetermined code set including one or more of the following: spread-spectrum codes, multiple-access codes, channel codes, encryption codes, multi-level codes, compression codes, hybrid codes, invertible-transform codes, and CI codes.

A CI symbol combiner, such as the symbol combiner **610**, includes any algorithm, system, or device adapted to group CI symbols to generate at least one CI chip sequence. A symbol combiner may append, concatenate, interleave, shift, puncture, or re-order one or more symbol sets. A symbol combiner may combine CI symbols with other symbols. A symbol combiner may provide a CI chips sequence with at least one parity-check symbol.

FIG. **6**B illustrates a CI transmitter adapted to generate at least one CI-coded information signal. A CI encoder **600** encodes at least one input information signal relative to at least one CI code produced by a CI code generator **603**. CI coded information signals are optionally coupled to a transmission system **602** that may include a pre-transmission processor (not shown).

FIG. **6**C illustrates basic components of a CI decoder that include a CI code generator **603** and a coherent combiner **605** adapted to decode at least one CI-encoded signal with respect to at least one code generated by the CI code generator **603**. Optionally, the decoder may be coupled to a front-end receiver processor **604** that provides the at least one CI-encoded signal to the decoder.

Channel coding provides signal transformations that are designed to improve communication performance by enabling transmitted signals to better withstand the effects of various channel impairments (e.g., noise, fading, interference). CI channel coding may include waveform coding and/or structured sequences. CI waveform coding (such as M-ary signaling, orthogonal coding, bi-orthogonal coding, trans-orthogonal coding, etc.) transforms waveforms to make them less subject to error. CI-structured sequences transform a data sequence into one or more sequences having structured redundancy. Redundant bits are used for detecting and/or correcting errors.

CI coding may include replacing a data set with an orthogonal codeword set. In one embodiment, a CI coder may multiplex multiple coded data symbols together by providing an orthogonal codeword set. A CI codeword set may be selected in which each codeword vector has zero projection onto all other CI codeword vectors except for its complex conjugate. A decoder may include multiple matched filters (or equivalent systems or algorithms) that output zero unless a corresponding encoded data symbol is received.

FIG. **7** illustrates a relationship between CI symbol values w_n and data symbols s_n. CI code chip values are arranged in columns with respect to phase spaces, such as phase space (column) **701**. A phase space may be analogous to a pulse position. The phase spaces (e.g., pulse positions) may be orthogonal or quasi-orthogonal. Thus, the number of CI symbols w_n may differ from the maximum number of data symbols s_n. Each data symbol value s_n is impressed upon a phase space such that each set of CI code chip values in that phase space expresses the value of the corresponding data symbol s_n. Each code chip value is analogous to a complex weight applied to a particular CI carrier. A superposition of these carriers produces a CI waveform (e.g., pulse) bearing the data symbol value s_n.

A CI superposition waveform bearing multiple data-symbol/pulse-position characteristics can be created by applying weights to CI carriers that correspond to sums of carrier weights for each data-symbol/pulse-position. Similarly, each CI symbol, such as symbol w_2, corresponds to a summed row of data-bearing CI code chips, such as row **703**. The code chips may be transmitted over multiple time intervals, carrier frequencies, polarizations, and/or other orthogonal diversity parameter values.

Decoding may include any appropriate inverse of the coding operation represented by FIG. **7**. For example, to extract an nth data-symbol value s_n from a vector of received CI symbol values w, the complex conjugate of a vector of the nth phase space (or CI code) values w_n may be correlated with the received CI symbol vector w. Equivalent decoding processes may be performed. The decoding process may be performed with respect to one or more combining techniques, such as, but not limited to, MMSE, EGC, maximum likelihood combining, or any combination thereof. Decoding may include turbo decoding.

FIG. **8**A illustrates basic components of a CI coding system and a CI decoding system. A data symbol stream **801** is processed by a CI symbol generator **820** that outputs a plurality of CI symbol values w_n representing a coded version of the data symbols s_n. The symbols w_n may be interleaved by an optional interleaver **804** prior to being prepared for transmission into a communication channel **899** by a pre-transmission processor (not shown) in a transmission system **805**. The symbols w_n are typically multiplexed onto one or more diversity-parameter spaces prior to transmission.

A receiver system **806** couples transmitted signals from the channel **899**, and a front-end receiver processor (not

shown) performs any necessary processing, such as filtering, amplification, demultiplexing, de-spreading, decoding, and/or beam forming, prior to outputting an IF or baseband digital signal. Optionally, channel compensation **807** may be performed to mitigate effects of channel distortion and/or interference. Any necessary de-interleaving processes **808** may be performed prior to processing by a CI symbol decoder **830**. The decoder **830** processes received CI symbols w'_n to produce data-symbol estimates **801'**. The data-symbol estimates **801'** may be output to additional signal-processing systems (not shown).

The CI Symbol Generator **820** converts a predetermined number of input data symbols s_n to a plurality of CI code symbols w_n. This conversion may involve summing information-modulated CI code chips. A first step in a CI symbol generation process may include generating code chips and/or acquiring code chips stored in memory or received from an input data stream. Code chips may be generated from a reduced set (e.g., an orthonormal basis) of code chips or code vectors.

A second step in a CI symbol generation process involves impressing at least one data symbol s_n onto at least one set of code chips. The code chips may be multiplied, phase shifted, modulated, or otherwise impressed with data symbol values s_n. The code chips may represent a phase space, such as a pulse position. Optionally, the code chips may be provided with phase offsets, such as for crest-factor reduction or encryption.

A third step in a CI symbol generation process involves combining the code chips to produce one or more CI code symbols w_n. FIG. **7** illustrates how rows of information-modulated CI code chips are summed to produce CI code symbols w_n. Predistortion may be provided applying channel-compensation weights to the CI code symbols w_n.

The decoder **830** processes received CI symbols w'_n to produce data-symbol estimates **801'**. A first step in a CI decoding method includes generating code chips and/or acquiring code chips stored in memory or received from an input data stream. Code chips may be generated from a set of orthonormal codes or a subset of chips comprising one or more orthonormal codes.

A second step in a CI signal processing method includes combining or correlating at least one vector of the code chips with a vector of the received data symbols w'_n. A correlation process may include a scalar multiplication between the code chip vector and the received data symbol vector followed by combining (e.g., integrating) the products. Another embodiment of correlation includes adding together selected samples over a predetermined symbol interval T_s. Additional processing may be performed to produce estimates of the transmitted data symbols.

The decoder **830** may perform various types of combining, such as weighted combining as part of an MMSE, EGC, maximal likelihood, or any other performance-based optimization process. The decoder **830** may perform channel compensation. The decoder **830** may include a front-end receiver processor (not shown).

The bandwidth requirements for bi-orthogonal CI codes are half of the requirements for comparable orthogonal codes. Bi-orthogonal codes have slightly better performance over orthogonal codes because antipodal signal vectors have better distance properties than orthogonal signals. Trans-orthogonal (e.g., simplex) codes, when compared to orthogonal and bi-orthogonal codes, require the minimum SNR for a particular symbol error rate. Channel codes may be overlaid onto multiple-access codes. Depending on the processing gain of the multiple-access codes, channel coding may not require additional bandwidth.

FIG. **8**B shows a system diagram of a CI transceiver. An information source **851** provides data symbols to a CI coder/interleaver **852**. A modulator **853** modulates the coded symbols onto one or more carriers that are transmitted by a transmitter **805** into a communication channel **899**. The channel **899** may be characterized by AWGN and/or multi-path. Other channel distortions may be considered. A receiver **806** couples the transmitted signals out of the channel **899**. A demodulator **863** retrieves symbols from the received signal. A CI decoder/de-interleaver **862** decodes (and de-interleaves, if necessary) the received symbols into information symbols that are optionally processed in an information processor or sink **861**.

In one embodiment, the coder **852** maps data symbols to CI code words using a look-up table. In another embodiment, the CI code words are generated with respect to each data symbol. Codeword generation may be performed with a CI code generation matrix G. CI codes of a given set of CI code words may be constructed from a combination of linearly independent code vectors that form the CI code generation matrix G.

Although code generation is described with respect to basic CI codes, orthonormal basis vectors and a corresponding CI code generation matrix may be constructed for advanced CI codes. Each code in a basic CI code set can be defined by a different number of full rotations in the complex plain. For example, an orthonormal basis for a set of N=64 basic CI codes can be defined by the CI code generation matrix:

$$G = \begin{bmatrix} C(\text{rotations} = 1) \\ C(\text{rotations} = 2) \\ C(\text{rotations} = 4) \\ C(\text{rotations} = 8) \\ C(\text{rotations} = 16) \\ C(\text{rotations} = 32) \end{bmatrix}$$

where C(rotations=m), m=0, 1, . . . , N−1, is a code vector corresponding to:

$$C(m)=e^{im\phi'}(1,e^{im\phi},e^{i2m\phi}, \ldots ,e^{i(N-1)m\phi})$$

Since this basic CI code set is totally defined by G, the coder **852** needs to store only k rows of G instead of 2^k vectors of the CI code matrix. Furthermore, since the first half of each row vector C(m) of G is the same as the second half (except C(l)'s first and second halves differ by a factor of −1), the coder **852** and decoder **862** need only store one half of each row vector C(m).

A CI receiver may perform error detection using any of several techniques. Symmetry relationships between the first and second halves of a received code can be exploited to determine whether an error occurred. Other relationships between code symbols may be used to provide error detection and/or correction. For example, adjacent CI code symbols (except for the all-ones code) are typically not identical. Depending on the code, the values of adjacent code symbols change in a predetermined way. For example, adjacent code chips of an mth basic code C(m) differ by $e^{im\Phi}$.

A parity-check matrix H (defined by the equation, $GH^T=0$) can be used to test whether a received vector is a member of a codeword set. The decoder **862**, upon detecting an error, may perform forward error correction and/or request a retransmission. Preferably, the decoder **862** esti-

mates the transmitted code vector using some optimizing strategy, such as the maximum-likelihood algorithm. The receiver may erase ambiguous signals. The decoder **862** may implement error correction to correct erasures and/or errors.

It is preferable that the coder **852** select codes that maximize the Hamming distance between codes. An advantage of using polyphase codes is that they provide a superior Hamming distance compared to binary codes. For example, (n,k)=(8,3) binary code has an n-tuple space of $2^n=2^8=256$ binary words, of which $2^k=2^3=8$ are code words. An octonary-phase (m=8) (8,3) code has an n-tuple space of $2^m=2^{64}$ octonary words. The fraction of words that are code words decreases dramatically with increasing values of m. When a small fraction of the n-tuple space is used for code words, a large Hamming distance can be created.

CI codes may be processed as cyclic codes, which are described in many prior-art references, such as B. Sklar, *Digital Communications, Fundamentals and Applications*, Prentice-Hall, Inc., New Jersey, 1988. For example, components of a CI code vector $C=(C_0, C_1, \ldots, C_{N-1})$ can be treated as coefficients of a polynomial U(X), as follows:

$$U(X)=u_0+u_1X+u_2X^2+\ldots+u_{N-1}X^{N-1}$$

where $X=e^{i2\pi nk/N}$, where k is the order of the code: k=0, 1, . . . , N−1. Well-known cyclic code processing may then be performed.

4. CI Networks

FIG. **9**A illustrates a tree network that may be implemented in aspects of the present invention. Transmissions passed to one or more nodes in the network may be branched off, or routed, to a plurality of nodes. Routing may include processing any combination of network addresses conveyed in headers and network addresses conveyed by codes (e.g., spreading codes, multiple-access codes, channel codes, etc.).

Network addresses may provide routing information and/or directions. For example, multiple addresses may convey one or more paths between a source node and a destination node. Various types of control information may be included in a code. For example, certain codes may convey priority information, identify the type of data payload, and/or otherwise tag the transmission.

FIG. **9**B illustrates a network design that permits a plurality of communication paths to each node. Multiple network connections between a source node and a destination node may be provided for redundancy. Alternatively, each path may be selected based on one or more criteria, such as channel conditions and load balancing.

FIG. **9**C illustrates a network design adapted to provide array processing performance advantages. A plurality of nodes **926**, **927**, **902**, **920**, **921**, and **922** are adapted to provide complex-weighted transmissions to at least one destination node, such as nodes **931** and **932**. For example, a data sequence addressed to node **931** is routed to nodes **926**, **927**, **902**, **920**, **921**, and **922**, which provide appropriate weights to the data transmission to generate a phase front **941** that converges at the destination node **931**. Similarly, appropriate delays or complex weights may be provided to transmissions to produce a coherent phase front **942** that converges at destination node **932**. Signals received by the nodes **926**, **927**, **902**, **920**, **921**, and **922** may be combined with respect to any combining technique, including optimal combining.

Nodes in a wireless network may generate weighted transmissions (or process received signals) to perform various types of array processing. Individual nodes may include one or more transceiver (e.g., antenna) elements. Array-processing operations may include combinations of local and global processing. For example, diversity combining may be performed at each multi-element node and signals from each node may be combined in a central processor to perform sub-space (i.e., directional) processing. Other combinations of local and global processing may be employed.

Array processing may include space-time processing, space-frequency processing, beam forming, null steering, blind-adaptive processing, long baseline interferometry, frequency-diversity interferometry, etc. Array processing may be performed to achieve any combination of sub-space processing (i.e., increased capacity) and diversity benefits in (i.e., improved performance). Selection of transmitting and receiving nodes in an array-processing network can be adapted to changing node positions, network loads, throughput requirements, user services, bandwidth availability, frequency-reuse requirements, channel conditions, etc.

FIG. **9**D illustrates a concentric ring network configuration in which a base station **900** or access point provides direct or indirect communication links to a plurality of subscriber units **901** to **935** arranged in a plurality of concentric-ring regions **951** to **953**. Subscriber units **901** to **906** in region **951** are adapted to route signals to one or more subscriber units **921** to **935** in one or more regions, such as region **953**. Similarly, subscriber units **911** to **918** in region **952** may be adapted to route signals to subscribers in other regions. In some applications, one or more subscribers may be adapted to route signals to at least one other subscriber in the same region.

Region shapes and sizes may be adapted to numbers of users and/or the geographical distributions of the users. Similarly, regions may be adapted to balance network loads. For example, subscriber power consumption and processing requirements associated with routing signals through subscribers near the base **900** can be mitigated by distributing routing operations over a larger number of subscribers. Thus, subscribers in regions **951** and **952** perform routing associated with a direct transmission from and/or to the base **900**. Similarly, the number of subscribers in primary arteries of tree networks (or other networks) can be increased. Routing functions can be assigned to subscribers based on subscriber location, subscriber load, channel conditions, and network load. The network configuration illustrated in FIG. **9**D may be integrated with other network architectures, such as tree configurations, or otherwise adapted to geographical distributions of subscribers and other network transceivers.

FIG. **9**E illustrates a network configuration adapted to the geographic distribution of a plurality of subscribers **921** to **926** and **931** to **936** located along a roadway. In this case, there are two routing paths **961** and **962** provided by subscriber routing. Network configurations, including transmission paths, may be adapted to subscriber distributions and channel conditions. For example, urban channel environments are typically characterized by a waveguide grid. Thus, routing paths may be provided with a grid architecture in urban areas.

A transmission may include multiple levels of coding intended to be stripped off at each node along a predetermined path to a particular address. FIG. **9**F illustrates three nodes **901**, **902**, and **904**. The first node is adapted to decode a one-rotation basic CI code by applying complex-conjugate decoding of the one-rotation code. A basic CI code c_m characterized by m rotations (m<N) is expressed by the following equation:

$$c_m = e^{im\phi'} \sum_{n=0}^{N-1} e^{imn2\pi/N} \hat{n}$$

The complex-conjugate decoding essentially unwinds the code. Similarly, nodes **902** and **904** are adapted to decode two-rotation and four-rotation codes, respectively. For simplicity, the rotations are provided in a common predetermined direction.

In one aspect of the invention, each node splits a received signal into at least two signals. Δt least one of the split signals is decoded at the node to extract any information intended for that node. A node may be associated with one or more addresses, or codes. Δt least one split signal is passed through the node without any decoding. Thus, node **901** receives signals coded (or addressed) with one code rotation, node **902** receives signals coded (or addressed) with two code rotations, etc.

In another aspect of the invention, a signal input to a node is not split prior to being decoded to extract any signals intended for that node. The decoded signal is then re-encoded with respect to the complex conjugate of the decoding operation. Thus, any unwinding associated with decoding is reversed prior to re-transmission of the coded information signal. Optionally, a node transceiver may cancel or otherwise remove signals addressed to itself prior to re-encoding.

In yet another aspect of the invention, coded transmissions are coded with respect to the intended path(s) to a predetermined address, thus obviating the need for splitting or re-encoding. For example, an information signal addressed to nodes **902** and **904** input to the first node **901** is encoded with a pair of basic CI codes having three rotations and seven rotations, respectively:

$$r_{node901} = \sum_{n=0}^{N-1} (s_2(t)e^{i3n2\pi/N} + s_4(t)e^{i7n2\pi/N})\hat{n}$$

Decoding at the first node **901** unwinds the coded signals by one rotation. The decode signal is characterized by C*(1), which is the complex conjugate of code C(1). Thus, node **901** passes a coded information signal to node **902** expressed by two-rotation and six-rotation codes:

$$r_{node902} = \sum_{n=0}^{N-1} (s_2(t)e^{i2n2\pi/N} + s_4(t)e^{i6n2\pi/N})\hat{n}$$

A sum of the decoded chips yields zero because there are no input signals coded with a single-rotation code. A sum of the chips generated at node **901** is zero because the non-zero rotations cause the chip values to cancel.

Decoding with decode signal C*(2) at node **902** unwinds the coded signals by two rotations. Thus, a sum of the decoded signal at node **902** coherently combines chip values associated with signal $s_2(t)$ and cancels chip values associated with signal $s_4(t)$. Node **902** produces a coded information signal expressed by:

$$r_{node904} = \sum_{n=0}^{N-1} (s_2(t) + s_4(t)e^{i4n2\pi/N})\hat{n}$$

The values $s_2(t)$ may optionally be removed (such as by cancellation, dc-offset removal, etc.) prior to transmission to node **904**. A node transceiver at node **902** may ensure non-zero chip values prior to transmission.

Coded signals received by node **904** are processed with a complex-conjugate code C*(4) that unwinds the coded signal by four rotations. The resulting decoded signal is expressed by:

$$r_{node904'} = \sum_{n=0}^{N-1} s_4(t)\hat{n}$$

Decoding and summing the code chips at node **904** coherently combines signal values $s_4(t)$ associated with a four-rotation code C(4).

FIG. **9**G illustrates a simple tree-style CI-based network. Nodes **901**, **902**, and **904** are provided with decode signals corresponding to C*(1), C*(2), and C*(4), respectively. A branch node **903** employs a decode signal C*(3) adapted to decode signals characterized by three rotations in a predetermined direction. A signal addressed with basic CI codes corresponding to rotations of seven, three, and six are input to node **901**. Signals output by node **901** to node **902** correspond to rotations of six, two, and five. Node **902** provides a decode signal of C*(2) to its input signal. Thus, the input corresponding to two rotations is decoded and the resulting value is processed at the node **902**. The resulting output signal(s) from node **902** is expressed by rotations as four, zero, three. The zero value may characterize a substantially null signal resulting from cancellation of the decoded signal at node **902**.

Node **902** may provide a broadcast signal to nodes **903** and **904**. Alternatively, node **902** may duplicate the signal four, zero, three and provide a signal to each of the nodes **903** and **904**. In some cases, node **902** may be adapted to separate its input signal into a plurality of components relative to addresses. Each component may be forwarded directly to its intended node. In some cases, separate signals may be provided via beam forming. In other cases, some form of multiple access, including header addresses, may be employed.

FIG. **9**H illustrates a simple multipath CI-based network. Node **902** is provided with coded signals (expressed in rotations as 2, 5, 6, 3, 4). The value two is addressed to node **902**. The values five and six are addressed to nodes **903** and **904**. A fourth node **906** receives transmissions from nodes **903** and **904**. Thus, values three and four characterize paths through nodes **903** and **904**, respectively, that are addressed to node **906**. Signals received and decoded at node **906** may be combined coherently. Such combining may include optimal combining.

In some aspects of the invention, node **906** may be provided with additional decode values (e.g., C*(5)) to enhance reception. Furthermore, two or more decode values (e.g., C*(6) and C*(5)) may be exploited in appropriate combinations to provide beam forming (or equivalent array processing) operations. Various combining operations may be performed to provide any combination of interference rejection, diversity enhancement, and sub-space processing (i.e., capacity enhancement).

FIG. **9**I illustrates a plurality of nodes **901** to **905** and at least two communication paths. A first communication path includes nodes **902**, **904** and **905**. A second communication path includes nodes **901**, **903**, and **905**. In this case, the two

paths illustrate communication to node **5**. Alternatively communication paths may be provided indicating communications from node **905**.

Signals arriving from the first communication path are encoded with at least one code $c_1(n)$. Similarly, the signals arriving from the second communication path are encoded with at least one code $c_2(n)$. In various applications of the invention, additional communication paths (not shown) may be provided.

The codes $c_1(n)$ and $c_2(n)$ may be address codes or they may include address codes. The codes $c_1(n)$ and $c_2(n)$ may be similar or different. Alternatively, the codes $c_1(n)$ and $c_2(n)$ may be separate (or different) from address codes. In some cases, address codes may be adapted to provide additional coding or achieve other objectives, such as, but not limited to, encryption, verification, authentication, identification, anti-jamming, and/or diversity benefits.

In one set of embodiments of the invention, redundant information signals or signals providing redundant information are routed along the multiple paths to the destination node **905**. This can provide diversity benefits. The codes $c_1(n)$ and $c_2(n)$ may include similar or different channel codes. Signals provided along the multiple paths may be decoded (if necessary) and coherently combined in a receiver at the node **905**. Combining may include one or more optimal-combining techniques. The number of transmission paths that are coherently combined is proportional to an effective processing gain of the combining process. Consequently, low-power information-bearing transmissions may be employed over the multiple transmission paths. Signals received from different paths may be processed via soft-decision processing to provide confidence measurements for symbol estimates and/or enhance channel compensation and/or iterative decoding.

In another set of embodiments, each of a plurality of signals routed along different paths to a given node may provide necessary keys (or equivalent information) necessary for decoding. For example, signals routed along a first path may provide a coded information signal to a predetermined destination. Signals routed along a second path to the same destination may provide a decode sequence to decode the coded information signal. The codes $c_1(n)$ and $c_2(n)$ may include codes that are complex conjugates of each other. The first code $c_1(n)$ may include a public key and the second code $c_2(n)$ may include a private key wherein the two codes $c_1(n)$ and $c_2(n)$ contribute the necessary code keys for decoding a coded information signal transmitted along the first and/or second paths, or along a third path. Various pluralities of codes, paths, and/or coded information signals may be employed.

The process of providing multiple decoder keys across multiple transmission paths may be part of an authentication and/or verification process. The codes $c_1(n)$ and $c_2(n)$ may include channel-specific codes that characterize the channel between at least one transceiver and the destination node **905**. The codes $c_1(n)$ and $c_2(n)$ may include channel compensation. Consequently, a channel analysis of received signals at the destination node **905** will indicate the likelihood that the signals were transmitted from known nodes, such as nodes **903** and **904**. Similarly, channel analysis may be employed to determine the local source node of a given transmission. The codes $c_1(n)$ and $c_2(n)$ may include beamforming weights.

In some aspects of the invention, channel estimation may be performed on a signal received from a transceiver attempting to access the network. Various location-finding processes (e.g., direction-of-arrival determination, geo-location tracking, triangulation, etc.) may be implemented to determine the transceiver's location relative to a set or range of allowed locations. In some applications, identification of unauthorized users may be combined with location finding.

FIG. **9**J illustrates a node **902** used in a plurality of crossing communication paths. Nodes **901**, **902**, and **904** are part of a first communication path. Nodes **911**, **902**, and **913** are part of a second communication path characterized by at least one unique diversity parameter value. In this case, the communication paths are distinguished by different carrier frequencies. Alternatively, communication paths may be differentiated by code, polarization, subspace, time, phase, subspace, or any combination thereof.

Although basic CI codes are illustrated in the exemplary network architectures, other types of codes (including, but not limited to, complex CI codes, Walsh codes, multi-code sets, multi-level (or stacked) codes, and/or codes derived from invertible transforms) may be implemented in the examples shown, as well as in variations, adaptations, permutations, and combinations of the exemplary network architectures. Network address codes may be employed for one or more additional functions, including, but not limited to, spread spectrum, multiple access, channel coding, and encryption. Network designs shown in the figures and described in the specification are intended to convey basic principles and various aspects of the invention. These network designs do not limit the scope of the invention. Consequently, various network designs may be considered as building blocks for complex network architectures.

Network designs and other aspects of the invention may be combined with prior-art network designs, systems, devices, protocols, formats, and/or methods. Such combinations are clearly anticipated and suggested. Aspects and embodiments of the invention may serve as portions of networks. Network designs, systems, and/or methods of the invention may be adapted to various types of networks, such as long-haul, short-haul, last-mile, local-area, metropolitan-area, sensor, RF-identification, tracking, ad-hoc, mobile radio, personal communication, cellular, airborne, air-ground, and/or satellite networks. Network architectures of the invention may include one or more types of multiple access. Network architectures of the invention may include any combination of addressing, including address codes and packet headers containing addresses.

FIG. **10**A illustrates a multi-level cellular architecture that may be employed by systems and methods of the present invention. Δt least one macro-cell **1021** is subdivided into one or more micro-cells **1031**. Various multiple-access techniques may be used to separate communications in different cells. For example, a predetermined code may be provided to transmissions within the macro-cell **1021**. Macro-cell codes may be provided for inter-cell multiple access or radio isolation. Micro-cell codes may be provided for intra-cell multiple access. Codes applied to transmissions may implement additional network functions, such as spread spectrum, encryption, authentication, channel coding, addressing, and/or interference mitigation.

In some applications, multi-level codes may be implemented. In some cases, macro-cell codes may provide greater processing gain than the micro-cell codes. For example, macro-cell codes may consist of long codes and micro-cell codes may consist of shorter channel codes and/or multiple-access codes. Either or both micro-cell codes and macro-cell codes may implement CI and/or CI-based coding. Coding may be implemented with, or as part of, array processing.

FIG. **10**B illustrates three cells **1021** to **1023** in a cellular network of the present invention. Each cell **1021** to **1023** employs a different long code C_{L1} to C_{L3}, respectively, to differentiate between communications in adjacent cells. Each cell **1021** to **1023** provides intra-cell communications with codes $C_{s1\text{-}N}$ to differentiate between subscriber units in each cell. Coding may include CI and/or CI-based codes. Additional multiple-access techniques may be employed to provide for inter-cell and intra-cell multiple access.

FIG. **10**C shows a cellular architecture of the present invention that includes a plurality of cells **1021** to **1025** and a plurality of base stations **1001** to **1005** located on cell boundaries. The base stations **1001** to **1005** may include spatially sectorized antennas to provide communication to a plurality of cells. For example, base **1002** may be adapted to service users in cells **1021**, **1022**, and **1023**.

The base stations **1001** to **1005** may be adapted to route coded information across multiple cells. For example, coded data and/or control information is routed from base **1002** to base **1003**. A coded signal may be duplicated or decomposed for routing to multiple bases or subscriber units. For example, base **1003** transmits coded information to bases **1004** and **1005**. In some applications, subscriber units, such as subscriber units **1011** and **1012** may be employed to route information between two or more base stations. In any of the implementations of the invention, transmission paths through a network may be selected based on one or more criteria, including transceiver availability, transceiver locations, network loads, channel conditions, transmission-power requirements, etc.

FIG. **10**D illustrates a cellular network of the invention including a plurality of cells **1021** to **1030**, a plurality of base stations **1000** to **1009**, and a plurality of subscriber units, such as subscriber units **1061** to **1063** and **1071** to **1073**. In this case, the bases **1000** to **1009** are located inside each cell **1021** to **1030**. Other cellular architectures may be employed.

A base station (e.g., base **1000**) may route information directly to other bases (e.g., bases **1001**, **1002**, **1004**, **1005**, and **1006**). Such direct transmissions paths are indicated by transmission paths **1041** to **1045**. A direct transmission path **1046** may be provided to a base (such as base **1009**) that is not adjacent to the originating base **1000**. A transmission between bases may be routed through intermediate bases. For example, base **1005** acts as a router for transmissions between base **1000** and bases **1007** and **1008**. Similarly, subscriber units (such as subscriber units **1071** and **1072** may be employed as routers for communications between bases (e.g., bases **1000** and **1003**), between subscribers, and/or between bases and subscribers.

5. CI Routing Systems

FIG. **11**A illustrates a CI transceiver adapted to perform routing. Transmitted signals are received by a receiver system **1101** that outputs a baseband or IF signal. The receiver system **1101** performs RF and (optionally) baseband processes typically performed to convert an RF signal to a baseband or intermediate frequency signal. For example, the receiver system **1101** may perform channel selection, filtering, amplification, frequency conversion, and A/D conversion.

A CI decoder **1102** is adapted to decode the baseband signal relative to one or more address codes intended for the transceiver. The decoder **1102** may select a signal relative to an address in a header prior to decoding. A signal processor **1103** may process the decoded signals prior to producing an output data stream. Signal processing may include one or more signal-processing operations, including, but not limited to, quantization, channel decoding, multiple access decoding, demultiplexing, formatting, demodulation, channel estimation, channel compensation, synchronization, filtering, error detection, error correction, signal-quality analysis, multi-user detection, phase jitter compensation, frequency-offset correction, time-offset correction, etc.

A control system **1104** is adapted to select, adapt, or otherwise control the operation of one or more transceiver components. For example, channel estimates and/or signal-quality analysis performed by the signal processor **1103** may be processed in the control system **1104** to adapt decoding performed by the decoder **1102**. The control system **1104** may provide power-control information to the transmission system **1106**. For example, power control may include mitigating the effects of near-far interference. Channel selection may also be performed to mitigate near-far interference. The control system **1104** may provide other types of network control. For example, CI coding may be adapted by the control system **1104**.

A CI coder **1105** is adapted to process input data bits to produce a coded signal that is coupled to a transmission system **1106**. The transmission system **1106** performs signal-processing operations typically performed to prepare a baseband signal for transmission into a communication channel. The transmission system **1106** may perform one or more processes, including, but not limited to, D/A conversion, modulation, filtering, amplification, frequency conversion, beam forming, etc.

Signals from the receiver system **1101** are coupled to a CI decoder **1112**, which may include a bank of CI decoders. The decoder **1112** decodes received signals that are to be retransmitted. The decoded signals are processed in a signal processor **1113**. The signal processor **1113** may perform similar signal-processing operations as signal processor **1103**. Additionally, the signal processor **1113** may perform duplication, addressing, signal removal, information insertion, re-routing functions, and/or transmitter **1106** control. Furthermore, the signal processor **1113** may perform pre-processing operations prior to coding in a CI coder **1115**. The coder **1115** may include a CI coder bank. A control system **1114** is adapted to select, adapt, or otherwise control the operation of one or more of the transceiver components **1112**, **1113**, and **1115**.

The control system **1114** and the coder **1115** may provide channel-compensation and/or beam-forming weights to the coded symbols. Such weights may be regarded as part of the routing process. Since routing decodes some signals that are not intended for the transceiver, the router components **1112**, **1113**, **1114**, and **1115** are isolated from the rest of the transceiver by a fire wall **1110**.

Code division duplexing or cancellation division duplexing may be employed to permit reliable reception while concurrently transmitting. Alternatively, other types of duplexing may be employed. Pseudo-random time, frequency, and/or phase codes are typically used to avoid self-jamming. However, CI codes and CI-based waveforms enable the frequency-domain processing required for optimal performance in a multipath environment while providing data redundancy (i.e., channel coding) needed to mitigate errors. Optionally, additional channel coding (e.g., block, convolutional, TCM, turbo, etc.) may be provided to CI waveforms and/or CI coding.

FIG. **11**B illustrates an alternative embodiment of a CI receiver adapted to perform routing. Many of the system components shown in FIG. **11**B are similar to components shown in FIG. **11**A and thus, are identified by corresponding

reference numbers. A portion of the baseband (or IF) signal (s) produced by the receiver system **1101** is optionally processed in a processor **1119** prior to being coupled into the transmission system **1106**.

The processor **1119** may perform one or more baseband or IF processes, including, but not limited to, signal shaping, filtering, re-quantization, error detection, error correction, interference mitigation, multi-user detection, amplification, up sampling, down sampling, frequency conversion, D/A conversion, AGC, symbol remapping, etc. The processor **1119** may be adapted to perform routing functions. In some applications, the processor **1119** may perform signal duplication, addressing, signal deletion, signal insertion, signal monitoring, address adjustment, re-routing, request retransmission, update header information, and/or insert or adjust control information.

FIG. **11**C illustrates a CI transceiver adapted to decode received signals intended for the transceiver and partially decode and route signals intended for one or more other transceivers. System components shown in FIG. **11**C are similar to components shown in FIG. **11**B, as indicated by similar reference numbers.

The CI decoder **1103** applies one or more decode signals to the received baseband signal. If the received baseband signal is coded with one or more codes including complex conjugates of the one or more decode signals, a sum of decoded baseband symbols over a code period combines coherently. The combined symbols have a value associated with one or more information signals. The combined symbols may be provided as a data output after one or more optional signal-processing operations.

Symbols generated by the CI decoder **1103** are optionally processed in processor **1119** prior to being coupled to a transmission system **1106** for re-transmission. CI-encoded signals not corresponding to complex conjugates of at least one of the decode signals (i.e., not intended for the transceiver) contribute a substantially zero value to the combined symbols. The processor **1119** may be adapted to remove one or more signal components intended for the transceiver. Since the signals intended for the transceiver provide a dc offset to the individual symbols generated by the CI decoder **1106**, these signals may be removed by filtering, cancellation, or some other dc-removal process.

6. CI Routing and Control Methods

FIG. **11**D illustrates a method whereby a transceiver in a network is provided with control information **1151** that includes information used to generate one or more array-processing weights **1153**. Array processing **1153** may be integrated into one or more transceiving functions **1153**, such as transmitting, receiving, routing, and/or relay operations.

A subscriber unit (or any other network transceiver) may be adapted to provide a directional or otherwise adaptable beam pattern. A beam pattern may be considered to include any type of array processing, including, but not limited to, space-frequency processing, space-time processing, spatial interferometry, null steering, diversity combining, spatial sweeping, and/or direction-of-arrival processing. A network transceiver, such as a subscriber unit, may act as an antenna element in an array including other network transceivers. Thus, a network transceiver may provide one or more weights to its transmitted and/or received signals as part of a larger array-processing scheme. Similarly, each antenna element of a multi-element network transceiver may be regarded as a transceiver element in a larger array. Each transceiver element may be provided with weights as part of a larger array-processing scheme. Array processing may be performed relative to one or more operational characteristics and/or objectives.

Array processing may depend on one or more network parameters, such as relative location of each destination address, relative location of each transmission source, interference characteristics (e.g., origin of interference, time-domain characteristics, frequency-domain characteristics, polarization, power, etc.), channel characteristics (e.g., multipath, Doppler, etc.), link priority, link security, spectrum management, power control, and network loads. Array processing may depend on the locations of one or more network transceivers, such as relays, routers, access points, base stations, and other subscriber units. Array processing may be adapted relative to changing locations of other network transceivers, changing operational configurations, interference, frequency-reuse plans, channel conditions, power-control specifications, performance measurements (e.g., BER, probability of error, SNR, SNIR, etc.), subscriber services, information type, modulation, formatting, channel selection, multiple-access protocol, frequency band, channel bandwidth, as well as any other Physical Layer and/or MAC Layer configurations.

FIG. **11**E illustrates a method in which individual network transceivers are adapted to perform array processing relative to local conditions. A channel-estimation step **1150** provides a characterization of the propagation environment to better optimize array processing **1152** and/or CI processing. Any combination of sub-space processing (i.e., capacity enhancement) and diversity combining (i.e., signal-quality enhancement) may be performed. Array processing **1152** may be integrated into a transceiver-operations step **1153**.

FIG. **11**F illustrates an array-processing method that employs at least one central processor to provide beam-forming operations across a plurality of spatially distributed network transceivers. Signals received by the distributed network transceivers are coupled to the central processor, which performs channel estimation **1160** to characterize one or more communication channels. Various operational characteristics and/or objectives (e.g., network parameters) are evaluated **1161**. The evaluation **1161** can affect calculations of array-processing weights in a step **1162** that provides control information to a plurality of network transceivers. Alternatively, the step of providing control information **1162** may include applications of array-processing weights to signals received from and/or transmitted to the network transceivers by the central processor.

FIG. **12**A illustrates a method for providing CI-coded transmissions of information and control signals. The method described in FIG. **12**A may be performed by a subscriber unit acting as a base station in a CI network. A CI code generation process **1201** provides CI codes and/or CI-based codes for at least one information signal and at least one control signal. A control signal may provide for one or more control functions, such as, but not limited to, power control, synchronization, code assignments, priority assignments, link assignments, channel assignments, duplexing control, training-signal generation, notice of transfer of control responsibilities, and request acknowledgement. Coding processes **1202** and **1203** encode the information signal (s) and control signal(s), respectively. A transmission process **1204** provides for transmission of the coded signals.

FIG. **12**B illustrates a method for managing network control in a CI network by one or more subscriber units adapted to function as base stations. A CI transceiver acting as a base station transmits CI-coded information and control

signals in a transmission step **1210**. In a network identification and communication restriction step **1211**, CI codes can be used, at least in part, to address the communication and control channels. CI codes can be allocated to restrict communications between transceivers permitted to operate in the network. CI codes can also be used to identify a radio network and each of the radio devices, as well as the type of communications being transmitted.

A duplexing step **1212** provides for management of transmission and reception. Various types of duplexing may be employed, such as time-division duplexing, frequency-division duplexing, code-division duplexing, polarization-division duplexing, etc. A CI transceiver may include a plurality of CI decoders in parallel to allow reception of more than one signal simultaneously. Similarly, transmission of coded signals may be performed simultaneously with reception when the transmitted CI codes differ from the code of the received signal. Furthermore, different CI codes may be used to encode transmissions to differentiate types of transmitted signals.

A network-control step **1213** indicates that at least one of the subscriber units becomes a network control station. A network control station initiates communications and maintains power control and time synchronization of the network in the same manner that a base station would normally function. A transfer step provides for transfer of network control from at least one subscriber to at least one other subscriber. The network control station can voluntarily transfer, or be commanded to transfer, power control and time synchronization of the network to any other radio in the network.

FIG. **12**C illustrates a network-control method of the present invention. A CI coding step **1221** provides different CI codes (such as may be used to spread a signal) to information and control signals. A network control station may provide time-division duplexing **1222** to regulate transmission and reception. A network-control step **1223** provides for network control by the network control station. Network control **1223** can include various operations, including, but not limited to, synchronization, power control, code assignment, channel assignments, channel coding, transmission-path selection, load balancing, and spectrum management.

FIG. **12**D shows a routing method of the present invention. A coding step **1231** provides a multi-address, CI-coded signal for transmission in a transmission step **1232**. The addresses may be provided by any combination of CI coding and header addressing. Transmitted signals may be routed via one or more paths through a network. A duplication step **1233** is provided when transmission paths through a node diverge. Duplicated signals are transmitted along their respective paths.

In the methods and systems of the present invention, an address may include any combination of coding and header information. A header typically includes fields that provide control information, information-processing directives, waveform identification, network identification, and/or other information for enabling and facilitating network control and information processing. Tags are typically included in a header of a transmission. An information signal may be provided with one or more tags identifying the type of transmitted information, the amount of information, coding, number of addresses, routing information, and/or any other processing or payload information.

Header fields may include frame-sequence numbers, precedence, security, and end-of-message fields. A header may include a field indicating whether an acknowledgment is required from the destination node. Acknowledgments may be requested upon receipt, reading, and/or printing of received information. An extend field may identify whether an address is an extended network address usable when the destination node corresponding to the network address has moved from one network to another network. Information may be included in the header for forwarding a message to the other network. Information may be provided for updating routing tables maintained at a node. An end-of-routing field may be provided for indicating whether a network address is the last address in a multi-address network header. Tags and/or address information may be included in a preamble of a transmission.

FIG. **13**A shows a relay method of the present invention. Received signals are decoded in a decoding step **1301** at each node. The decoding step **1301** may involve applying a code to a received signal corresponding to the complex conjugate of the node's address code. A processing step **1302** processes information signals coded with the node's address code. Processing **1302** may include summing the decoded symbols and performing hard and/or soft decisions. Information signals addressed to the node provide a de offset to the symbols of the decoded signal. This offset may optionally be removed **1303** prior to transmitting **1305** the resulting decoded signals.

FIG. **13**B illustrates an alternative embodiment of a relay method of the invention. Some of the steps in the relay method shown in FIG. **13**B are similar to the steps shown in FIG. **13**A, as indicated by similar reference numbers. A reverse-decoding step **1304** provided between steps **1303** and **1305** applies the complex conjugate of any codes applied to the received signals in the decoding step **1302**.

FIG. **13**C illustrates a transceiver processing and routing method of the invention. A decoding step **1301** processes received signals with at least one complex-conjugate code corresponding to at least one address code associated with the transceiver address and/or one or more predetermined addresses. Decoding **1301** may include one or more decoding processes, such as channel decoding, multiple-access decoding, spread-spectrum decoding, and decryption. The decoding step **1301** may optionally include a level-detect function (not shown) to verify that a received signal is present prior to decoding.

A processing step **1302** is adapted to provide one or more signal-processing steps to the decoded signals. The processing step **1302** may estimate the values of information or control signals impressed onto address codes corresponding to one or more complex-conjugate codes provided in the decoding step **1301**. For example, an adding step (not shown) may provide for coherent combining of addressed information symbols. A decision step (not shown) may follow the adding step (not shown). If any signal values are present, they may be passed to an optional error detection/correction step **1311**.

Error detection/correction **1311** may employ parity checks, trellis demodulation, convolutional decoding, block decoding, and/or any other channel decoding or error-checking technique. Errors may be corrected via receiver-side processing. Alternatively, error detection may initiate a request for re-transmission. Error detection/correction **1311** may include re-quantization, channel estimation, channel compensation, predistortion of transmissions, multi-user detection, and/or optimal combining. Error detection/correction **1311** may include decision processing, including hard decisions and/or soft decisions. Decision processing may include iterative feedback processing, such as turbo decoding.

The signal values may be provided to an optional system-function step **1312**. Confidence measures from soft-decision processes may be used to adapt receiver parameters (e.g., the processing step **1302**), such as to optimize reception. Similarly, received control information may be used to adjust receiver parameters. System functions **1312** may include AGC, adapting filter parameters, adjusting quantization constellations, and/or changing sampling parameters. System functions may also include removing symbols or values associated with one or more predetermined addresses from the input signal values.

The signal values may be provided to an optional network-function step **1313**. Network functions **1313** may be selected or adapted relative to received control information. Network functions **1313** may include routing, addressing, power control, synchronization, request re-transmission, multiple-access control, channel selection, authentication, verification, identification, link-priority assignments, load balancing, spectrum management, and/or error processing. Network functions **1313** may include adding, removing, and/or changing system control information.

Data and control information are re-encoded in a coding step **1304**. Re-encoding **1304** may include the application of one or more codes, including address codes, multiple-access codes, spreading codes, channel codes, and encryption. Coded signals are processed for transmission into a communication channel in a transmission step **1305**.

FIG. **13**D illustrates a transceiver processing and routing method of the invention. A received signal is duplicated in a duplication step **1300**. Δt least one duplicated signal is coupled into a decoding step **1321** that applies a complex-conjugate code to the received signal. The complex-conjugate code is related to the address code of the transceiver. The decoded signal is processed in a processing step **1322** to extract or otherwise estimate information values addressed to the transceiver.

Δt least one of the duplicated signals is input to a secure procedure **1310**. For example, the at least one duplicated signal is passed through a fire wall (not shown). A decoding step **1316** provides for decoding signals addressed to one or more destinations other than the current transceiver. A processing step **1318** is adapted to provide one or more signal-processing steps to the decoded signals. The processing step **1318** may estimate the values of information or control signals impressed onto address codes corresponding to the complex-conjugate code(s) provided in the decoding step **1310**.

Processed signals may be coupled to one or more optional processing steps, including error detection/correction **1311**, system function **1312**, and network function **1313** steps. The processed signals are encoded **1314** prior to being transmitted **1305**. Similarly, data input to the transceiver is encoded **1324** prior to being transmitted **1305**.

7. Scope of the Invention

In the preferred embodiments, several kinds of addressing, coding, and routing are demonstrated to provide a basic understanding of applications of CI processing in ad-hoc and peer-to-peer networks. With respect to this understanding, many aspects of this invention may vary.

For illustrative purposes, flowcharts and signal diagrams represent the operation of the invention. It should be understood, however, that the use of flowcharts and diagrams is for illustrative purposes only, and is not limiting. For example, the invention is not limited to the operational embodiments represented by the flowcharts. The invention is not limited to specific network architectures shown in the drawings. Instead, alternative operational embodiments and network architectures will be apparent to persons skilled in the relevant art(s) based on the discussion contained herein. Also, the use of flowcharts and diagrams should not be interpreted as limiting the invention to discrete or digital operation.

In practice, as will be appreciated by persons skilled in the relevant art(s) based on the discussion herein, the invention can be achieved via discrete or continuous operation, or a combination thereof. Furthermore, the flow of control represented by the flowcharts is provided for illustrative purposes only. As will be appreciated by persons skilled in the relevant art(s), other operational control flows are within the scope and spirit of the present invention.

Exemplary structural embodiments for implementing the methods of the invention are also described. It should be understood that the invention is not limited to the particular embodiments described herein. Alternate embodiments (equivalents, extensions, variations, deviations, combinations, etc.) of the methods and structural embodiments of the invention and the related art will be apparent to persons skilled in the relevant arts based on the teachings contained herein. The invention is intended and adapted to include such alternate embodiments. Such equivalents, extensions, variations, deviations, combinations, etc., are within the scope and spirit of the present invention.

Signal processing with respect to sinusoidal oscillating signals are described herein. Those skilled in the art will recognize that other types of periodic oscillating signals that can be used, including, but not limited to, sinusoids, square waves, triangle waves, wavelets, repetitive noise waveforms, pseudo-noise signals, and arbitrary waveforms.

The foregoing discussion and the claims that follow describe the preferred embodiments of the present invention. With respect to the claims, it should be understood that changes can be made without departing from the essence of the invention. To the extent such changes embody the essence of the present invention, each naturally falls within the breadth of protection encompassed by this patent. This is particularly true for the present invention because its basic concepts and understandings are fundamental in nature and can be broadly applied.

The invention claimed is:

1. A method comprising:

dividing a block of complex-valued symbols into a plurality of sets of complex-valued symbols;

transform precoding each of the plurality of sets of complex-valued symbols into a block of transform-precoded complex-valued symbols; and

generating an Orthogonal Frequency Division Multiplex (OFDM) signal comprising a plurality of OFDM subcarriers modulated by the transform-precoded complex-valued symbols, wherein the transform precoding generates a plurality of orthogonal spreading codes to provide a superposition of the plurality of OFDM subcarriers with a reduced peak-to-average-power ratio.

2. The method of claim **1**, wherein the transform precoding spreads the block of complex-valued symbols with a plurality of orthogonal spreading codes comprising complex-valued coefficients of a discrete Fourier transform (DFT) to produce the block of transform-precoded complex-valued symbols.

3. The method of claim **2**, wherein the DFT is a fast Fourier transform (FFT).

4. The method of claim 2, wherein:

$M_{sc}^{PUSCH}=M_{RB}^{PUSCH}*N_{sc}^{RB}$;

M_{RB}^{PUSCH} is a scheduled bandwidth for uplink transmission expressed as a number of resource blocks; and

N_{sc}^{RB} is a resource block size in the frequency domain expressed as a number of subcarriers.

5. The method of claim 4, wherein:

$M_{RB}^{PUSCH}\leq N_{RB}^{UL}$; and

N_{RB}^{UL} is an uplink bandwidth configuration expressed in multiples of N_{sc}^{RB}.

6. The method of claim 1, comprising:

mapping the block of transform-precoded complex-valued symbols to physical resource blocks assigned for transmission of a physical uplink shared channel.

7. The method of claim 6, wherein the mapping is responsive to an assignment of spectrum resources for selecting a plurality of OFDM subcarriers corresponding to at least one OFDM symbol interval.

8. The method of claim 6, wherein at least one of the transform precoding and the mapping is configured to weight each of the plurality of OFDM subcarriers with an amplitude scaling factor to adjust gain of the superposition.

9. The method of claim 6, wherein the mapping is configured to select the plurality of OFDM subcarriers according to at least one of a frequency division multiple access scheme, a time division multiple access scheme, a space division multiple access scheme, a code division multiple access scheme, and a frequency-hoping scheme.

10. The method of claim 1, comprising:

scrambling a block of bits of one subframe of a physical uplink shared channel resulting in a block of scrambled bits; and

modulating the block of scrambled bits resulting in the block of complex-valued symbols.

11. The method of claim 10, wherein the scrambling is configured to scramble the block of bits into a block of scrambled bits with at least one pseudo-noise code.

12. The method of claim 1, wherein the transform precoding is applied according to

$$z(l\cdot M_{sc}^{PUSCH}+k)=\frac{1}{\sqrt{M_{sc}^{PUSCH}}}\sum_{i=0}^{M_{sc}^{PUSCH}-1}d(l\cdot M_{sc}^{PUSCH}+i)e^{-j\frac{2\pi ik}{M_{sc}^{PUSCH}}},$$

wherein:

the block of complex-valued symbols and the block of transform-precoded complex-valued symbol comprises a plurality of resource elements;

l represents a time-domain index of each of the plurality of resource elements;

k represents a frequency-domain index of each of the plurality of resource elements;

M_{sc}^{PUSCH} is a scheduled bandwidth for uplink transmission expressed as a number of subcarriers;

$d(l\cdot M_{sc}^{PUSCH}+i)$ represents resource elements of the block of complex-valued symbols; and

$z(l\cdot M_{sc}^{PUSCH}+k)$ represents resource elements of the block of transform precoded complex-valued symbols.

13. The method of claim 12, wherein:

the transform precoding spreads the block of complex-valued symbols with a plurality of orthogonal spreading codes comprising complex-valued coefficients of a discrete Fourier transform (DFT) to produce the block of transform precoded complex-valued symbols; and

M_{sc}^{PUSCH} is a length of the DFT corresponding to the plurality of orthogonal spreading codes.

14. The method of claim 13, wherein:

each transform-precoded set of complex-valued symbols of the block of transform-precoded complex-valued symbols is a single-carrier frequency division multiple access symbol; and

said each transform precoded set of complex-valued symbols is processed by the DFT.

15. The method of claim 12, wherein:

the block of transform-precoded complex-valued symbols comprises carrier interferometry symbol values (w_n); and

the block of complex-valued symbols comprises data symbols (s_n).

16. The method of claim 15, wherein carrier interferometry code chip values are arranged with respect to a plurality of phase spaces.

17. The method of claim 16, wherein the plurality of phase spaces comprises orthogonal phase spaces.

18. The method of claim 16, wherein each of the data symbol values is impressed upon one of the plurality of phase spaces.

19. The method of claim 15, wherein the number of carrier interferometry symbol values is different than the number of data symbols.

20. The method of claim 1, wherein each of the plurality of sets of complex-valued symbols is a single carrier frequency division multiple access (SC-FDMA) symbol.

21. The method of claim 1, comprising generating a time-continuous signal defined by:

$$s_l(t)=\sum_{k=-\lfloor N_{RB}^{UL}N_{sc}^{RB}/2\rfloor}^{\lfloor N_{RB}^{UL}N_{sc}^{RB}/2\rfloor-1}a_{k^{(-)},l}e^{j2\pi(k+1/2)\Delta f(t-N_{CP,l}T_s)},$$

wherein:

N_{sc}^{RB} is a resource block size in a frequency domain express as a number of subcarriers;

N_{RB}^{UL} is an uplink bandwidth configuration express in multiples of N_{sc}^{RB};

$a_{k^{(-)},l}$ is a value of a resource element;

Δf is subcarrier spacing;

$N_{CP,l}$ is a downlink cyclic prefix length for OFDM symbol l in a slot; and

T_s is a basic time unit.

22. The method of claim 21, wherein the time-continuous signal is generated in a single carrier frequency division multiple access (SC-FDMA) symbol.

23. The method of claim 1, wherein the transform precoding generates a plurality of quasi-orthogonal complex-valued spreading codes to provide a superposition of the plurality of OFDM subcarriers with a reduced peak-to-average-power ratio.

24. An apparatus, comprising:

a processor; and

a non-transitory computer-readable memory communicatively coupled to the processor, the memory including a set of instructions stored thereon and executable by the processor for:

dividing a block of complex-valued symbols into a plurality of sets of complex-valued symbols;

transform precoding each of the plurality of sets of complex-valued symbols into a block of transform precoded complex-valued symbols; and

generating an Orthogonal Frequency Division Multiplex (OFDM) signal comprising a plurality of OFDM subcarriers modulated with the transform-precoded complex-valued symbols, wherein the transform precoding generates a plurality of orthogonal spreading codes to provide a superposition of the plurality of OFDM subcarriers with a reduced peak-to-average-power ratio.

25. The apparatus of claim **24**, wherein the transform precoding spreads the block of complex-valued symbols with a plurality of orthogonal spreading codes comprising complex-valued coefficients of a discrete Fourier transform (DFT) to produce the block of transform-precoded complex-valued symbols.

26. The apparatus of claim **25**, wherein the DFT is a fast Fourier transform (FFT).

27. The apparatus of claim **25**, wherein:

$$M_{sc}^{PUSCH}=M_{RB}^{PUSCH}*N_{sc}^{RB};$$

M_{RB}^{PUSCH} is a scheduled bandwidth for uplink transmission expressed as a number of resource blocks; and

N_{sc}^{RB} is a resource block size in the frequency domain expressed as a number of subcarriers.

28. The method of claim **27**, wherein:

$$M_{RB}^{PUSCH}\leq N_{RB}^{UL};\text{ and}$$

N_{RB}^{UL} is an uplink bandwidth configuration expressed in multiples of N_{sc}^{RB}.

29. The apparatus of claim **24**, comprising instructions for:

mapping the block of transform-precoded complex-valued symbols to physical resource blocks assigned for transmission of a physical uplink shared channel.

30. The apparatus of claim **29**, wherein the mapping is responsive to an assignment of spectrum resources for selecting a plurality of OFDM subcarriers corresponding to at least one OFDM symbol interval.

31. The apparatus of claim **29**, wherein at least one of the transform precoding and the mapping is configured to weight each of the plurality of OFDM subcarriers with an amplitude scaling factor to adjust gain of the superposition.

32. The apparatus of claim **29**, wherein the mapping is configured to select the plurality of OFDM subcarriers according to at least one of a frequency division multiple access scheme, a time division multiple access scheme, a space division multiple access scheme, a code division multiple access scheme, and a frequency-hoping scheme.

33. The apparatus of claim **24**, comprising instructions for:

scrambling a block of bits of one subframe of a physical uplink shared channel resulting in a block of scrambled bits; and

modulating the block of scrambled bits resulting in the block of complex-valued symbols.

34. The apparatus of claim **33**, wherein the scrambling is configured to scramble the block of bits into a block of scrambled bits with at least one pseudo-noise code.

35. The apparatus of claim **24**, wherein the transform precoding is applied according to

$$z(l\cdot M_{sc}^{PUSCH}+k)=\frac{1}{\sqrt{M_{sc}^{PUSCH}}}\sum_{i=0}^{M_{sc}^{PUSCH}-1}d(l\cdot M_{sc}^{PUSCH}+i)e^{-j\frac{2\pi ik}{M_{sc}^{PUSCH}}},$$

wherein:

the block of complex-valued symbols and the block of transform-precoded complex-valued symbol comprises a plurality of resource elements;

l represents a time-domain index of each of the plurality of resource elements;

k represents a frequency-domain index of each of the plurality of resource elements;

M_{sc}^{PUSCH} is a scheduled bandwidth for uplink transmission expressed as a number of subcarriers;

$d(l\cdot M_{sc}^{PUSCH}+i)$ represents resource elements of the block of complex-valued symbols; and

$z(l\cdot M_{sc}^{PUSCH}+k)$ represents resource elements of the block of transform precoded complex-valued symbols.

36. The apparatus of claim **35**, wherein:

the transform precoding spreads the block of complex-valued symbols with a plurality of orthogonal spreading codes comprising complex-valued coefficients of a discrete Fourier transform (DFT) to produce the block of transform precoded complex-valued symbols; and

M_{sc}^{PUSCH} is a length of the DFT corresponding to the plurality of orthogonal spreading codes.

37. The apparatus of claim **36**, wherein:

each transform-precoded set of complex-valued symbols of the block of transform-precoded complex-valued symbols is a single-carrier frequency division multiple access symbol; and

said each transform precoded set of complex-valued symbols is processed by the DFT.

38. The apparatus of claim **36**, wherein the time-continuous signal is generated in a single carrier frequency division multiple access (SC-FDMA) symbol.

39. The method of claim **35**, wherein:

the block of transform-precoded complex-valued symbols comprises carrier interferometry symbol values (w_n); and

the block of complex-valued symbols comprises data symbols (s_n).

40. The method of claim **39**, wherein carrier interferometry code chip values are arranged with respect to a plurality of phase spaces.

41. The method of claim **40**, wherein the plurality of phase spaces comprises orthogonal phase spaces.

42. The method of claim **39**, wherein the number of carrier interferometry symbol values is different than the number of data symbols.

43. The method of claim **40**, wherein each of the data symbol values is impressed upon one of the plurality of phase spaces.

44. The method of claim **24**, wherein each of the plurality of sets of complex-valued symbols is a single carrier frequency division multiple access (SC-FDMA) symbol.

45. The method of claim **24**, comprising generating a time-continuous signal defined by:

$$s_l(t)=\sum_{k=-\lfloor N_{RB}^{UL}N_{sc}^{RB}/2\rfloor}^{\lfloor N_{RB}^{UL}N_{sc}^{RB}/2\rfloor-1}a_{k(-),l}e^{j2\pi(k+1/2)\Delta f(t-N_{CP,l}T_s)},$$

wherein:

N_{sc}^{RB} is a resource block size in a frequency domain express as a number of subcarriers;

N_{RB}^{UL} is an uplink bandwidth configuration express in multiples of N_{sc}^{RB};

$a_{k(-),l}$ is a value of a resource element;

Δf is subcarrier spacing;

$N_{CP,l}$ is a downlink cyclic prefix length for OFDM symbol **1** in a slot; and

T_s is a basic time unit.

46. The apparatus of claim **24**, wherein the transform precoding generates a plurality of quasi-orthogonal complex-valued spreading codes to provide a superposition of the plurality of OFDM subcarriers with a reduced peak-to-average-power ratio.

47. A computer program product, comprising a non-transitory computer readable hardware storage device having computer readable program code stored therein, said program code containing instructions executable by one or more processors of a computer system to implement a method comprising:

dividing a block of complex-valued symbols into a plurality of sets of complex-valued symbols; and

transform precoding each of the plurality of sets of complex-valued symbols into a block of transform precoded complex-valued symbols; and

generating an Orthogonal Frequency Division Multiplex (OFDM) signal comprising a plurality of OFDM subcarriers modulated with the transform-precoded complex-valued symbols, wherein the transform precoding generates a plurality of orthogonal spreading codes to provide a superposition of the plurality of OFDM subcarriers with a reduced peak-to-average-power ratio.

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(54) **MULTICARRIER SUB-LAYER FOR DIRECT SEQUENCE CHANNEL AND MULTIPLE-ACCESS CODING**

(71) Applicant: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

(72) Inventor: **Steve Shattil**, Cheyenne, WY (US)

(73) Assignee: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

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None
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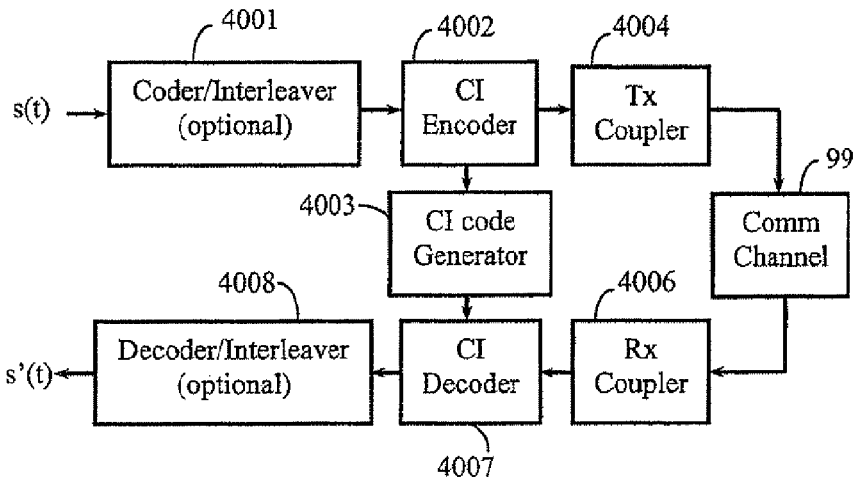
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Primary Examiner — Diane L Lo
(74) *Attorney, Agent, or Firm* — Steven J Shattil

(57) **ABSTRACT**

Carrier Interferometry (CI) provides wideband transmission protocols with frequency-band selectivity to improve interference rejection, reduce multipath fading, and enable operation across non-continuous frequency bands. Direct-sequence protocols, such as DS-CDMA, are provided with CI to greatly improve performance and reduce transceiver complexity. CI introduces families of orthogonal polyphase codes that can be used for channel coding, spreading, and/or multiple access. Unlike conventional DS-CDMA, CI coding is not necessary for energy spreading because a set of CI carriers has an inherently wide aggregate bandwidth. Instead, CI codes are used for channelization, energy smoothing in the frequency domain, and interference suppression. CI-based ultra-wideband protocols are implemented via frequency-domain processing to reduce synchronization problems, transceiver complexity, and poor multipath performance of conventional ultra-wideband systems. CI allows wideband protocols to be implemented with space-frequency processing and other array-processing techniques to provide either or both diversity combining and sub-space processing. CI also enables spatial processing without antenna arrays. Even the bandwidth efficiency of multicarrier protocols is greatly enhanced with CI. CI-based wavelets avoid time and frequency resolution trade-offs associated with conventional wavelet processing. CI-based Fourier transforms eliminate all multiplications, which greatly simplifies multi-frequency processing. The quantum-wave principles of CI improve all types of baseband and radio processing.

27 Claims, 111 Drawing Sheets



Related U.S. Application Data

continuation of application No. 16/027,191, filed on Jul. 3, 2018, now Pat. No. 10,574,497, which is a continuation of application No. 15/642,850, filed on Jul. 6, 2017, now Pat. No. 10,015,034, which is a continuation of application No. 15/489,664, filed on Apr. 17, 2017, now Pat. No. 9,800,448, which is a continuation of application No. 15/149,382, filed on May 9, 2016, now Pat. No. 9,628,231, which is a continuation-in-part of application No. 14/727,769, filed on Jun. 1, 2015, which is a continuation of application No. 14/276,309, filed on May 13, 2014, now Pat. No. 9,048,897, which is a continuation of application No. 12/545,572, filed on Aug. 21, 2009, now Pat. No. 8,750,264, which is a division of application No. 11/187,107, filed on Jul. 22, 2005, now Pat. No. 8,670,390.

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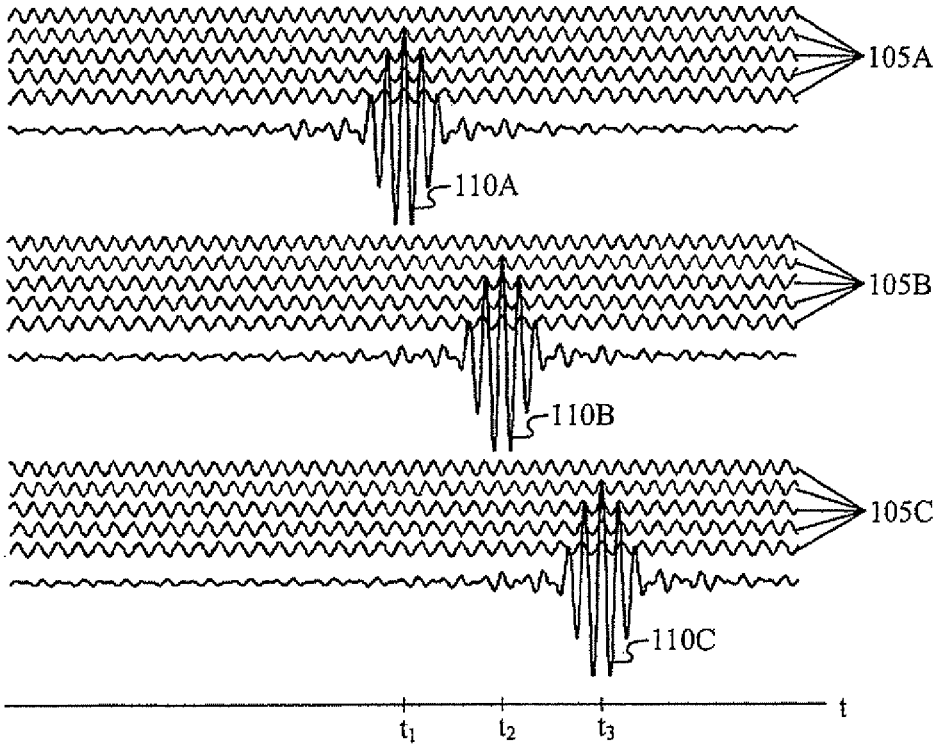


FIG. 1A

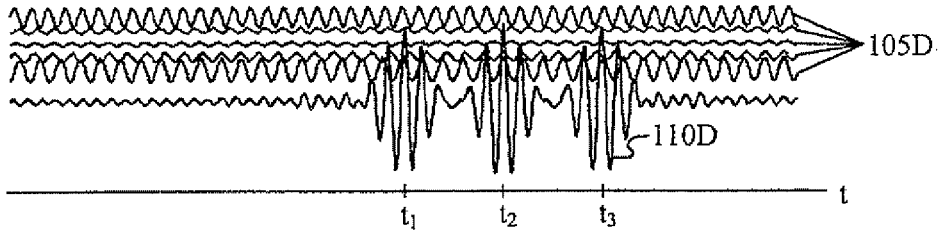


FIG. 1B

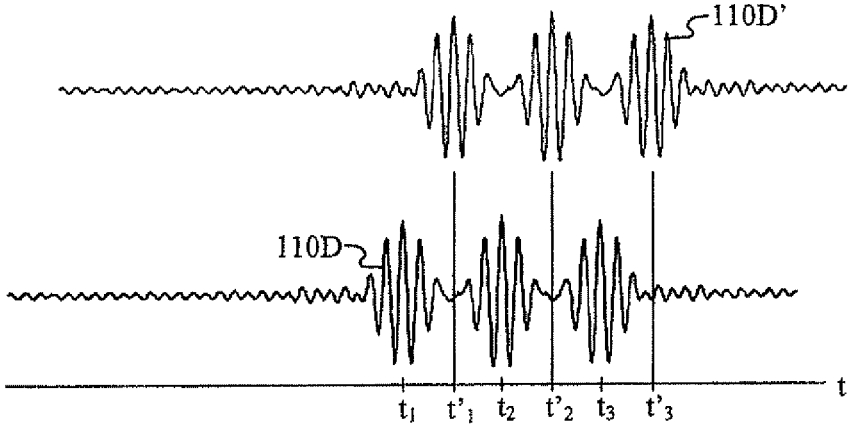


FIG. 1C

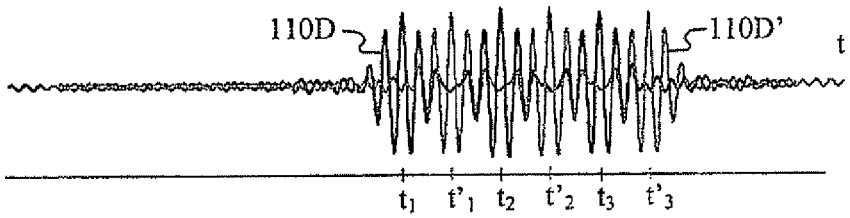


FIG. 1D

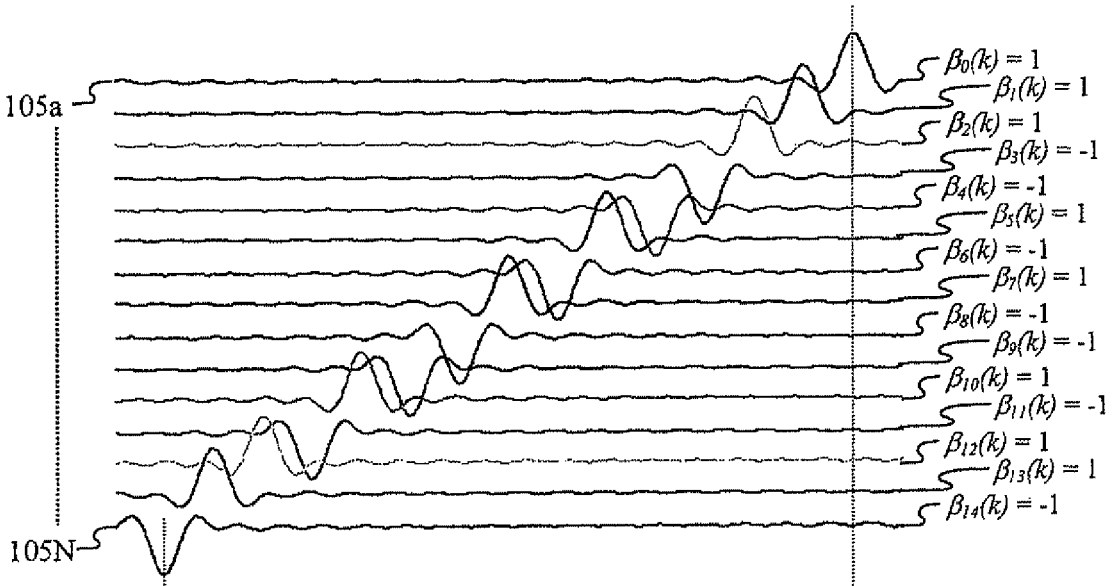

105a
105N
$\beta_0(k) = 1$
$\beta_1(k) = 1$
$\beta_2(k) = 1$
$\beta_3(k) = -1$
$\beta_4(k) = -1$
$\beta_5(k) = 1$
$\beta_6(k) = -1$
$\beta_7(k) = 1$
$\beta_8(k) = -1$
$\beta_9(k) = -1$
$\beta_{10}(k) = 1$
$\beta_{11}(k) = -1$
$\beta_{12}(k) = 1$
$\beta_{13}(k) = 1$
$\beta_{14}(k) = -1$

FIG. 2A

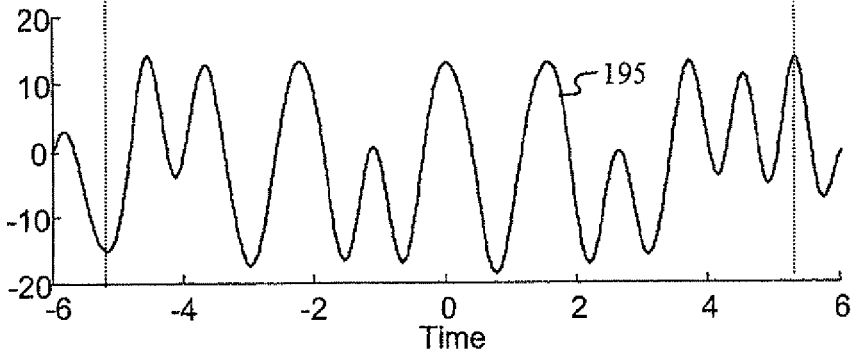

20
10
0
-10
-20
-6
-4
-2
0
2
4
6
Time
195

FIG. 2B

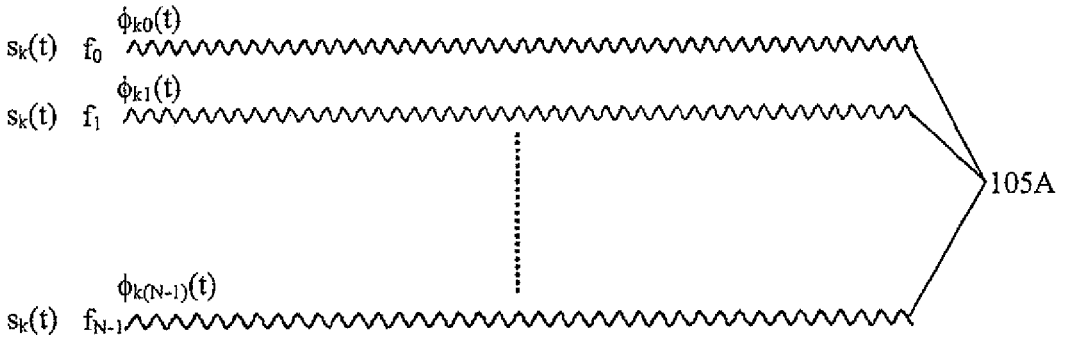


FIG. 3

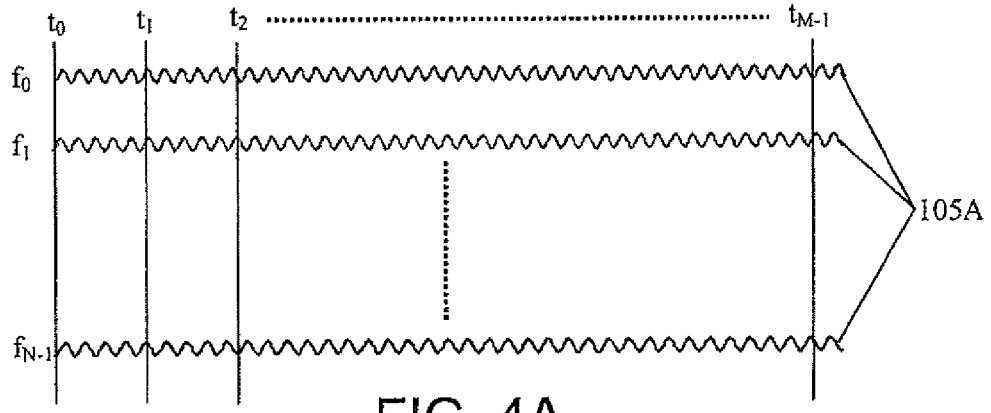


FIG. 4A

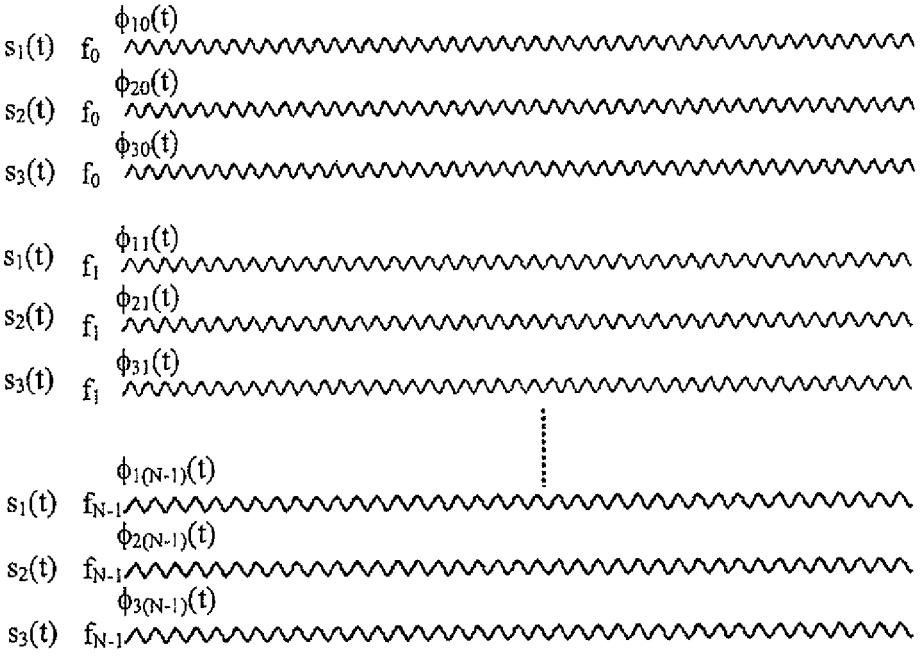


FIG. 4B

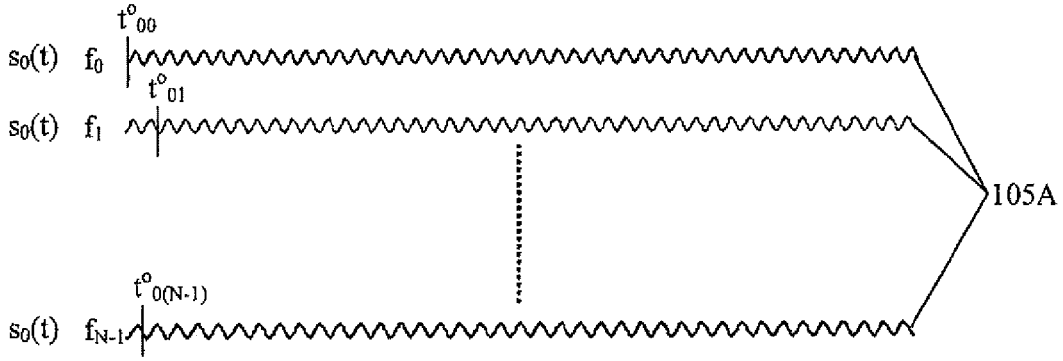


FIG. 5

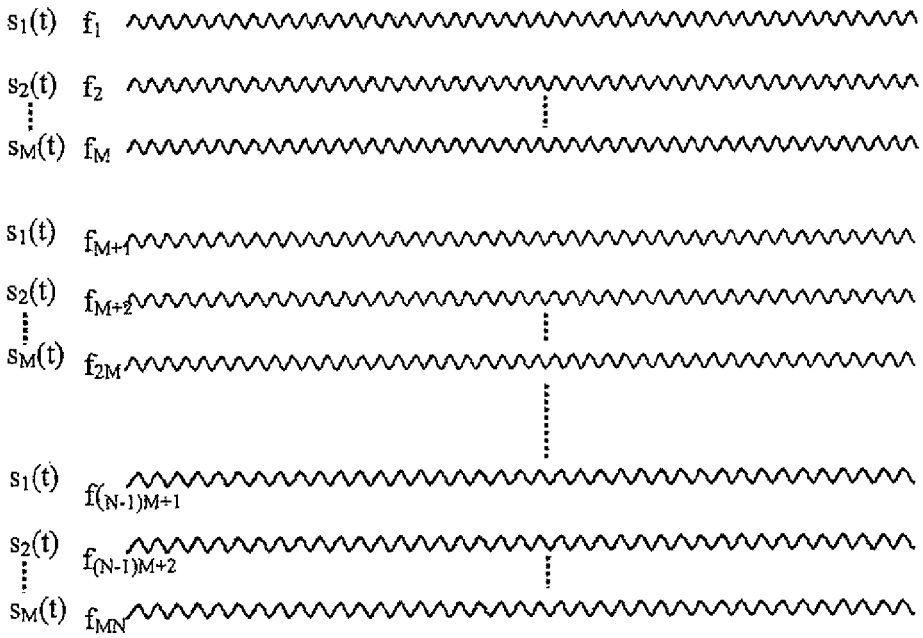


FIG. 6A

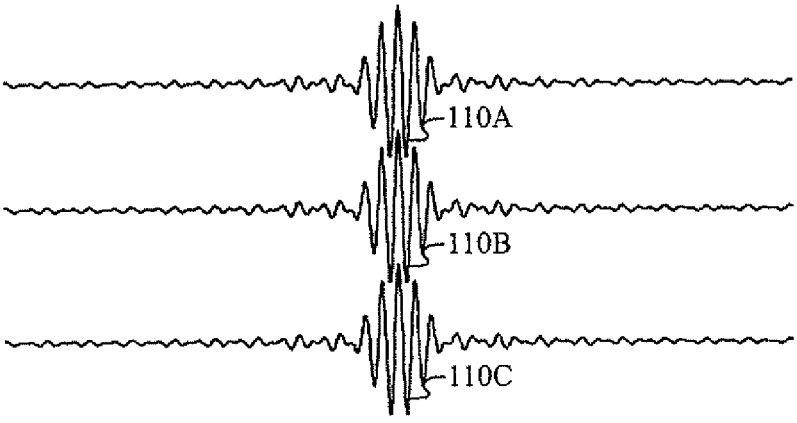


FIG. 6B

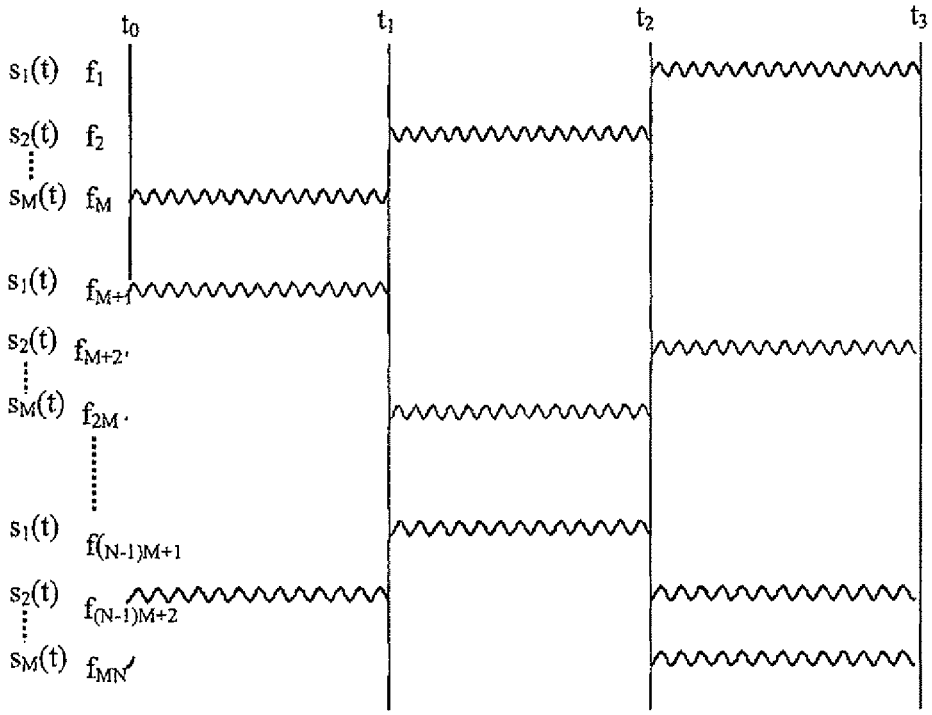

t0
t1
t2
t3
s1(t) f1
s2(t) f2
sM(t) fM
s1(t) fM+1
s2(t) fM+2
sM(t) f2M
s1(t) f(N-1)M+1
s2(t) f(N-1)M+2
sM(t) fMN

FIG. 7

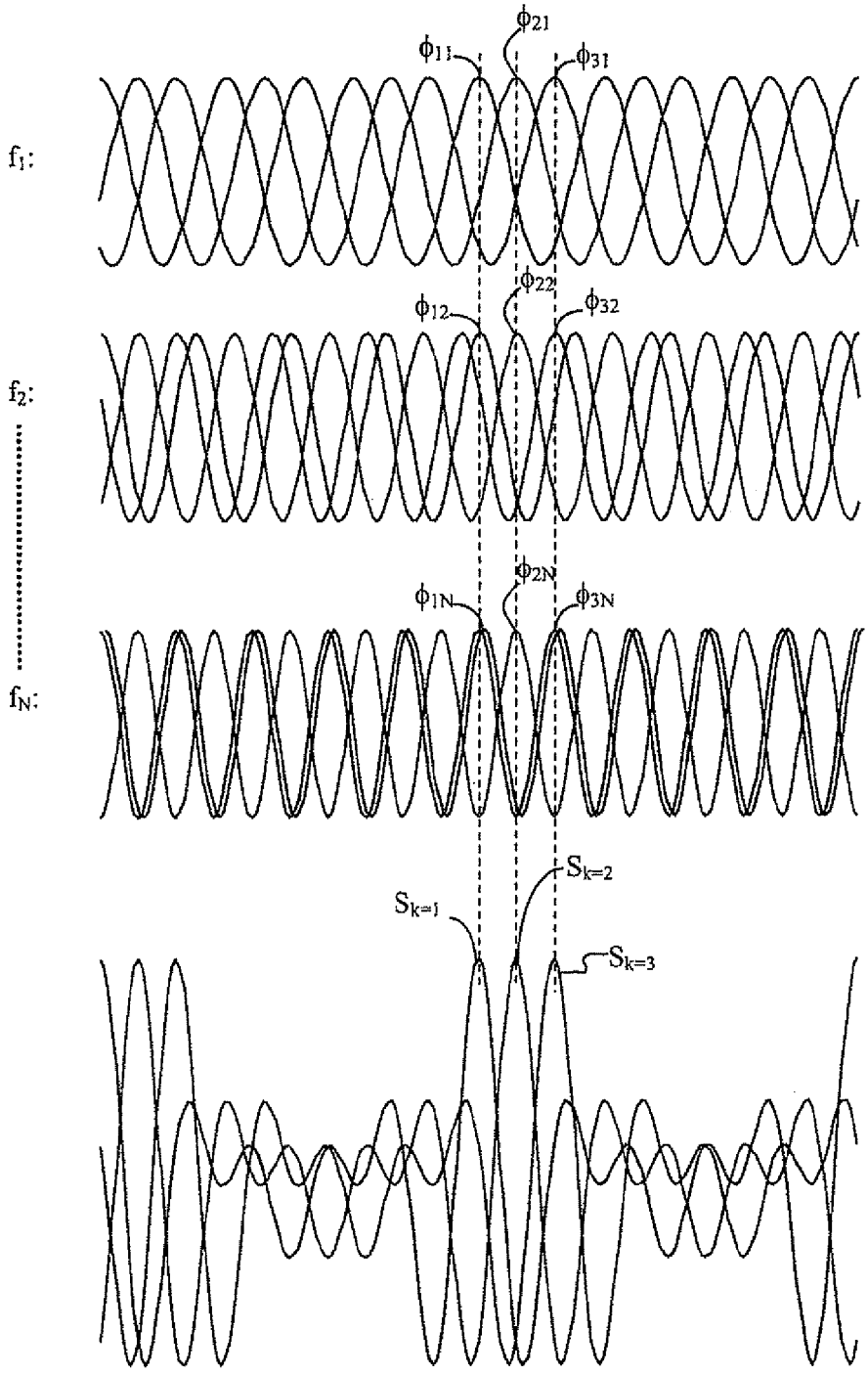

ϕ_{21}
ϕ_{11}
ϕ_{31}
f_1:
ϕ_{22}
ϕ_{12}
ϕ_{32}
f_2:
ϕ_{2N}
ϕ_{1N}
ϕ_{3N}
f_N:
$S_{k=2}$
$S_{k=1}$
$S_{k=3}$

FIG. 8

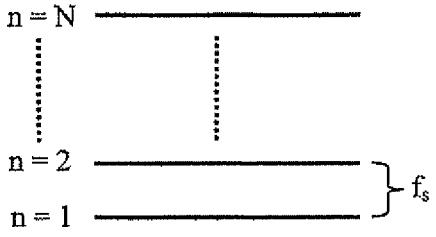


FIG. 9A

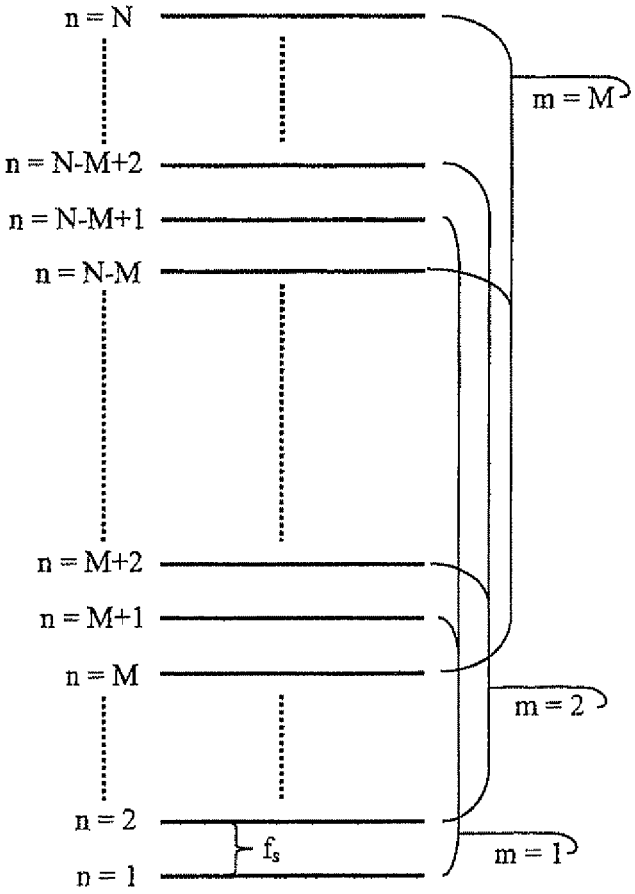


FIG. 9B



FIG. 10A

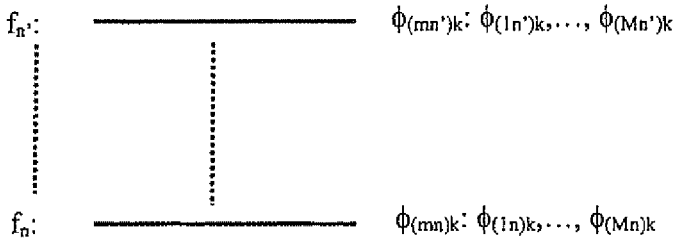


FIG. 10B

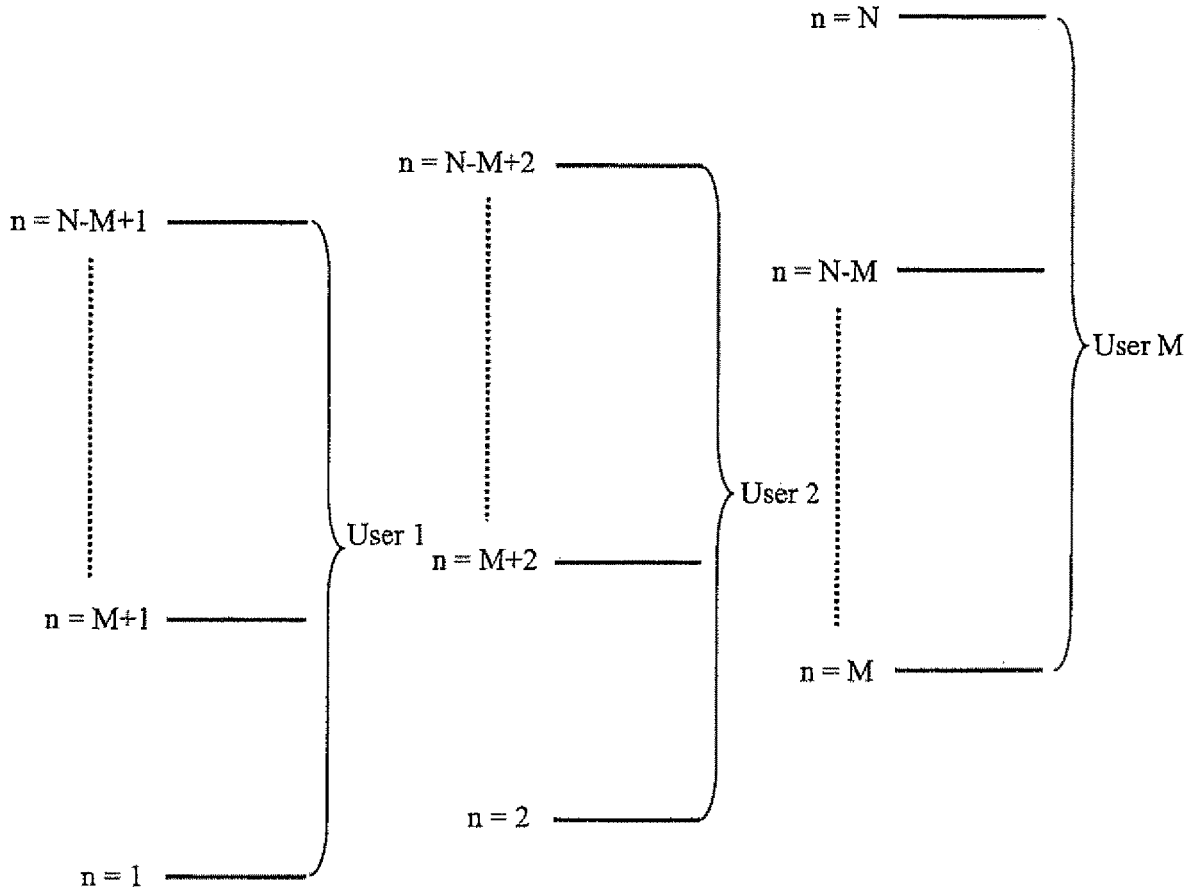

n = N
n = N-M+2
n = N-M+1
n = N-M
User M
User 2
User 1
n = M+2
n = M+1
n = M
n = 2
n = 1

FIG. 11

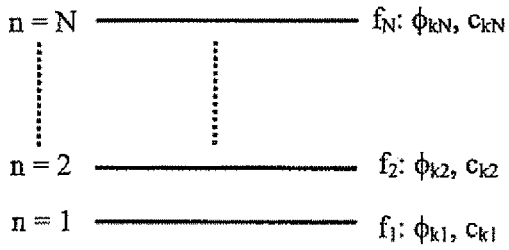

n = N
f_N: ϕ_{kN}, c_{kN}
n = 2
f_2: ϕ_{k2}, c_{k2}
n = 1
f_1: ϕ_{k1}, c_{k1}

FIG. 12

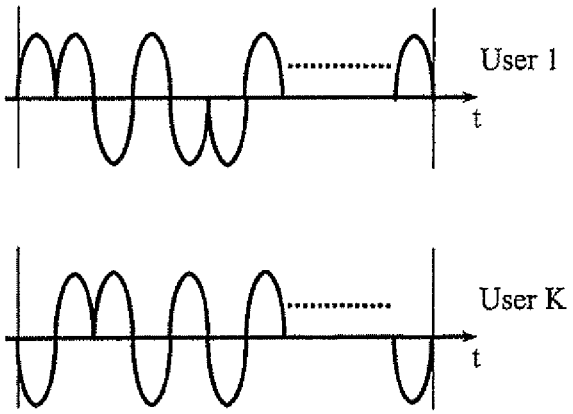


FIG. 13A

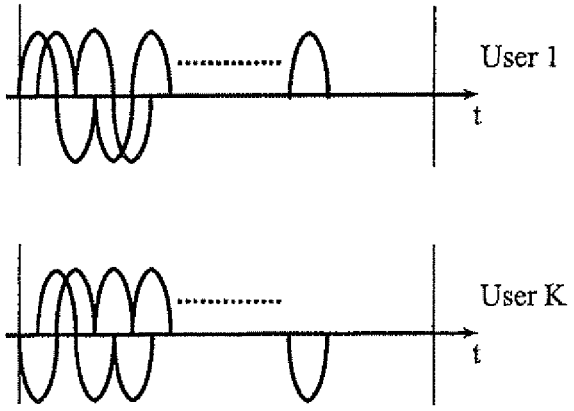


FIG. 13B

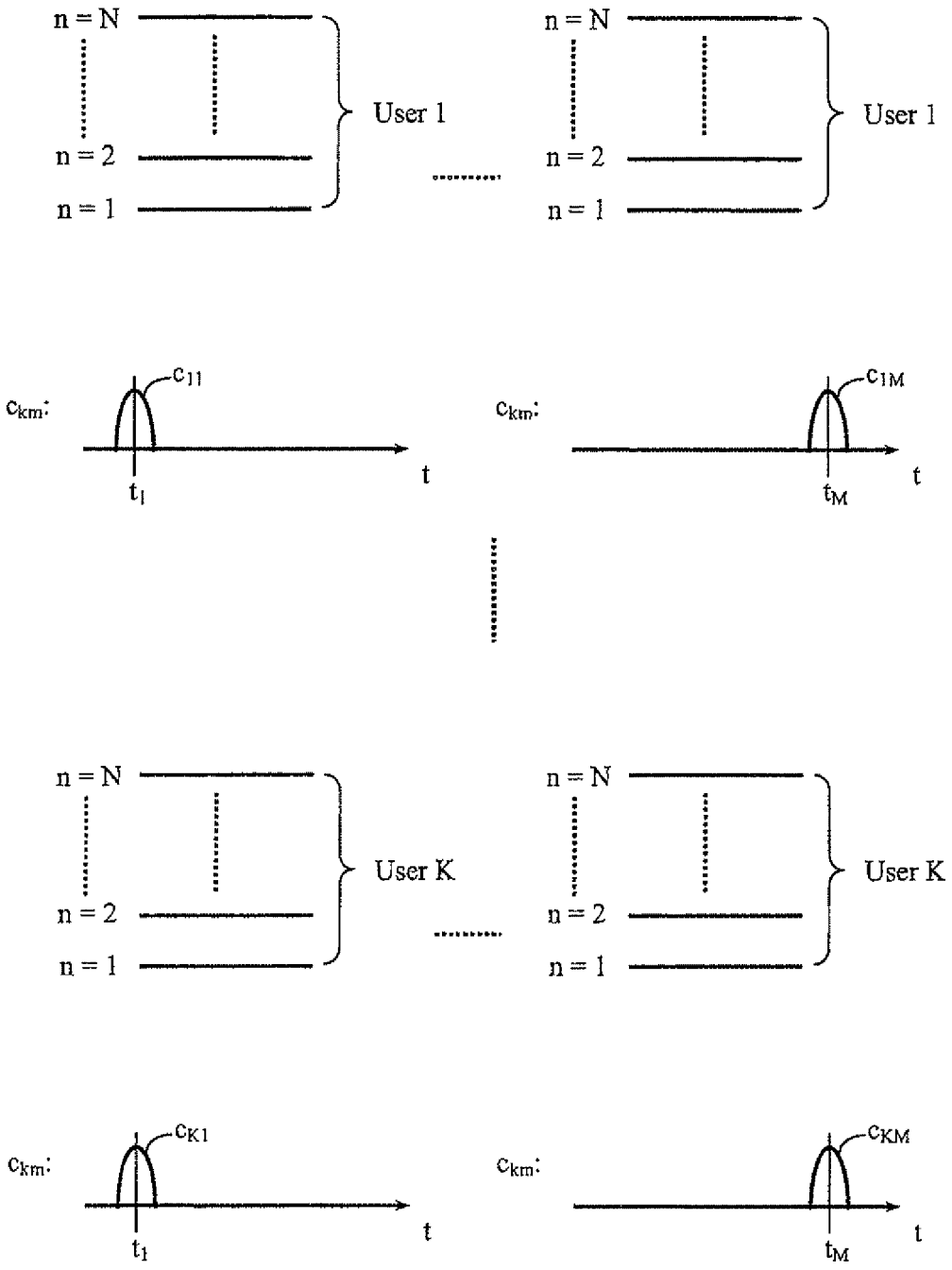


FIG. 13C

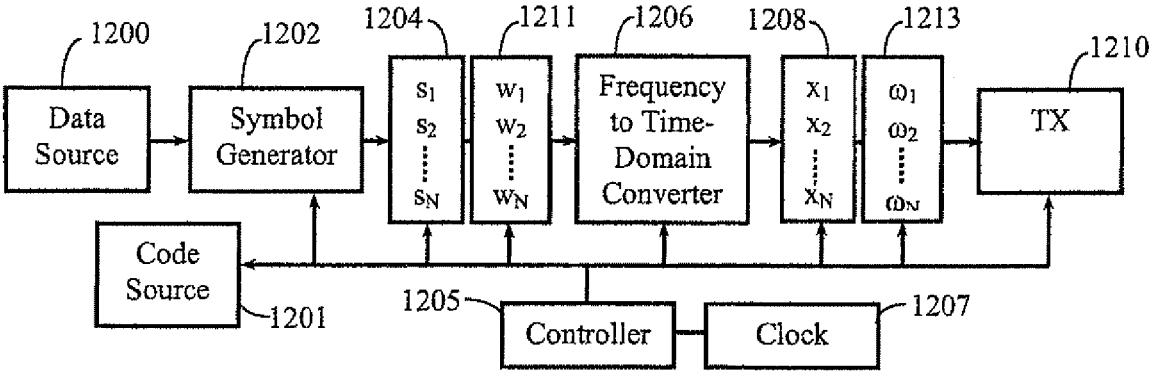


FIG. 14A

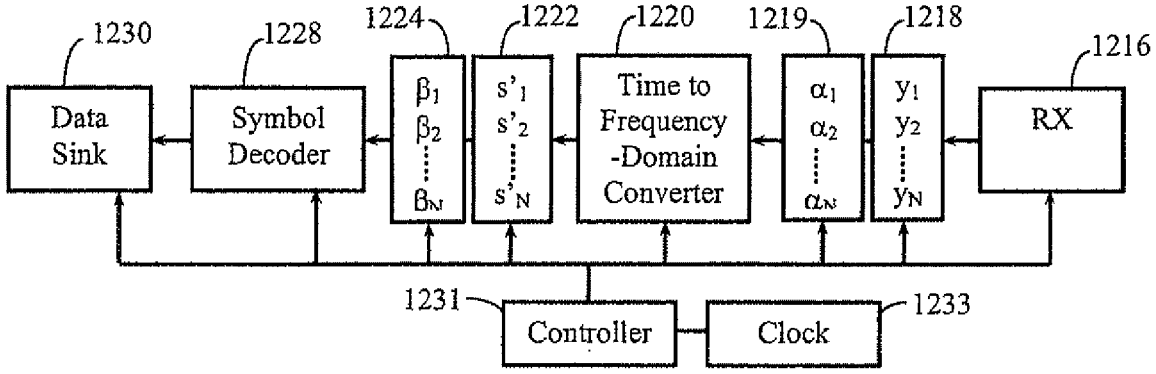


FIG. 14B

	$Ps(0)$	$Ps(1)$	$Ps(2)$	.....	$Ps(N-1)$
f_0:	ϕ_0	ϕ_0	ϕ_0		ϕ_0
f_1:	ϕ_1	$\phi_1 + 2\pi T_{ps} f_1$	$\phi_1 + 2\pi 2 T_{ps} f_1$	.....	$\phi_1 + 2\pi(N-1) T_{ps} f_1$
f_2:	ϕ_2	$\phi_2 + 2\pi T_{ps} f_2$	$\phi_2 + 2\pi 2 T_{ps} f_2$	.....	$\phi_2 + 2\pi(N-1) T_{ps} f_2$
⋮	⋮	⋮	⋮		⋮
f_{N-1}:	ϕ_{N-1}	$\phi_{N-1} + 2\pi T_{ps} f_{N-1}$	$\phi_{N-1} + 2\pi 2 T_{ps} f_{N-1}$	.....	$\phi_{N-1} + 2\pi(N-1) T_{ps} f_{N-1}$

FIG. 15A

	$Ps(0)$	$Ps(1)$	$Ps(2)$	.....	$Ps(N-1)$
f_0:	s_0	s_1	s_2		s_{N-1}
f_1:	s_0	$s_1 e^{i2\pi T_{ps} f_s}$	$s_2 e^{i2\pi 2 T_{ps} f_s}$	.....	$s_{N-1} e^{i2\pi(N-1) T_{ps} f_s}$
f_2:	s_0	$s_1 e^{i2\pi T_{ps} 2 f_s}$	$s_2 e^{i2\pi 2 T_{ps} 2 f_s}$	.....	$s_{N-1} e^{i2\pi(N-1) T_{ps} 2 f_s}$
⋮	⋮	⋮	⋮		⋮
f_{N-1}:	s_0	$s_1 e^{i2\pi T_{ps}(N-1) f_s}$	$s_2 e^{i2\pi 2 T_{ps}(N-1) f_s}$	.....	$s_{N-1} e^{i2\pi(N-1) T_{ps}(N-1) f_s}$

FIG. 15B

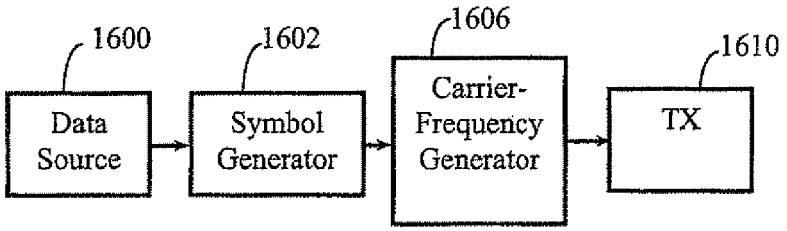


FIG. 16A

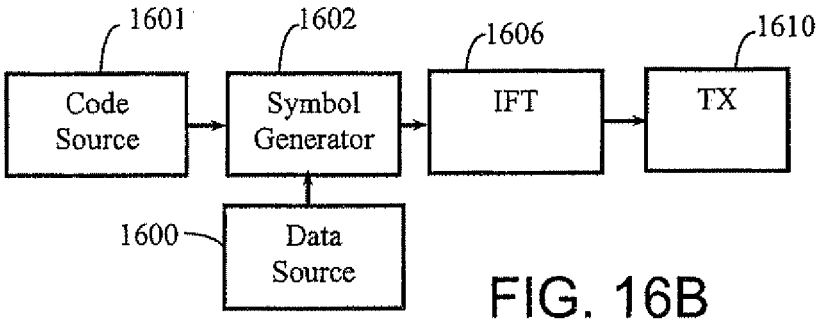


FIG. 16B

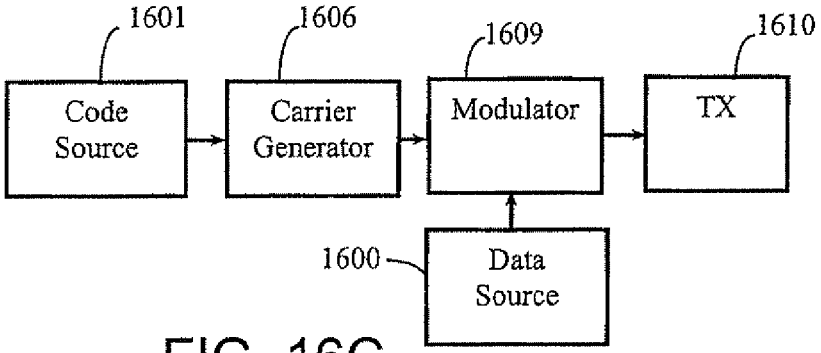


FIG. 16C

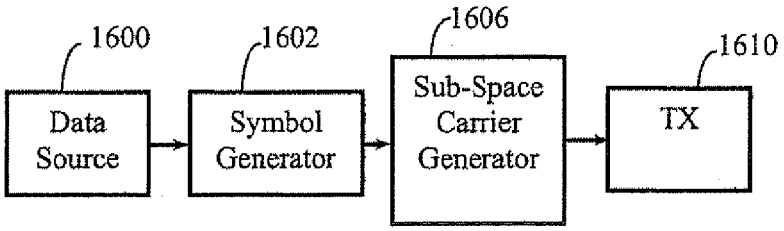


FIG. 16D

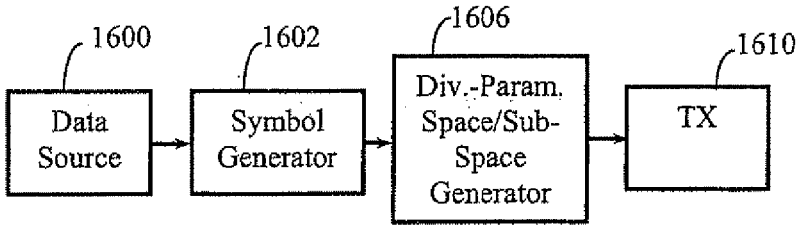


FIG. 16E

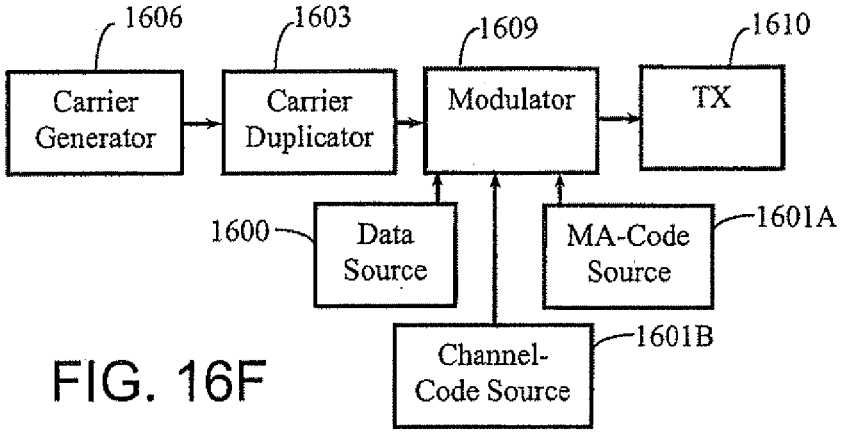


FIG. 16F

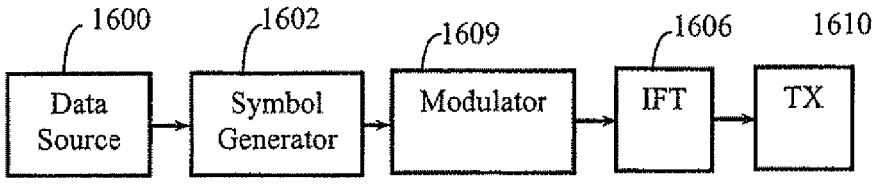


FIG. 16G

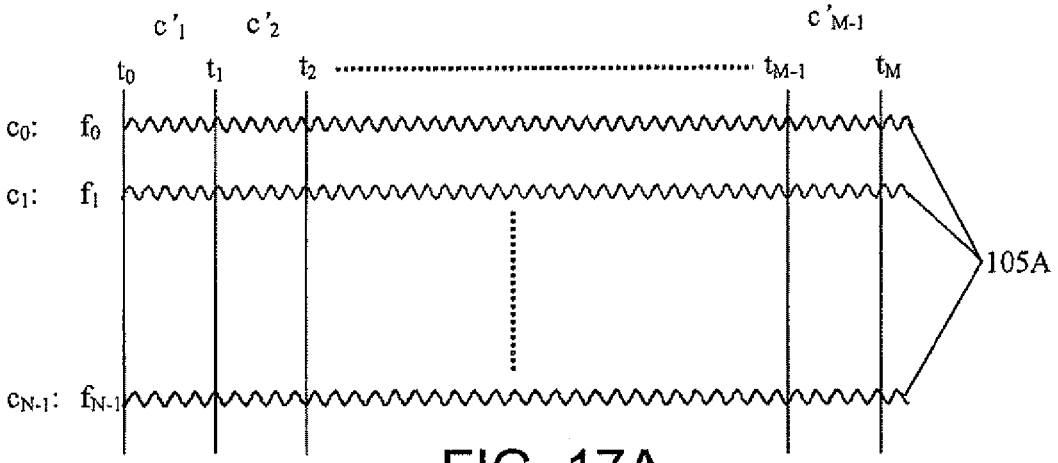


FIG. 17A

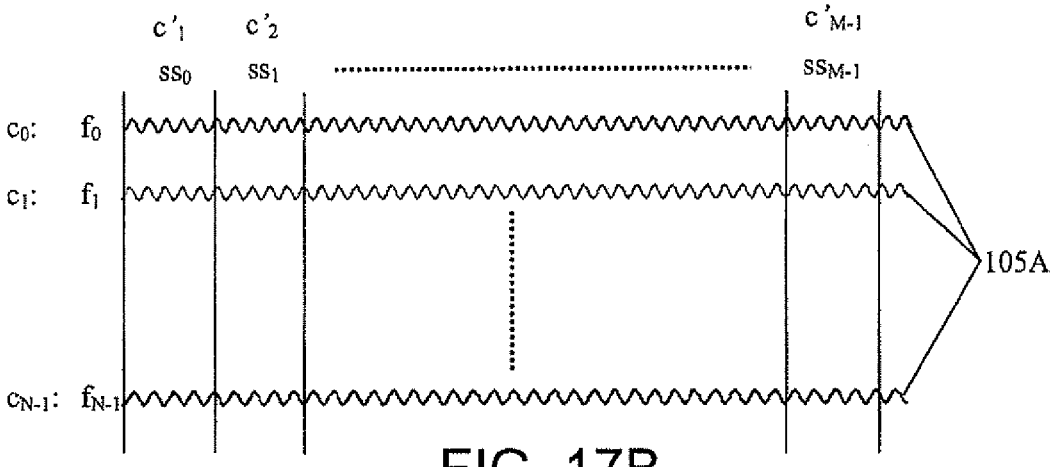


FIG. 17B

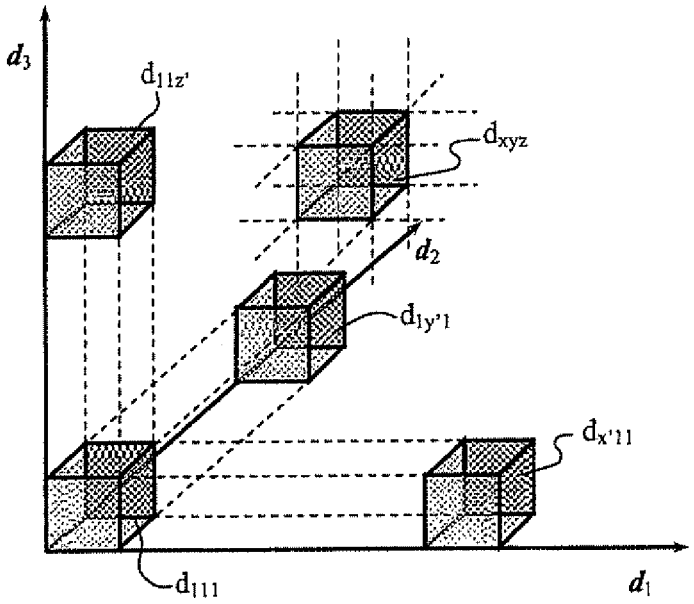


FIG. 17C

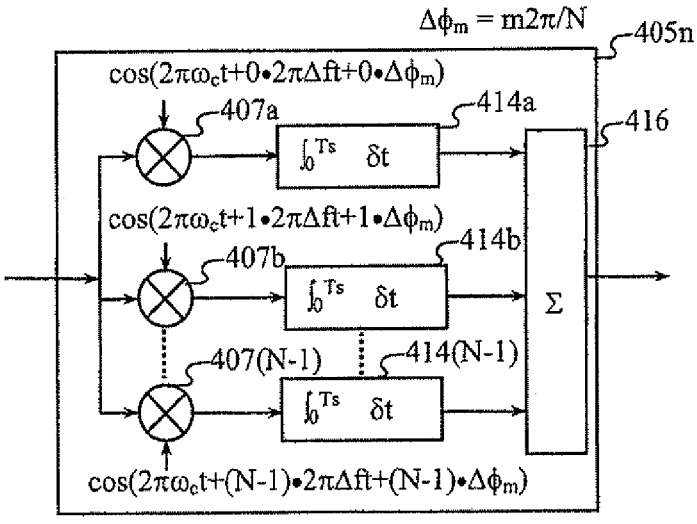


FIG. 18A

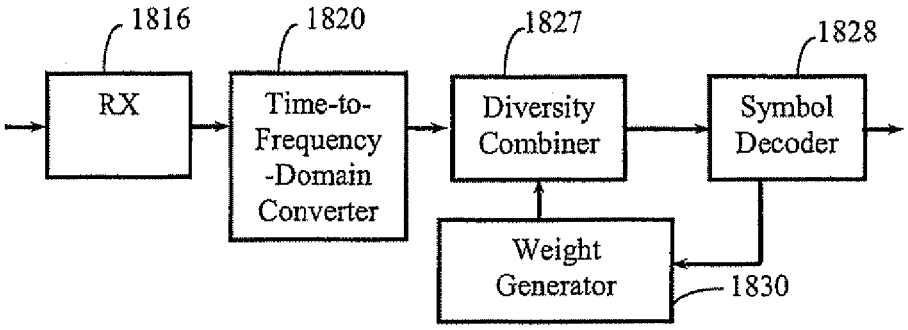


FIG. 18B

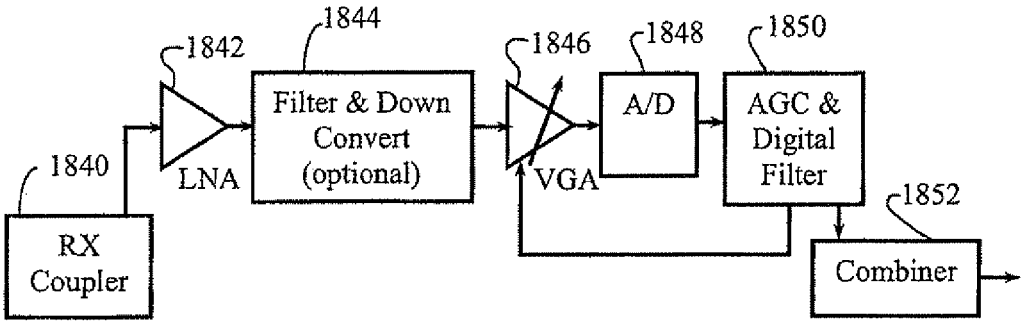


FIG. 18C

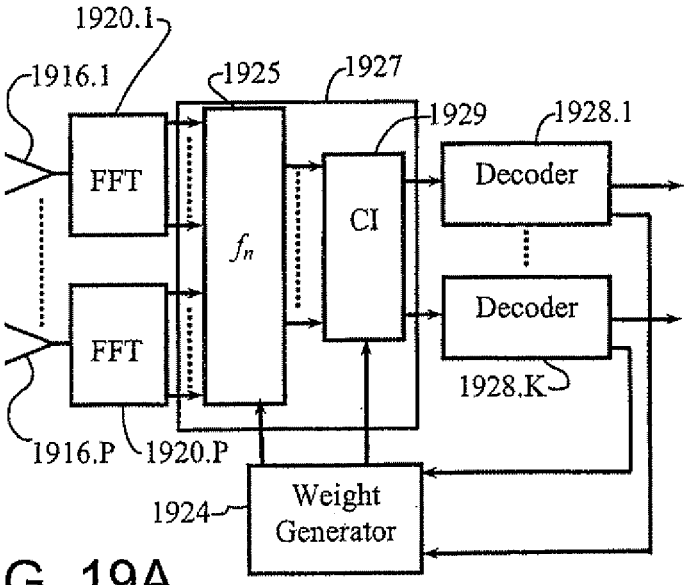


FIG. 19A

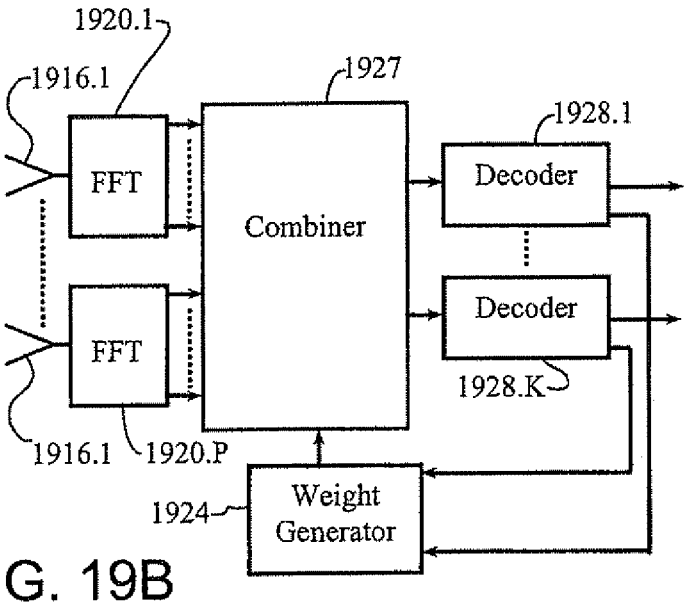


FIG. 19B

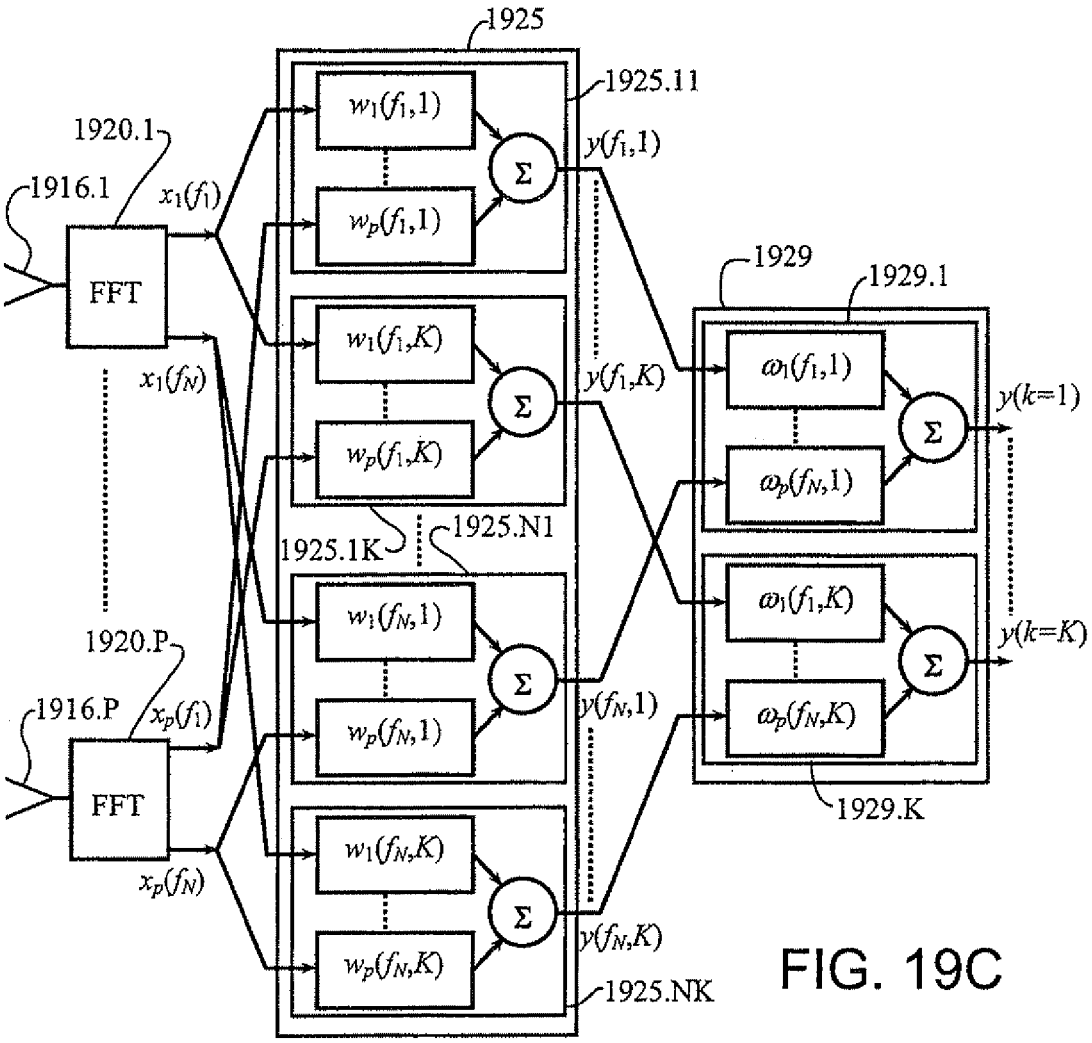

1925
1925.11
1920.1
1916.1
$x_1(f_1)$
FFT
$x_1(f_N)$
$w_1(f_1,1)$
$w_p(f_1,1)$
$y(f_1,1)$
$w_1(f_1,K)$
$w_p(f_1,K)$
$y(f_1,K)$
1925.1K
1925.N1
$w_1(f_N,1)$
$w_p(f_N,1)$
$y(f_N,1)$
$w_1(f_N,K)$
$w_p(f_N,K)$
$y(f_N,K)$
1925.NK
1920.P
1916.P
$x_p(f_1)$
FFT
$x_p(f_N)$
1929
1929.1
$\omega_1(f_1,1)$
$\omega_p(f_N,1)$
$y(k=1)$
$\omega_1(f_1,K)$
$\omega_p(f_N,K)$
$y(k=K)$
1929.K
Σ

FIG. 19C

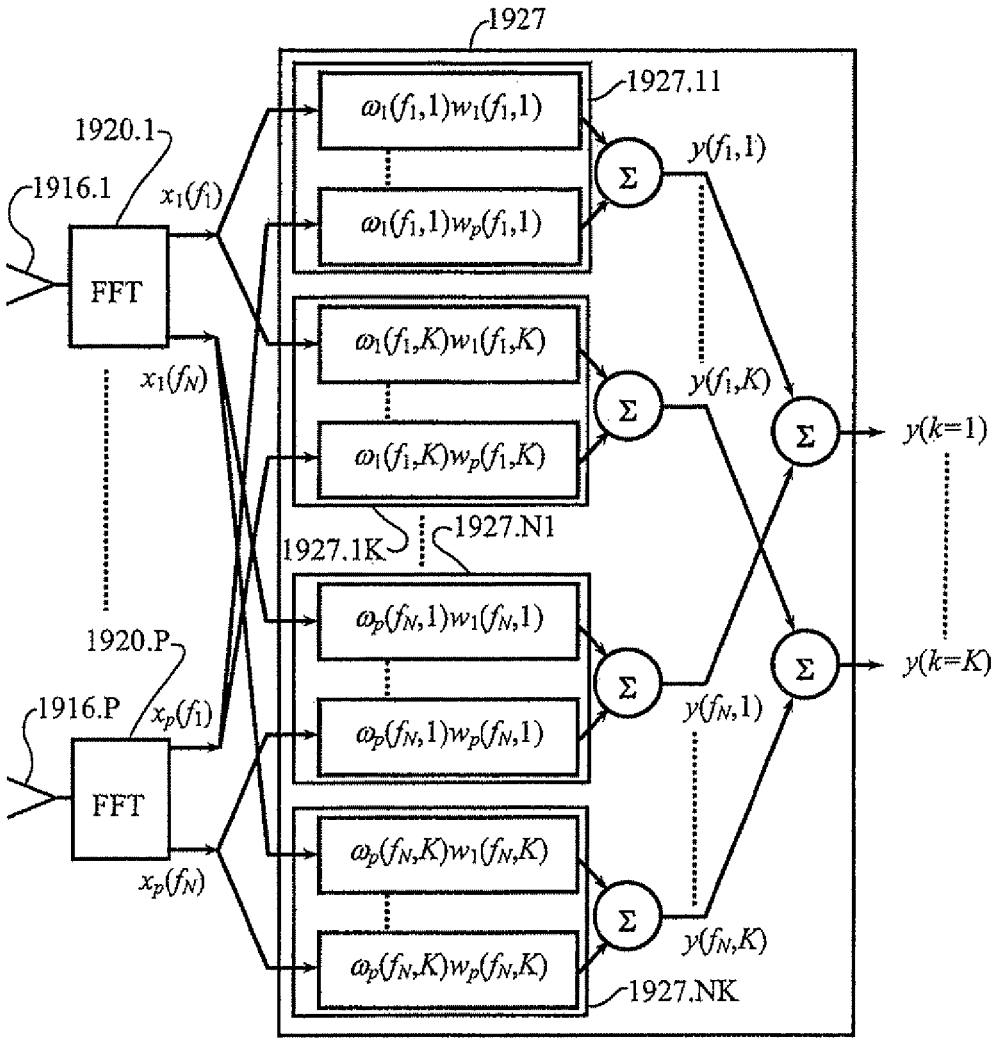

1927
1927.11
1920.1
1916.1
$x_1(f_1)$
FFT
$x_1(f_N)$
$\omega_1(f_1,1)w_1(f_1,1)$
$\omega_1(f_1,1)w_p(f_1,1)$
$\omega_1(f_1,K)w_1(f_1,K)$
$\omega_1(f_1,K)w_p(f_1,K)$
$y(f_1,1)$
$y(f_1,K)$
Σ
$y(k=1)$
1927.1K
1927.N1
1920.P
1916.P
$x_p(f_1)$
FFT
$x_p(f_N)$
$\omega_p(f_N,1)w_1(f_N,1)$
$\omega_p(f_N,1)w_p(f_N,1)$
$\omega_p(f_N,K)w_1(f_N,K)$
$\omega_p(f_N,K)w_p(f_N,K)$
$y(f_N,1)$
$y(f_N,K)$
$y(k=K)$
1927.NK

FIG. 19D

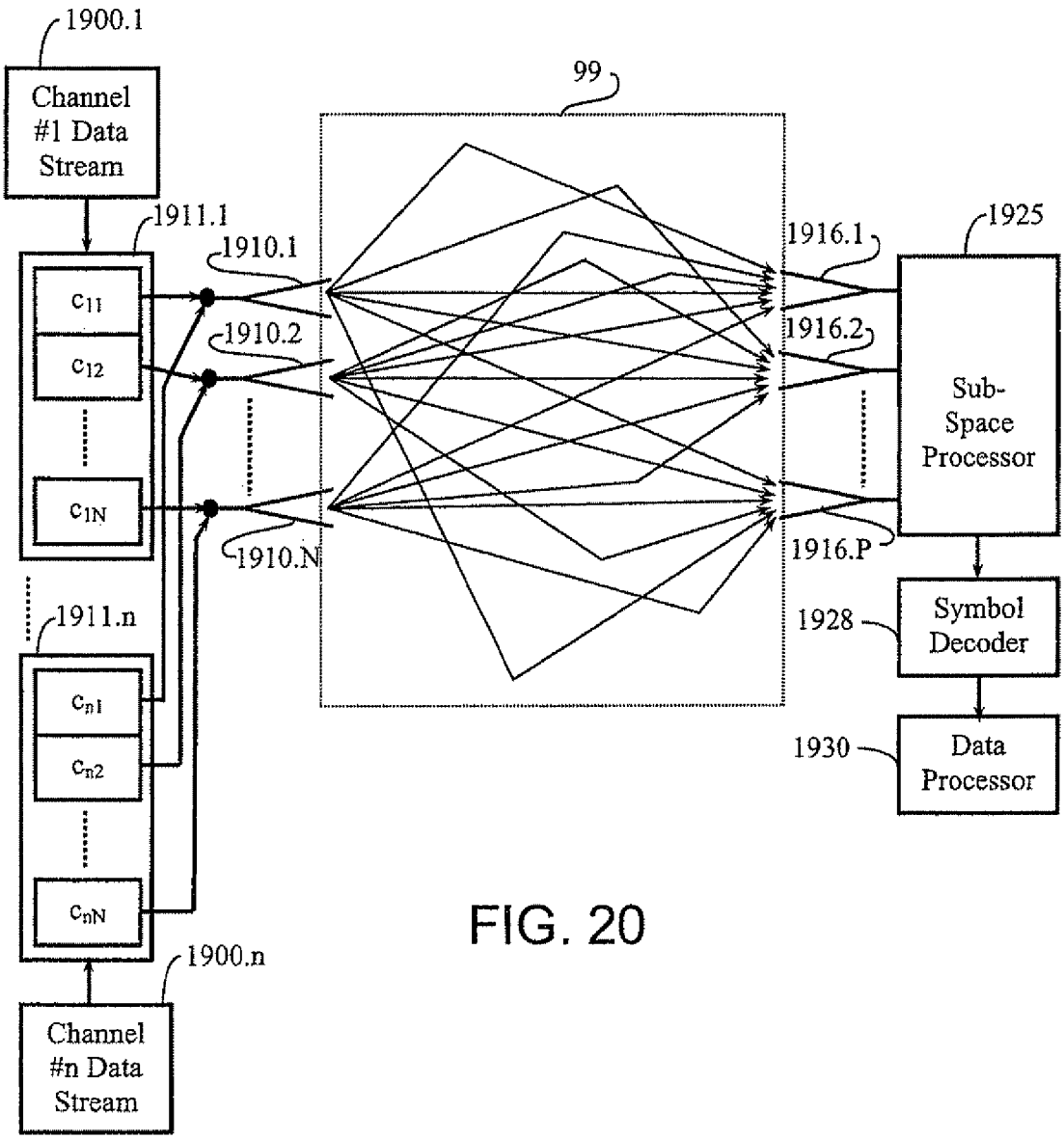

1900.1
Channel #1 Data Stream
99
1911.1
1910.1
1910.2
1910.N
1916.1
1916.2
1916.P
1925
Sub-Space Processor
Symbol Decoder
1928
Data Processor
1930
1911.n
1900.n
Channel #n Data Stream

FIG. 20

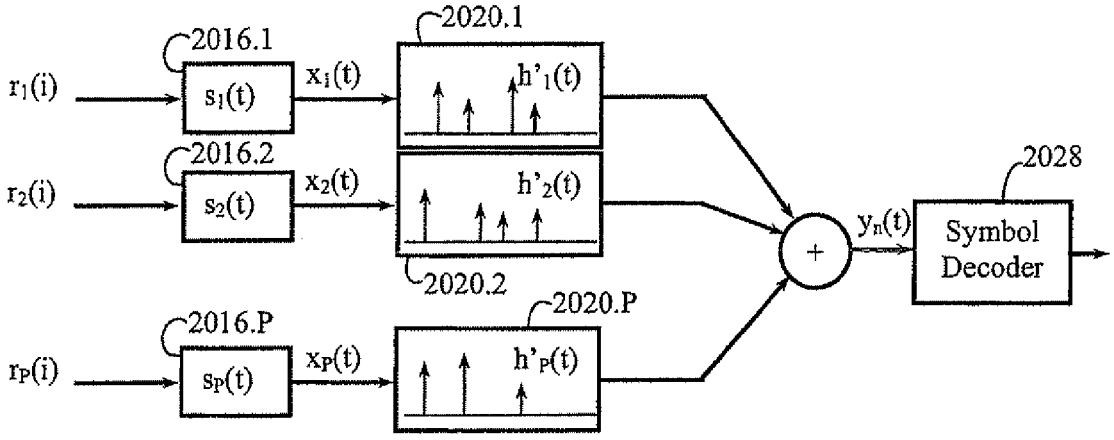


FIG. 21A

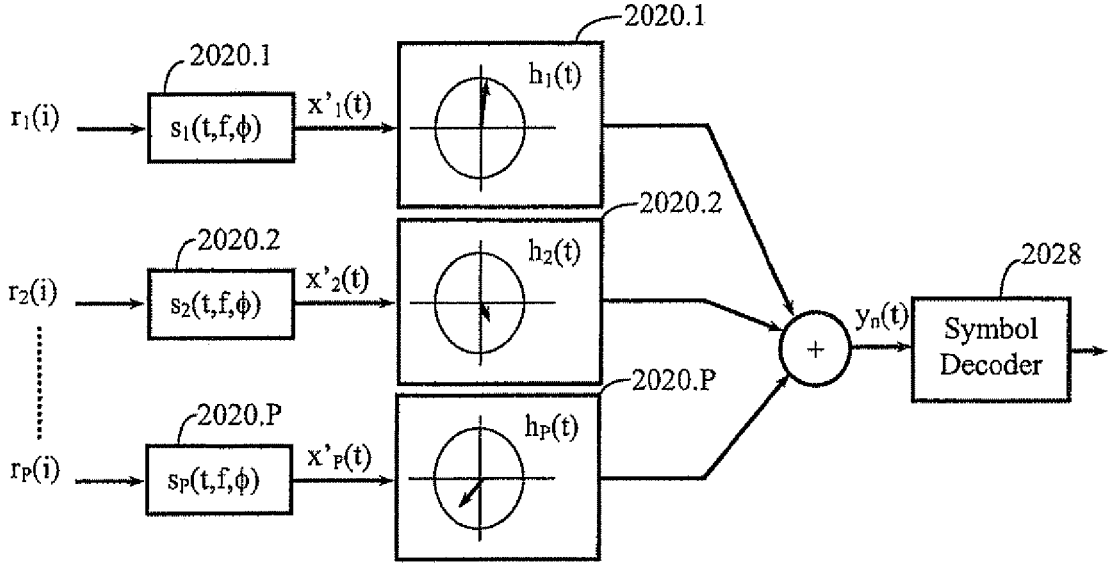


FIG. 21B

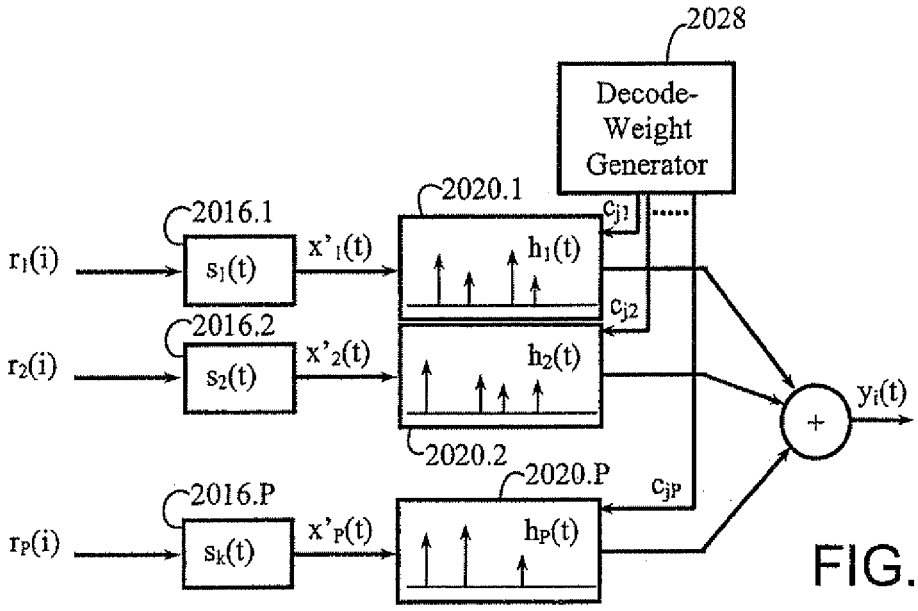


FIG. 21C

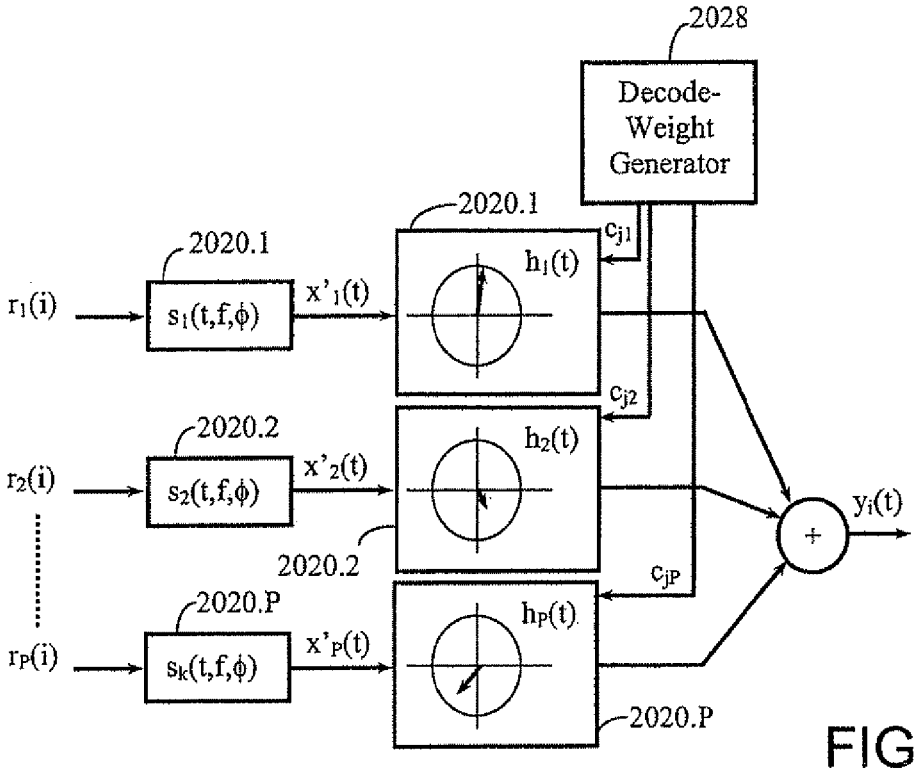


FIG. 21D

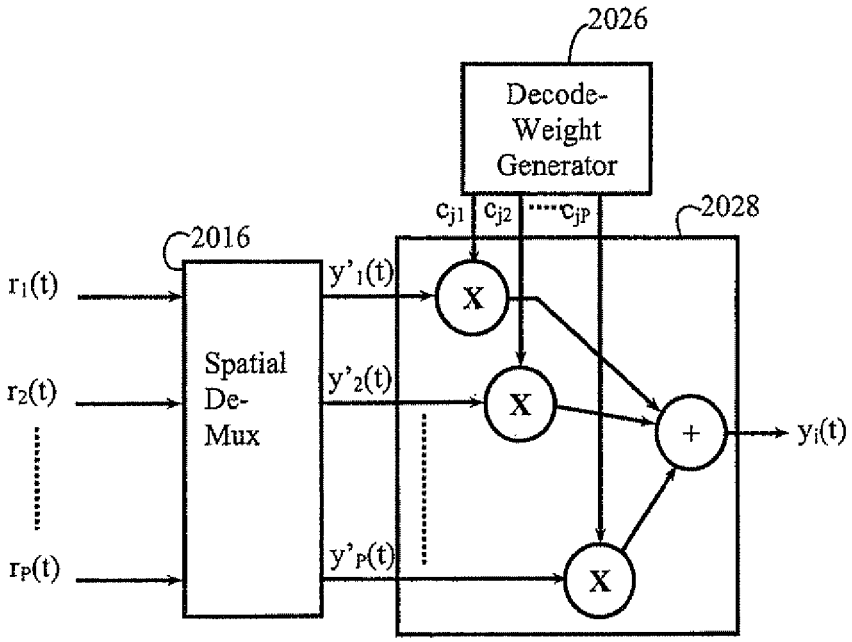


FIG. 21E

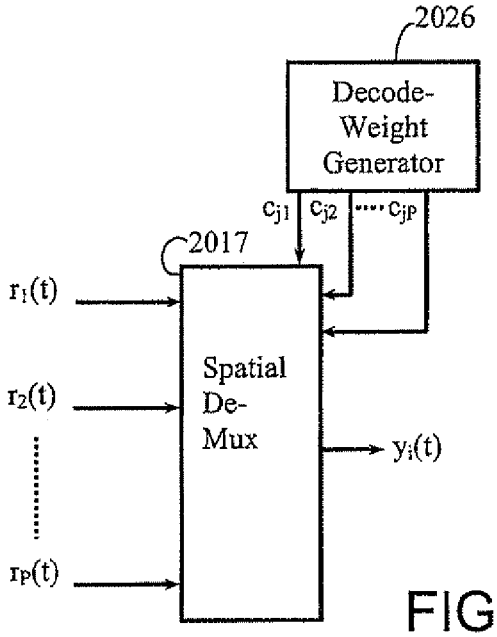


FIG. 21F

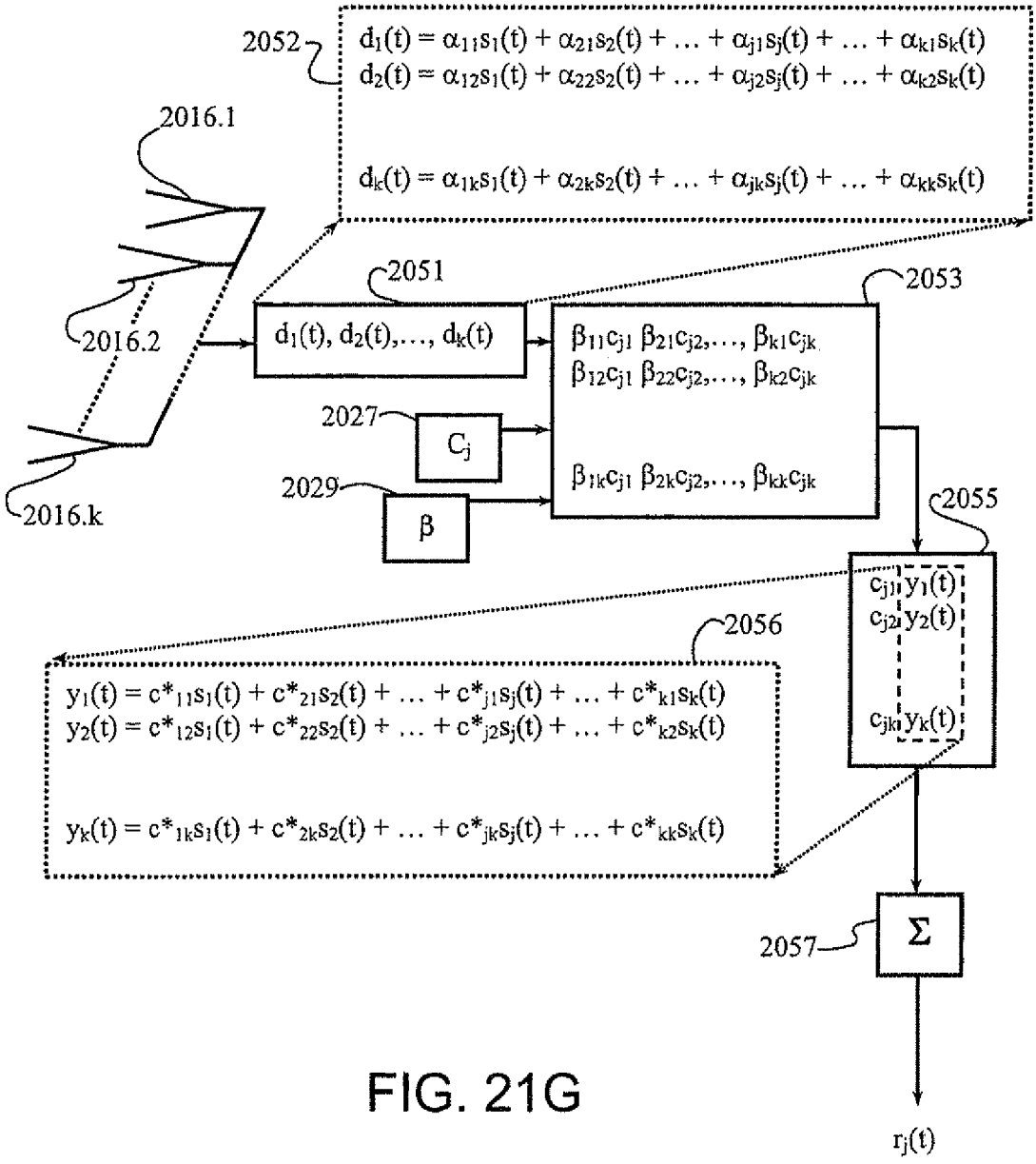

2052
$d_1(t) = \alpha_{11}s_1(t) + \alpha_{21}s_2(t) + \ldots + \alpha_{j1}s_j(t) + \ldots + \alpha_{k1}s_k(t)$
$d_2(t) = \alpha_{12}s_1(t) + \alpha_{22}s_2(t) + \ldots + \alpha_{j2}s_j(t) + \ldots + \alpha_{k2}s_k(t)$
$d_k(t) = \alpha_{1k}s_1(t) + \alpha_{2k}s_2(t) + \ldots + \alpha_{jk}s_j(t) + \ldots + \alpha_{kk}s_k(t)$
2016.1
2016.2
2016.k
2051
$d_1(t), d_2(t), \ldots, d_k(t)$
2053
$\beta_{11}c_{j1}\ \beta_{21}c_{j2}, \ldots, \beta_{k1}c_{jk}$
$\beta_{12}c_{j1}\ \beta_{22}c_{j2}, \ldots, \beta_{k2}c_{jk}$
$\beta_{1k}c_{j1}\ \beta_{2k}c_{j2}, \ldots, \beta_{kk}c_{jk}$
2027
C_j
2029
β
2055
$c_{j1}\ y_1(t)$
$c_{j2}\ y_2(t)$
$c_{jk}\ y_k(t)$
2056
$y_1(t) = c^*_{11}s_1(t) + c^*_{21}s_2(t) + \ldots + c^*_{j1}s_j(t) + \ldots + c^*_{k1}s_k(t)$
$y_2(t) = c^*_{12}s_1(t) + c^*_{22}s_2(t) + \ldots + c^*_{j2}s_j(t) + \ldots + c^*_{k2}s_k(t)$
$y_k(t) = c^*_{1k}s_1(t) + c^*_{2k}s_2(t) + \ldots + c^*_{jk}s_j(t) + \ldots + c^*_{kk}s_k(t)$
2057
Σ
$r_j(t)$

FIG. 21G

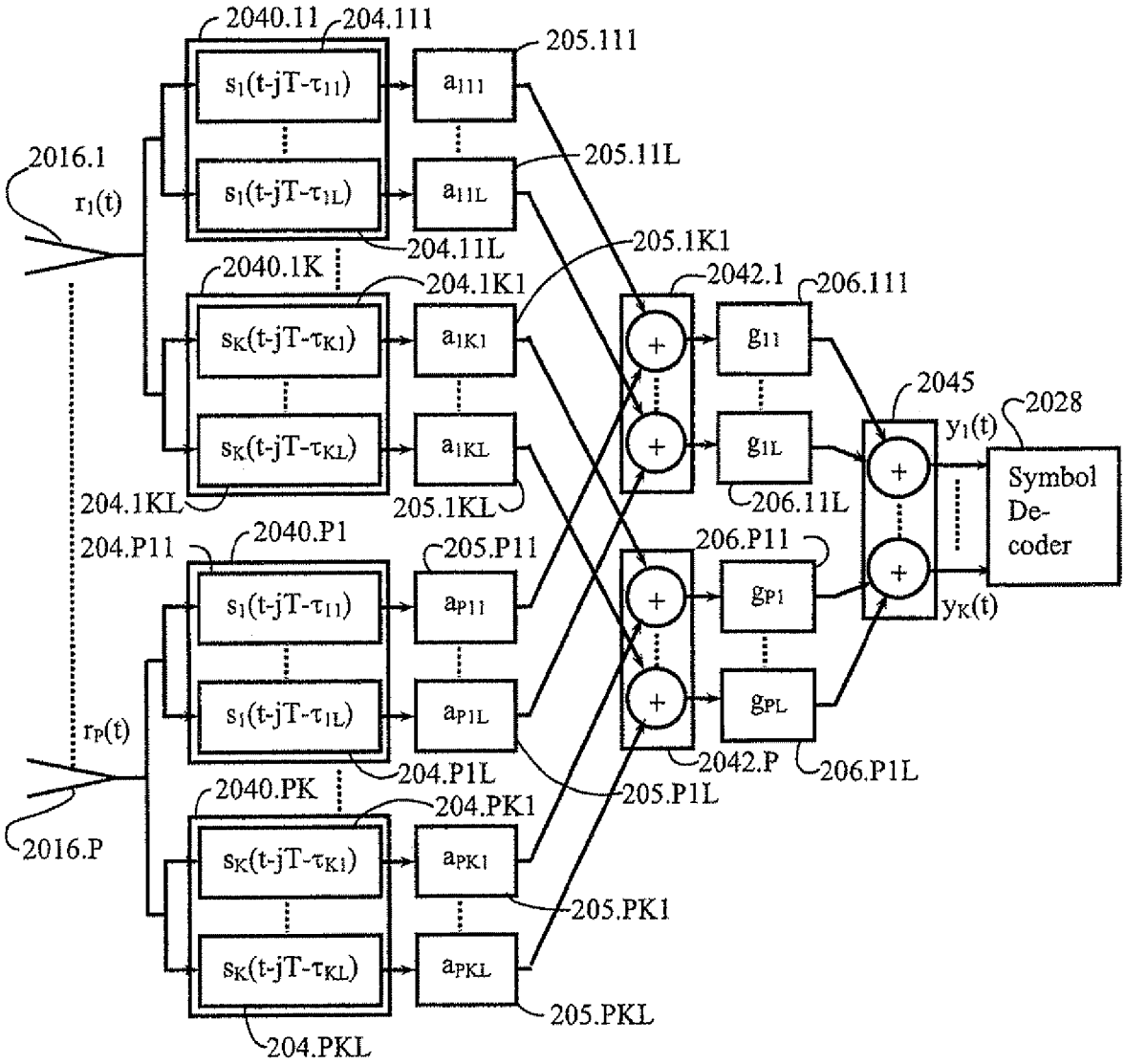

2040.11
204.111
205.111
$s_1(t-jT-\tau_{11})$
a_{111}
2016.1
$r_1(t)$
205.11L
$s_1(t-jT-\tau_{1L})$
a_{11L}
204.11L
205.1K1
2040.1K
204.1K1
2042.1
206.111
$s_K(t-jT-\tau_{K1})$
a_{1K1}
g_{11}
2045
2028
$y_1(t)$
$s_K(t-jT-\tau_{KL})$
a_{1KL}
g_{1L}
Symbol De-coder
204.1KL
205.1KL
206.11L
204.P11
2040.P1
205.P11
206.P11
$s_1(t-jT-\tau_{11})$
a_{P11}
g_{P1}
$y_K(t)$
$r_P(t)$
$s_1(t-jT-\tau_{1L})$
a_{P1L}
g_{PL}
204.P1L
2042.P
206.P1L
205.P1L
2040.PK
204.PK1
2016.P
$s_K(t-jT-\tau_{K1})$
a_{PK1}
205.PK1
$s_K(t-jT-\tau_{KL})$
a_{PKL}
205.PKL
204.PKL

FIG. 22

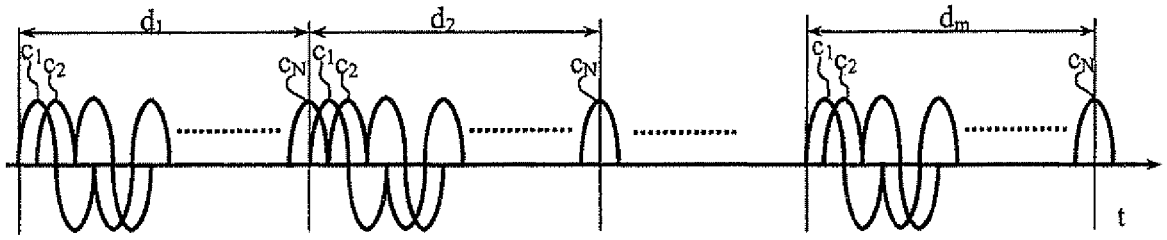


FIG. 23A

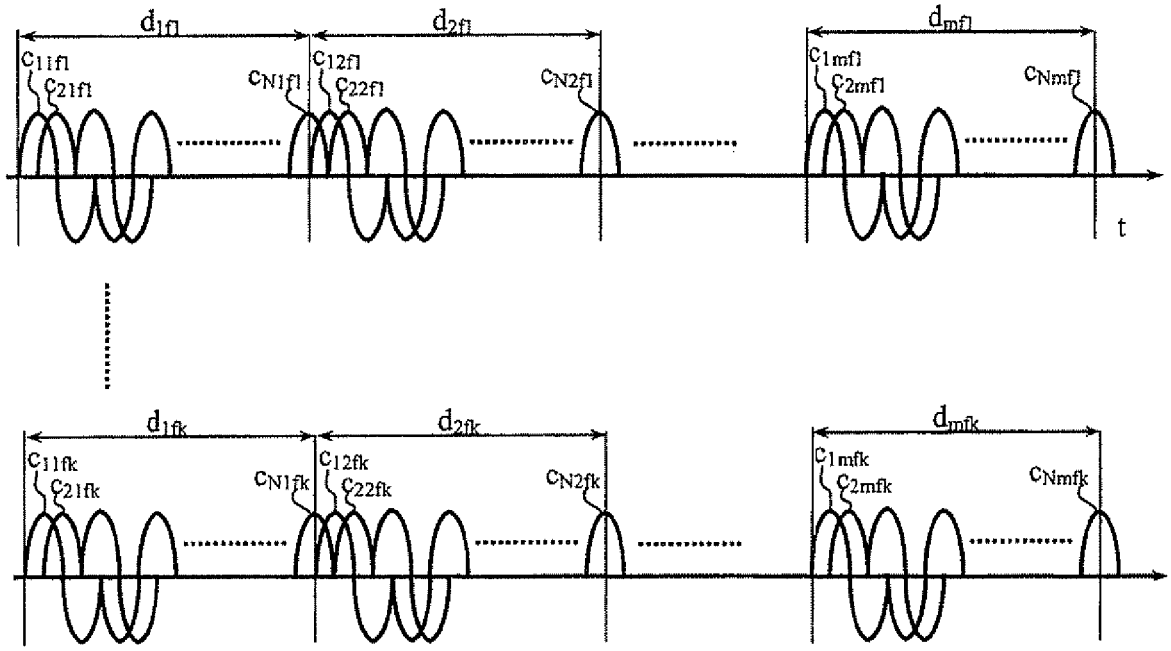


FIG. 23B

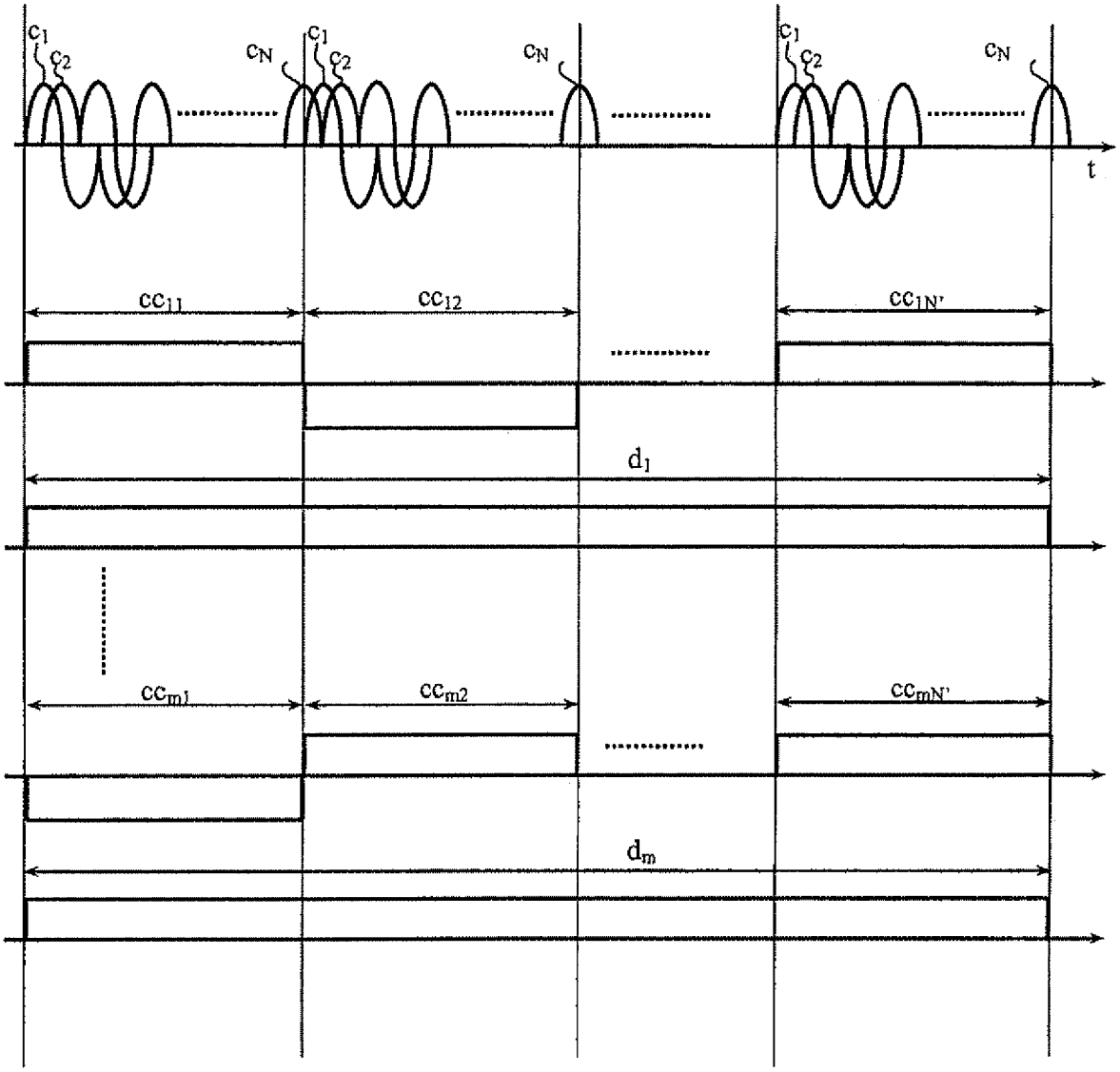


FIG. 24

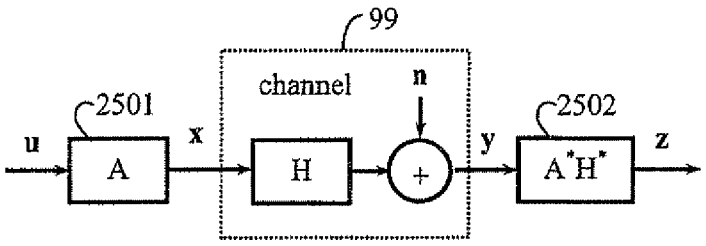


FIG. 25A

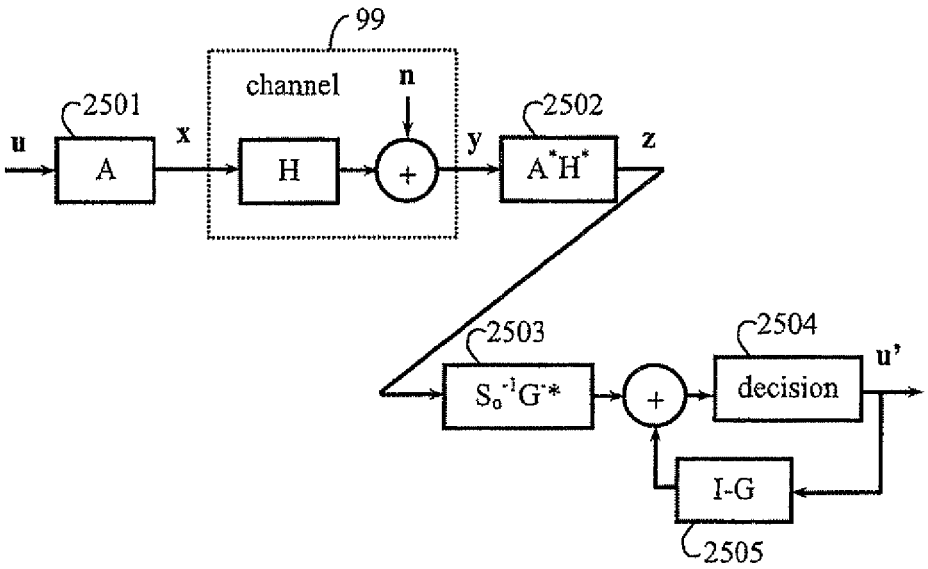


FIG. 25B

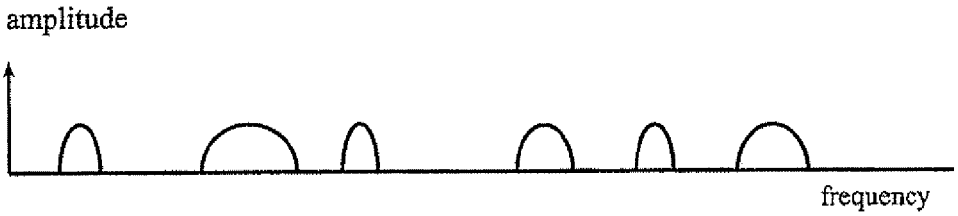


FIG. 26A

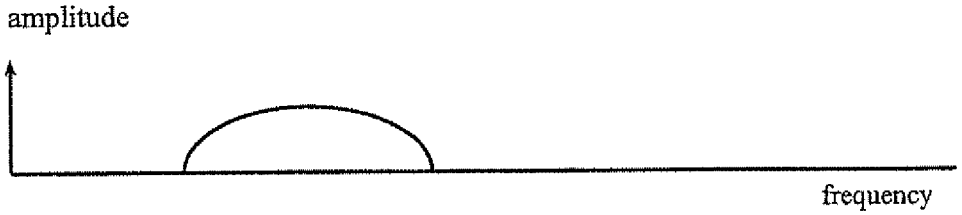


FIG. 26B

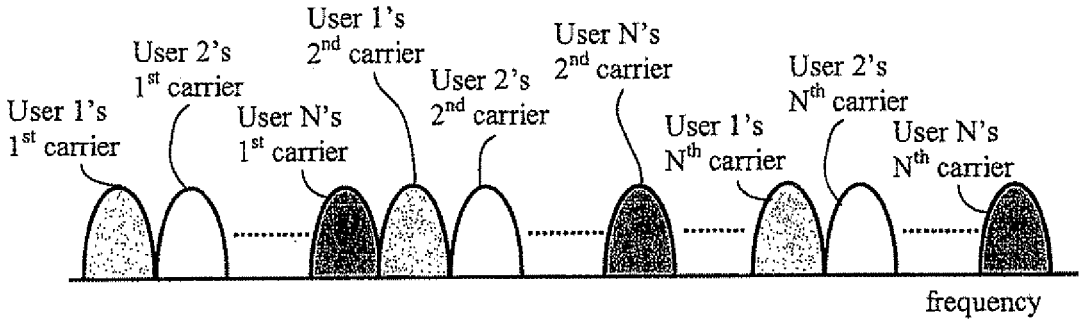


FIG. 27

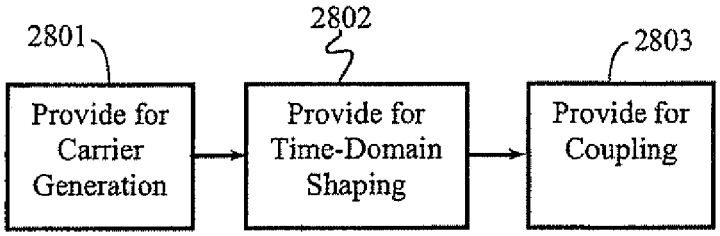


FIG. 28A

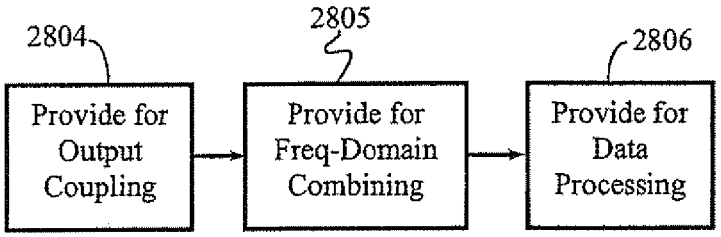


FIG. 28B

$HW_{4x4}(1)$: 1 1 1 1

$HW_{4x4}(2)$: 1 -1 1 -1

$HW_{4x4}(3)$: 1 1 -1 -1

$HW_{4x4}(4)$: 1 -1 -1 1

FIG. 29A

$CI_{4x4}(1)$: 1 1 1 1

$CI_{4x4}(2)$: 1 i -1 -i

$CI_{4x4}(3)$: 1 -1 1 -1

$CI_{4x4}(4)$: 1 -i -1 i

FIG. 29B

$HW_{4x4}(1)xCI_{4x4}(1)$:	1	1	1	1
$HW_{4x4}(1)xCI_{4x4}(2)$:	1	i	-1	-i
$HW_{4x4}(1)xCI_{4x4}(3)$:	1	-1	1	-1
$HW_{4x4}(1)xCI_{4x4}(4)$:	1	-i	-1	i

FIG. 30A

$HW_{4x4}(2)xCI_{4x4}(1)$:	1	-1	1	-1
$HW_{4x4}(2)xCI_{4x4}(2)$:	1	-i	-1	i
$HW_{4x4}(2)xCI_{4x4}(3)$:	1	1	1	1
$HW_{4x4}(2)xCI_{4x4}(4)$:	1	i	-1	-i

FIG. 30B

$HW_{4x4}(1)xCI_{4x4}(1)$:	1	1	-1	-1
$HW_{4x4}(1)xCI_{4x4}(2)$:	1	i	1	i
$HW_{4x4}(1)xCI_{4x4}(3)$:	1	-1	-1	1
$HW_{4x4}(1)xCI_{4x4}(4)$:	1	-i	1	-i

FIG. 30C

$HW_{4x4}(2)xCI_{4x4}(1)$:	1	-1	-1	1
$HW_{4x4}(2)xCI_{4x4}(2)$:	1	-i	1	-i
$HW_{4x4}(2)xCI_{4x4}(3)$:	1	1	-1	-1
$HW_{4x4}(2)xCI_{4x4}(4)$:	1	i	1	i

FIG. 30D

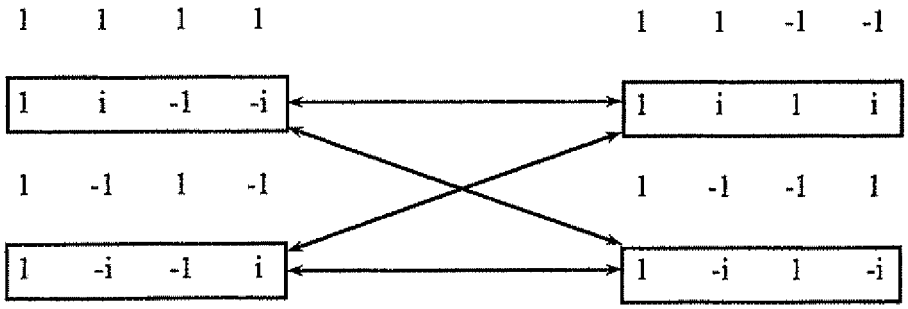


FIG. 31A

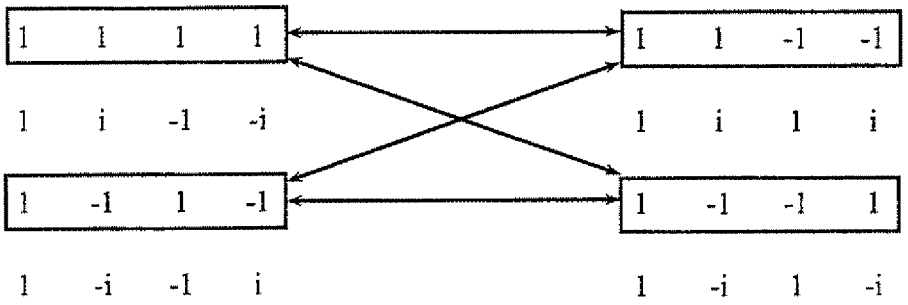


FIG. 31B

$PC_{4x4}(1)$: 1 i -1 -i

$PC_{4x4}(2)$: 1 i 1 i

$PC_{4x4}(3)$: 1 -i -1 i

$PC_{4x4}(4)$: 1 -i 1 -i

FIG. 31C

$HW_{8x8}(1)$:	1	1	1	1	1	1	1	1
$HW_{8x8}(2)$:	1	-1	1	-1	1	-1	1	-1
$HW_{8x8}(3)$:	1	1	-1	-1	1	1	-1	-1
$HW_{8x8}(4)$:	1	-1	-1	1	1	-1	-1	1
$HW_{8x8}(5)$:	1	1	1	1	-1	-1	-1	-1
$HW_{8x8}(6)$:	1	-1	1	-1	-1	1	-1	1
$HW_{8x8}(7)$:	1	1	-1	-1	-1	-1	1	1
$HW_{8x8}(8)$:	1	-1	-1	1	-1	1	1	-1

FIG. 32A

$PC4_{8x8}(1)$:	1	i	-1	-i	1	ı	-1	-i
$PC4_{8x8}(2)$:	1	i	1	i	1	i	1	i
$PC4_{8x8}(3)$:	1	-i	-1	i	1	-i	-1	i
$PC4_{8x8}(4)$:	1	-i	1	-i	1	-i	1	-i
$PC4_{8x8}(5)$:	1	i	-1	-i	-1	-i	1	i
$PC4_{8x8}(6)$:	1	i	1	i	-1	-i	-1	-i
$PC4_{8x8}(7)$:	1	-i	-1	i	-1	i	1	-i
$PC4_{8x8}(8)$:	1	-i	1	-i	-1	i	-1	i

FIG. 32B

$CI_{8x8}(1)$:	1	1	1	1	1	1	1	1
$CI_{8x8}(2)$:	1	$\frac{1+i}{\sqrt{2}}$	i	$\frac{-1+i}{\sqrt{2}}$	-1	$\frac{-1-i}{\sqrt{2}}$	-i	$\frac{1-i}{\sqrt{2}}$
$CI_{8x8}(3)$:	1	i	-1	-i	1	i	-1	-i
$CI_{8x8}(4)$:	1	$\frac{-1+i}{\sqrt{2}}$	-i	$\frac{1+i}{\sqrt{2}}$	-1	$\frac{1-i}{\sqrt{2}}$	i	$\frac{-1-i}{\sqrt{2}}$
$CI_{8x8}(5)$:	1	-1	1	-1	1	-1	1	-1
$CI_{8x8}(6)$:	1	$\frac{-1-i}{\sqrt{2}}$	i	$\frac{1-i}{\sqrt{2}}$	-1	$\frac{1+i}{\sqrt{2}}$	-i	$\frac{-1+i}{\sqrt{2}}$
$CI_{8x8}(7)$:	1	-i	-1	i	1	-i	-1	i
$CI_{8x8}(8)$:	1	$\frac{1-i}{\sqrt{2}}$	-i	$\frac{-1-i}{\sqrt{2}}$	-1	$\frac{-1+i}{\sqrt{2}}$	i	$\frac{1+i}{\sqrt{2}}$

FIG. 32C

$HW_{8x8}(1)xCI_{8x8}$

$HW_{8x8}(1)$:	1	1	1	1	1	1	1	1
$CI_{8x8}(1)$:	1	$\frac{1+i}{\sqrt{2}}$	i	$\frac{-1+i}{\sqrt{2}}$	-1	$\frac{-1-i}{\sqrt{2}}$	-i	$\frac{1-i}{\sqrt{2}}$
$PC4_{8x8}(1)$:	1	i	-1	-i	1	i	-1	-i
$CI_{8x8}(2)$:	1	$\frac{-1+i}{\sqrt{2}}$	-i	$\frac{1+i}{\sqrt{2}}$	-1	$\frac{1-i}{\sqrt{2}}$	i	$\frac{-1-i}{\sqrt{2}}$
$HW_{8x8}(2)$:	1	-1	1	-1	1	-1	1	-1
$CI_{8x8}(2)^*$:	1	$\frac{-1-i}{\sqrt{2}}$	i	$\frac{1-i}{\sqrt{2}}$	-1	$\frac{1+i}{\sqrt{2}}$	-i	$\frac{-1+i}{\sqrt{2}}$
$PC4_{8x8}(3)$:	1	-i	-1	i	1	-i	-1	i
$CI_{8x8}(1)^*$:	1	$\frac{1-i}{\sqrt{2}}$	-i	$\frac{-1-i}{\sqrt{2}}$	-1	$\frac{-1+i}{\sqrt{2}}$	i	$\frac{1+i}{\sqrt{2}}$

FIG. 33A

$HW_{8x8}(2)xCI_{8x8}$

$HW_{8x8}(2)$:	1	-1	1	-1	1	-1	1	-1
$CI_{8x8}(2)^*$:	1	$\frac{-1-i}{\sqrt{2}}$	i	$\frac{1-i}{\sqrt{2}}$	-1	$\frac{1+i}{\sqrt{2}}$	-i	$\frac{-1+i}{\sqrt{2}}$
$PC4_{8x8}(3)$:	1	-i	-1	i	1	-i	-1	i
$CI_{8x8}(1)^*$:	1	$\frac{1-i}{\sqrt{2}}$	-i	$\frac{-1-i}{\sqrt{2}}$	-1	$\frac{-1+i}{\sqrt{2}}$	i	$\frac{1+i}{\sqrt{2}}$
$HW_{8x8}(1)$:	1	1	1	1	1	1	1	1
$CI_{8x8}(1)$:	1	$\frac{1+i}{\sqrt{2}}$	i	$\frac{-1+i}{\sqrt{2}}$	-1	$\frac{-1-i}{\sqrt{2}}$	-i	$\frac{1-i}{\sqrt{2}}$
$PC4_{8x8}(1)$:	1	i	-1	-i	1	i	-1	-i
$CI_{8x8}(2)$:	1	$\frac{-1+i}{\sqrt{2}}$	-i	$\frac{1+i}{\sqrt{2}}$	-1	$\frac{1-i}{\sqrt{2}}$	i	$\frac{-1-i}{\sqrt{2}}$

FIG. 33B

$HW_{8x8}(3)xCI_{8x8}$

$HW_{8x8}(3)$:	1	1	-1	-1	1	1	-1	-1
$CI_{8x8}(6)$:	1	$\frac{1+i}{\sqrt{2}}$	-i	$\frac{1-i}{\sqrt{2}}$	-1	$\frac{-1-i}{\sqrt{2}}$	i	$\frac{-1+i}{\sqrt{2}}$
$PC4_{8x8}(2)$:	1	i	1	i	1	i	1	i
$CI_{8x8}(5)$:	1	$\frac{-1+i}{\sqrt{2}}$	i	$\frac{-1-i}{\sqrt{2}}$	-1	$\frac{1-i}{\sqrt{2}}$	-i	$\frac{1+i}{\sqrt{2}}$
$HW_{8x8}(4)$:	1	-1	-1	1	1	-1	-1	1
$CI_{8x8}(5)^*$:	1	$\frac{-1-i}{\sqrt{2}}$	-i	$\frac{-1+i}{\sqrt{2}}$	-1	$\frac{1+i}{\sqrt{2}}$	i	$\frac{1-i}{\sqrt{2}}$
$PC4_{8x8}(4)$:	1	-i	1	-i	1	-i	1	-i
$CI_{8x8}(6)^*$:	1	$\frac{1-i}{\sqrt{2}}$	i	$\frac{1+i}{\sqrt{2}}$	-1	$\frac{-1+i}{\sqrt{2}}$	-i	$\frac{-1-i}{\sqrt{2}}$

FIG. 33C

$HW_{8x8}(4)xCI_{8x8}$

$HW_{8x8}(4)$:	1	-1	-1	1	1	-1	-1	1
$CI_{8x8}(5)$:	1	$\frac{-1-i}{\sqrt{2}}$	-i	$\frac{-1+i}{\sqrt{2}}$	-1	$\frac{1+i}{\sqrt{2}}$	i	$\frac{1-i}{\sqrt{2}}$
$PC4_{8x8}(4)$:	1	-i	1	-i	1	-i	1	-i
$CI_{8x8}(6)$:	1	$\frac{1-i}{\sqrt{2}}$	i	$\frac{1+i}{\sqrt{2}}$	-1	$\frac{-1+i}{\sqrt{2}}$	-i	$\frac{-1-i}{\sqrt{2}}$
$HW_{8x8}(3)$:	1	1	-1	-1	1	1	-1	-1
$CI_{8x8}(6)^*$:	1	$\frac{1+i}{\sqrt{2}}$	-i	$\frac{1-i}{\sqrt{2}}$	-1	$\frac{-1-i}{\sqrt{2}}$	i	$\frac{-1+i}{\sqrt{2}}$
$PC4_{8x8}(2)$:	1	i	1	i	1	i	1	i
$CI_{8x8}(5)^*$:	1	$\frac{-1+i}{\sqrt{2}}$	i	$\frac{-1-i}{\sqrt{2}}$	-1	$\frac{1-i}{\sqrt{2}}$	-i	$\frac{1+i}{\sqrt{2}}$

FIG. 33D

$HW_{8x8}(5)xCI_{8x8}$

$HW_{8x8}(5)$:	1	1	1	1	-1	-1	-1	-1
$CI_{8x8}(3)$:	1	$\frac{1+i}{\sqrt{2}}$	i	$\frac{-1+i}{\sqrt{2}}$	1	$\frac{1+i}{\sqrt{2}}$	i	$\frac{-1+i}{\sqrt{2}}$
$PC4_{8x8}(5)$:	1	i	-1	-i	-1	-i	1	i
$CI_{8x8}(4)$:	1	$\frac{-1+i}{\sqrt{2}}$	-i	$\frac{1+i}{\sqrt{2}}$	1	$\frac{-1+i}{\sqrt{2}}$	-i	$\frac{1+i}{\sqrt{2}}$
$HW_{8x8}(6)$:	1	-1	1	-1	-1	1	-1	1
$CI_{8x8}(4)^*$:	1	$\frac{-1-i}{\sqrt{2}}$	i	$\frac{1-i}{\sqrt{2}}$	1	$\frac{-1-i}{\sqrt{2}}$	i	$\frac{1-i}{\sqrt{2}}$
$PC4_{8x8}(7)$:	1	-i	-1	i	-1	i	1	-i
$CI_{8x8}(3)^*$:	1	$\frac{1-i}{\sqrt{2}}$	-i	$\frac{-1-i}{\sqrt{2}}$	1	$\frac{1-i}{\sqrt{2}}$	-i	$\frac{-1-i}{\sqrt{2}}$

FIG. 33E

$HW_{8x8}(6)xCI_{8x8}$

$HW_{8x8}(6)$:	1	-1	1	-1	-1	1	-1	1
$CI_{8x8}(4)^*$:	1	$\frac{-1-i}{\sqrt{2}}$	i	$\frac{1-i}{\sqrt{2}}$	1	$\frac{-1-i}{\sqrt{2}}$	i	$\frac{1-i}{\sqrt{2}}$
$PC4_{8x8}(7)$:	1	-i	-1	i	-1	i	1	-i
$CI_{8x8}(3)^*$:	1	$\frac{-1-i}{\sqrt{2}}$	-i	$\frac{-1-i}{\sqrt{2}}$	1	$\frac{1-i}{\sqrt{2}}$	-i	$\frac{-1-i}{\sqrt{2}}$
$HW_{8x8}(5)$:	1	1	1	1	-1	-1	-1	-1
$CI_{8x8}(3)$:	1	$\frac{1+i}{\sqrt{2}}$	i	$\frac{-1+i}{\sqrt{2}}$	1	$\frac{1+i}{\sqrt{2}}$	i	$\frac{-1+i}{\sqrt{2}}$
$PC4_{8x8}(5)$:	1	i	-1	-i	-1	-i	1	i
$CI_{8x8}(4)$:	1	$\frac{-1+i}{\sqrt{2}}$	-i	$\frac{1+i}{\sqrt{2}}$	1	$\frac{-1+i}{\sqrt{2}}$	-i	$\frac{1+i}{\sqrt{2}}$

FIG. 33F

$HW_{8x8}(7)xCI_{8x8}$

$HW_{8x8}(7)$:	1	1	-1	-1	-1	-1	1	1
$CI_{8x8}(7)$:	1	$\frac{1+i}{\sqrt{2}}$	-i	$\frac{1-i}{\sqrt{2}}$	1	$\frac{1+i}{\sqrt{2}}$	-i	$\frac{1-i}{\sqrt{2}}$
$PC4_{8x8}(6)$:	1	i	1	i	-1	-i	-1	-i
$CI_{8x8}(8)$:	1	$\frac{-1+i}{\sqrt{2}}$	i	$\frac{-1-i}{\sqrt{2}}$	1	$\frac{-1+i}{\sqrt{2}}$	i	$\frac{-1-i}{\sqrt{2}}$
$HW_{8x8}(8)$:	1	-1	-1	1	-1	1	1	-1
$CI_{8x8}(8)^*$:	1	$\frac{-1-i}{\sqrt{2}}$	-i	$\frac{-1+i}{\sqrt{2}}$	1	$\frac{-1-i}{\sqrt{2}}$	-i	$\frac{-1+i}{\sqrt{2}}$
$PC4_{8x8}(8)$:	1	-i	1	-i	-1	i	-1	i
$CI_{8x8}(7)^*$:	1	$\frac{1-i}{\sqrt{2}}$	i	$\frac{1+i}{\sqrt{2}}$	1	$\frac{1-i}{\sqrt{2}}$	i	$\frac{1+i}{\sqrt{2}}$

FIG. 33G

$HW_{8x8}(8)xCI_{8x8}$

$HW_{8x8}(8)$:	1	-1	-1	1	-1	1	1	-1
$CI_{8x8}(8)^*$:	1	$\frac{-1-i}{\sqrt{2}}$	-i	$\frac{-1+i}{\sqrt{2}}$	1	$\frac{-1-i}{\sqrt{2}}$	-i	$\frac{-1+i}{\sqrt{2}}$
$PC4_{8x8}(8)$:	1	-i	1	-i	-1	i	-1	i
$CI_{8x8}(7)^*$:	1	$\frac{1-i}{\sqrt{2}}$	i	$\frac{1+i}{\sqrt{2}}$	1	$\frac{1-i}{\sqrt{2}}$	i	$\frac{1+i}{\sqrt{2}}$
$HW_{8x8}(7)$:	1	1	-1	-1	-1	-1	1	1
$CI_{8x8}(7)$:	1	$\frac{1+i}{\sqrt{2}}$	-i	$\frac{1-i}{\sqrt{2}}$	1	$\frac{1+i}{\sqrt{2}}$	-i	$\frac{1-i}{\sqrt{2}}$
$PC4_{8x8}(6)$:	1	i	1	i	-1	-i	-1	-i
$CI_{8x8}(8)$:	1	$\frac{-1+i}{\sqrt{2}}$	i	$\frac{-1-i}{\sqrt{2}}$	1	$\frac{-1+i}{\sqrt{2}}$	i	$\frac{-1-i}{\sqrt{2}}$

FIG. 33H

C(1) = [1 (1+i)/√2 i (-1+i)/ √2 -1 (-1-i)/ √2 -i (1-i)/ √2];

C(1)*= [1 (1-i)/ √2 -i (-1-i)/√2 -1 (-1+i)/√2 i (1+i)/√2];

C(2) = [1 (-1+i)/√2 -i (1+i)/√2 -1 (1-i)/√2 i (-1-i)/√2];

C(2)*= [1 (-1-i)/√2 i (1-i)/√2 -1 (1+i)/√2 -i (-1+i)/√2];

C(3) = [1 (1+i)/√2 i (-1+i)/√2 1 (1+i)/√2 i (-1+i)/√2];

C(3)*= [1 (1-i)/√2 -i (-1-i)/√2 1 (1-i)/√2 -i (-1-i)/√2];

C(4) = [1 (-1+i)/√2 i (-1-i)/√2 1 (-1+i)/√2 i (-1-i)/√2];

C(4)*= [1 (-1-i)/√2 -i (-1+i)/√2 1 (-1-i)/√2 -i (-1+i)/√2];

C(5) = [1 (-1-i)/√2 -i (-1+i)/√2 -1 (1+i)/√2 i (1-i)/√2];

C(5)*= [1 (-1+i)/√2 i (-1-i)/√2 -1 (1-i)/√2 -i (1+i)/√2];

C(6) = [1 (1-i)/√2 i (1+i)/√2 -1 (-1+i)/√2 -i (-1-i)/√2];

C(6)*= [1 (1+i)/√2 -i (1-i)/√2 -1 (-1-i)/√2 i (-1+i)/√2];

C(7) = [1 (1+i)/√2 -i (1-i)/√2 1 (1+i)/√2 -i (1-i)/√2];

C(7)*= [1 (1-i)/√2 i (1+i)/√2 1 (1-i)/√2 i (1+i)/√2];

C(8) = [1 (-1+i)/√2 -i (1+i)/√2 1 (-1+i)/√2 -i (1+i)/√2];

C(8)*= [1 (-1-i)/√2 i (1-i)/√2 1 (-1-i)/√2 i (1-i)/√2];

FIG. 34A

	C(1)	C(1)*	C(2)	C(2)*	C(3)	C(3)*	C(4)	C(4)*	C(5)	C(5)*	C(6)	C(6)*	C(7)	C(7)*	C(8)	C(8)*
CI(1)	0	8	0	0	0	0	0	0	4-4i	0	0	4+4i	0	0	0	0
CI(1)*	8	0	0	0	0	0	0	0	0	4+4i	4-4i	0	0	0	0	0
CI(2)	0	0	0	8	0	0	0	0	0	4-4i	4+4i	0	0	0	0	0
CI(2)*	0	0	8	0	0	0	0	0	4+4i	0	0	4-4i	0	0	0	0
CI(3)	0	0	0	0	0	8	0	4-4i	0	0	0	0	4+4i	0	0	0
CI(3)*	0	0	0	0	8	0	4+4i	0	0	0	0	0	0	4-4i	0	0
CI(4)	0	0	0	0	0	4+4i	0	8	0	0	0	0	0	0	4-4i	0
CI(4)*	0	0	0	0	4-4i	0	8	0	0	0	0	0	0	0	0	4+4i
CI(5)	4-4i	0	0	4+4i	0	0	0	0	0	8	0	0	0	0	0	0
CI(5)*	0	4+4i	4-4i	0	0	0	0	0	8	0	0	0	0	0	0	0
CI(6)	0	4-4i	4+4i	0	0	0	0	0	0	0	0	8	0	0	0	0
CI(6)*	4+4i	0	0	4-4i	0	0	0	0	0	0	8	0	0	0	0	0
CI(7)	0	0	0	0	4+4i	0	0	0	0	0	0	0	0	8	0	4-4i
CI(7)*	0	0	0	0	0	4-4i	0	0	0	0	0	0	8	0	4+4i	0
CI(8)	0	0	0	0	0	0	4-4i	0	0	0	0	0	0	4+4i	0	8
CI(8)*	0	0	0	0	0	0	0	4+4i	0	0	0	0	4-4i	0	8	0

FIG. 34B

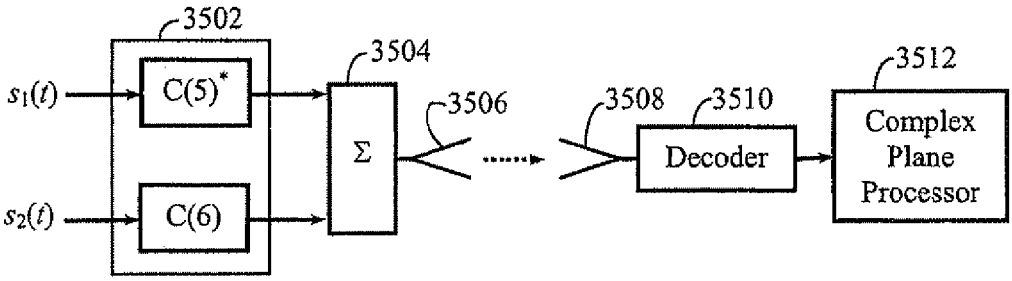


FIG. 35

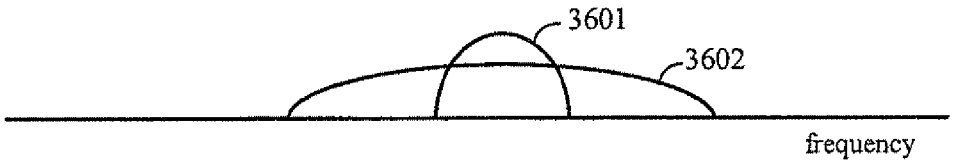


FIG. 36A

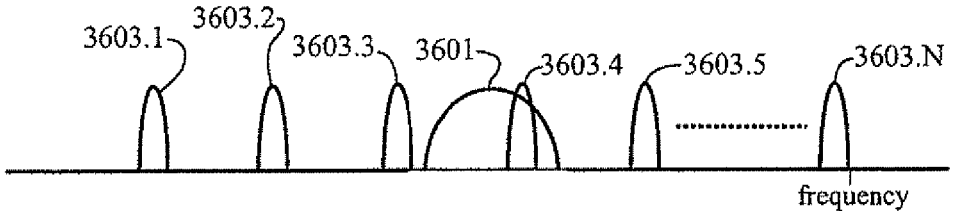


FIG. 36B

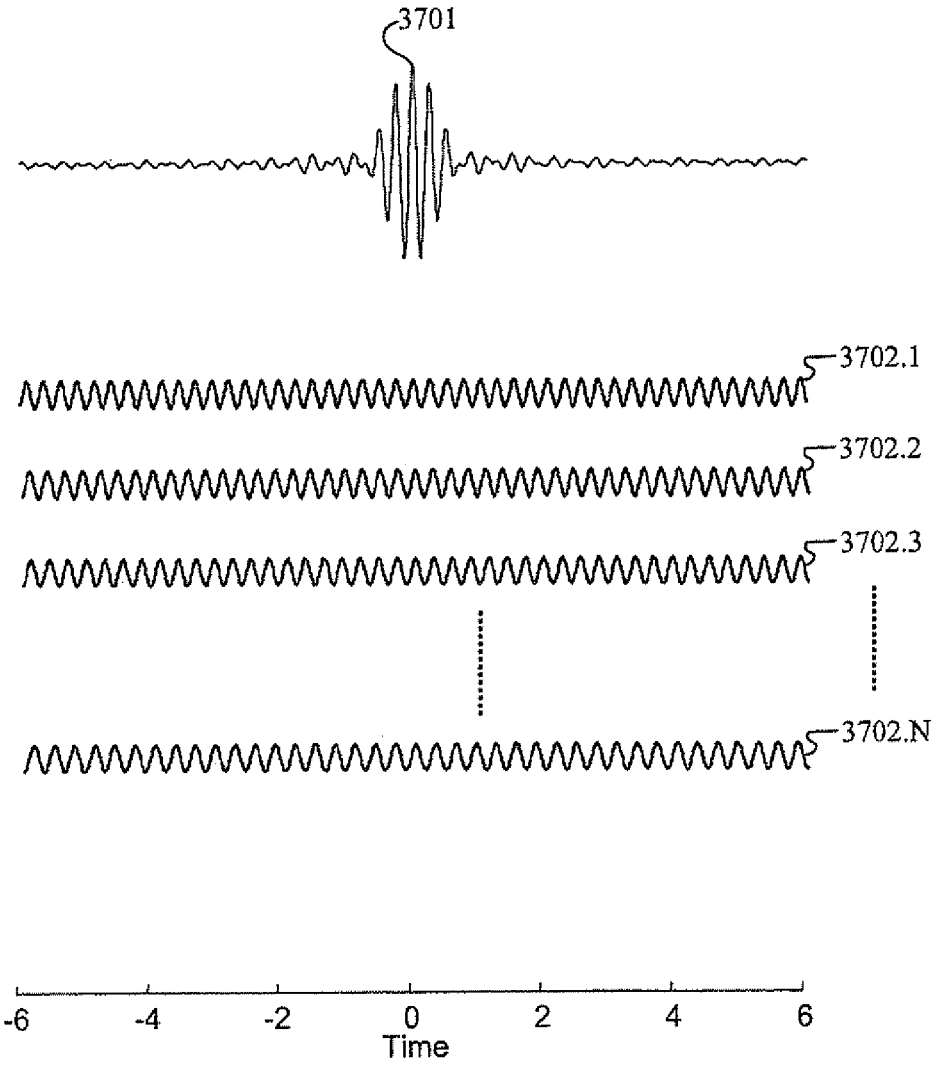


FIG. 37

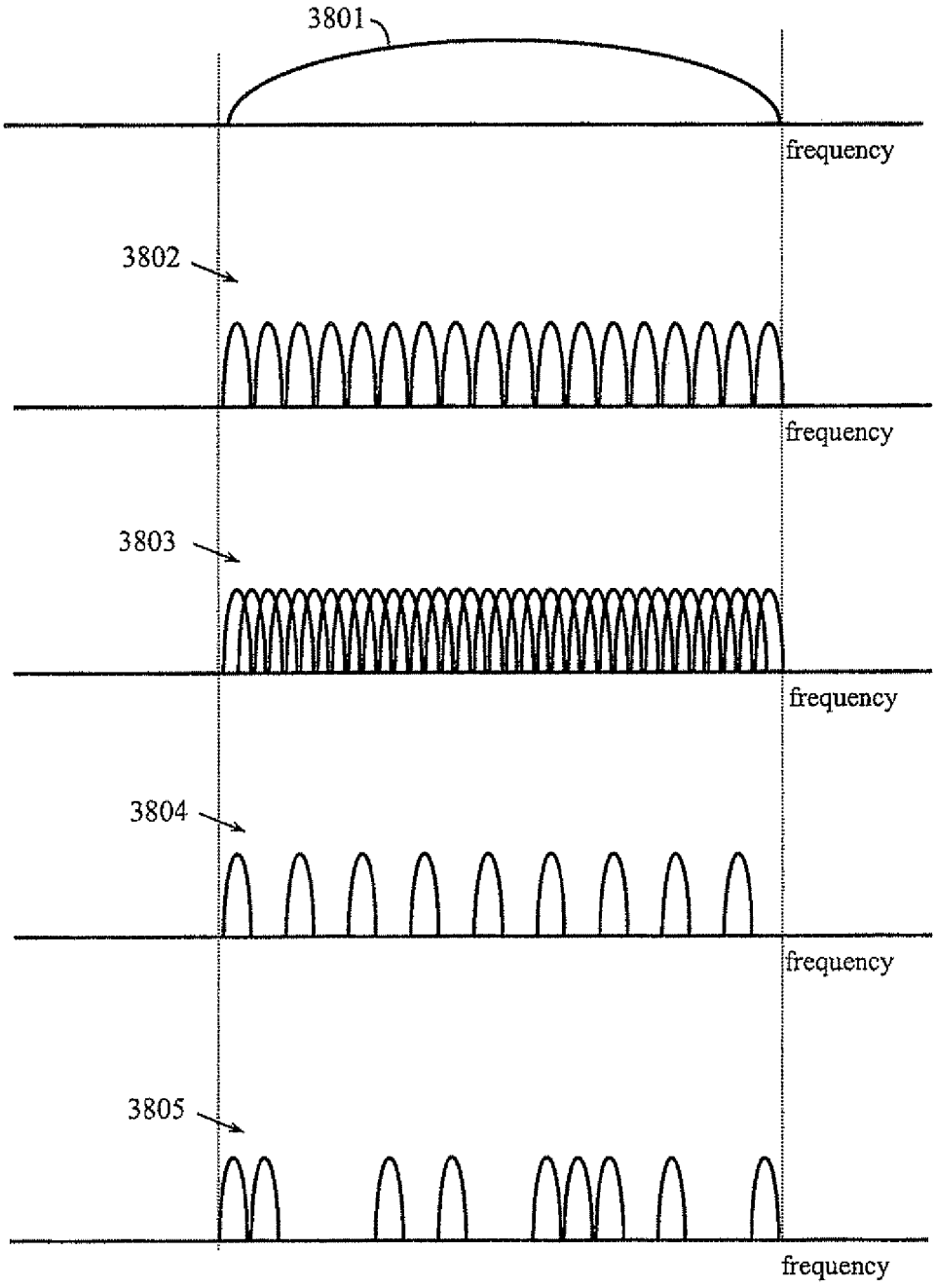

3801
frequency
3802
frequency
3803
frequency
3804
frequency
3805
frequency

FIG. 38

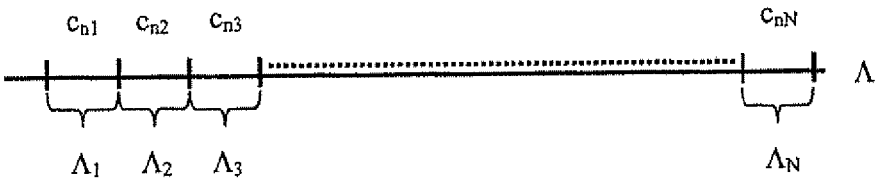


FIG. 39A

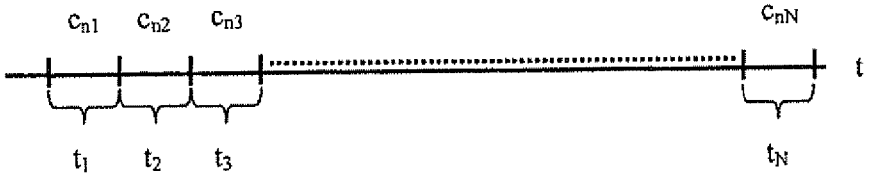


FIG. 39B

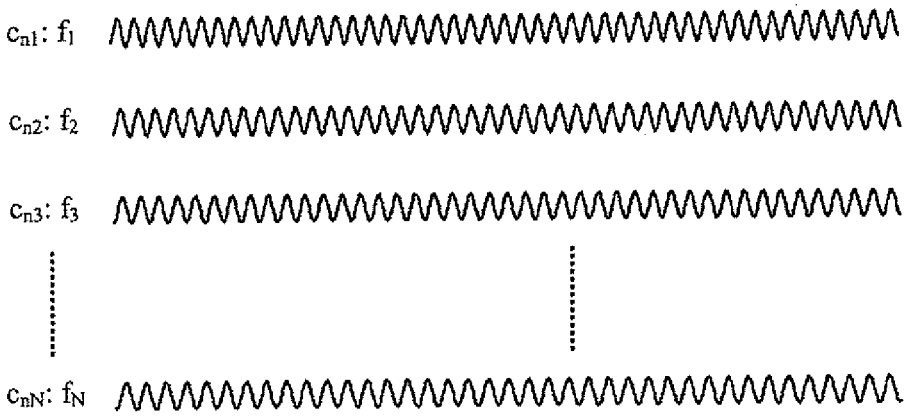


FIG. 39C

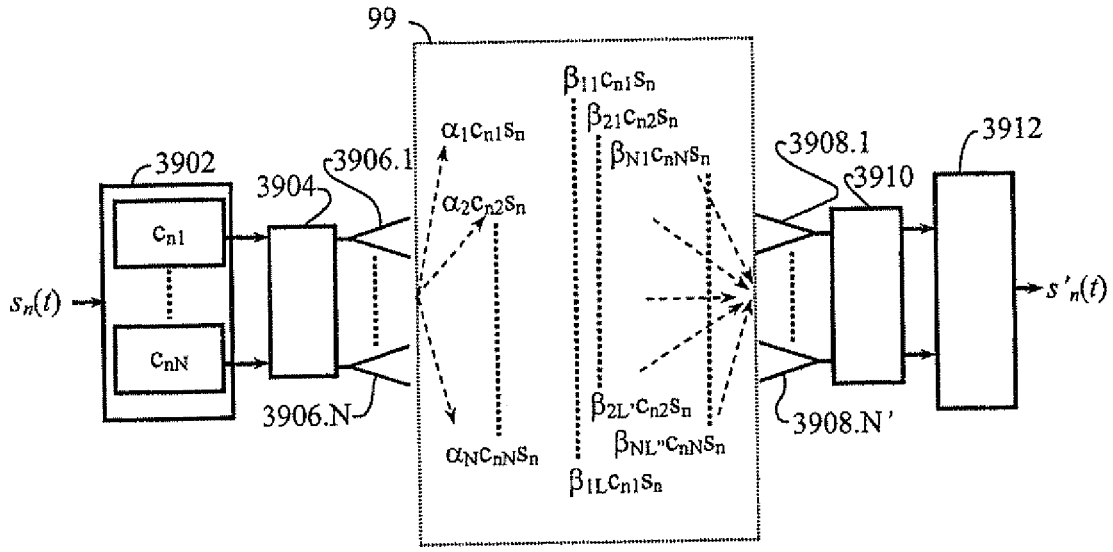


FIG. 39D

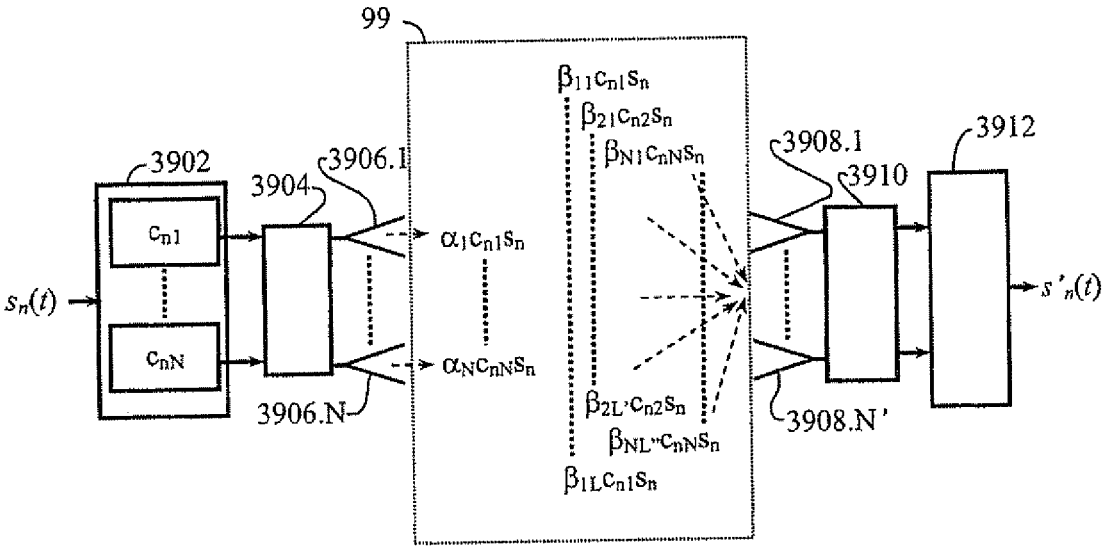


FIG. 39E

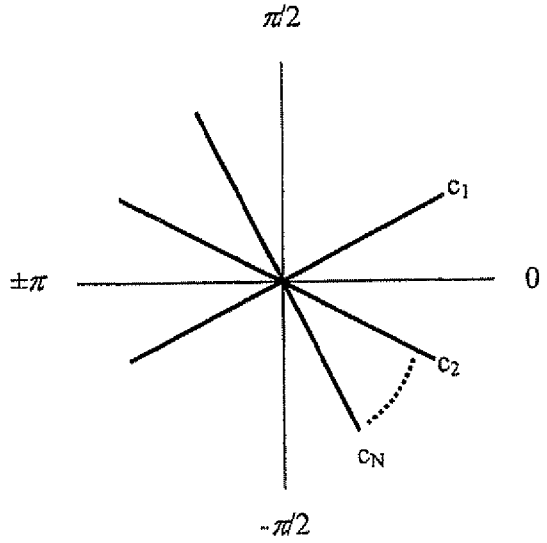


FIG. 39F

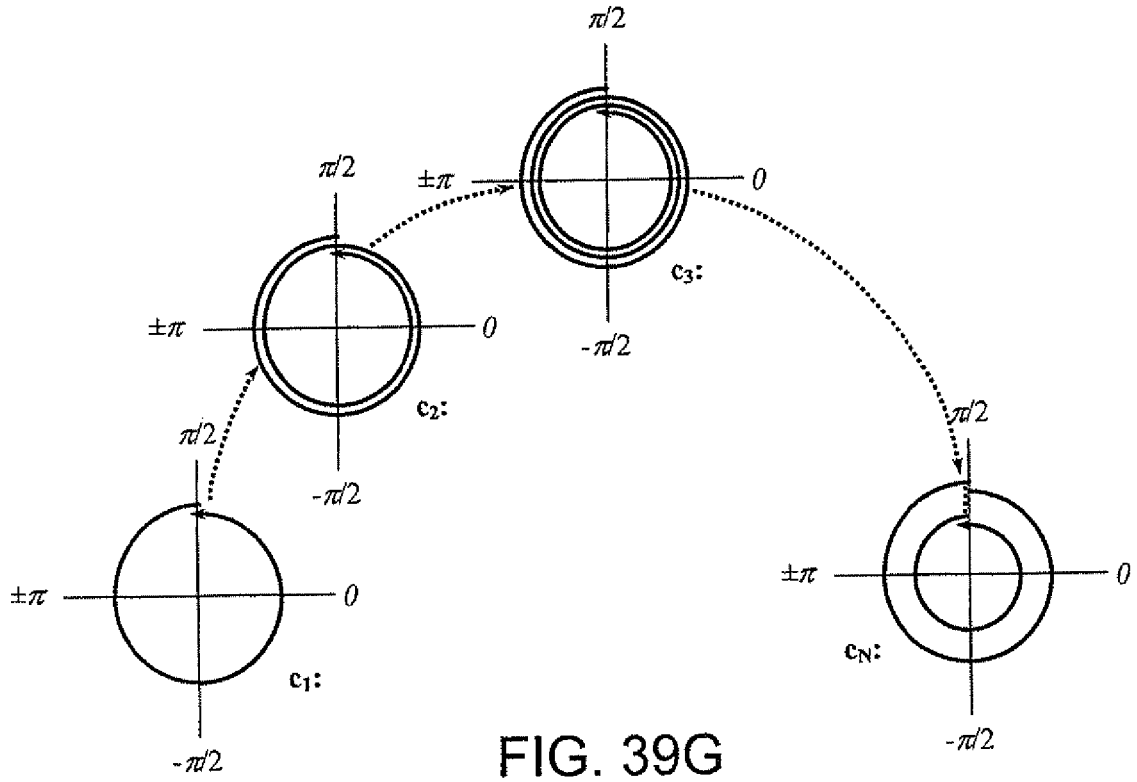


FIG. 39G

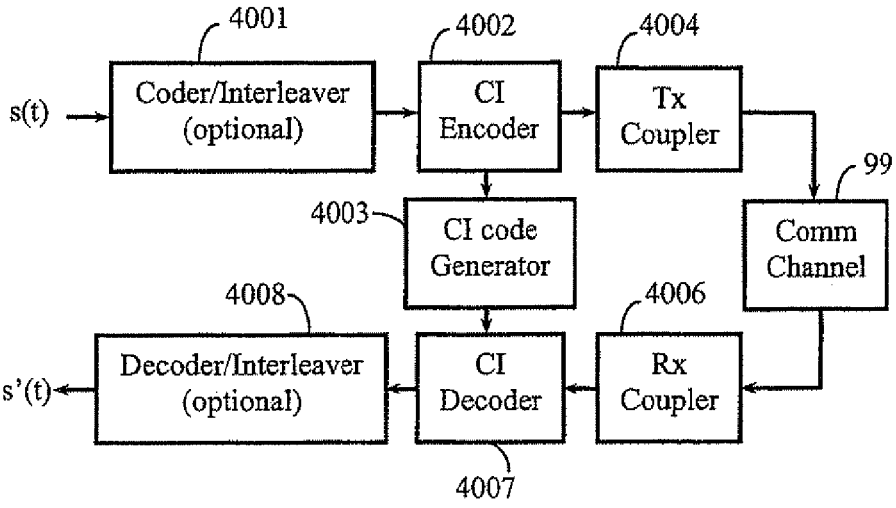


FIG. 40A

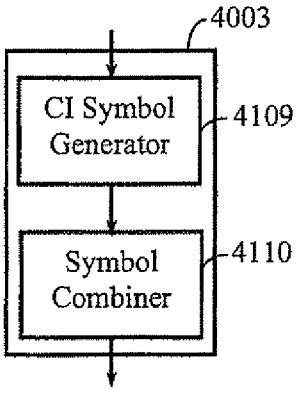


FIG. 40B

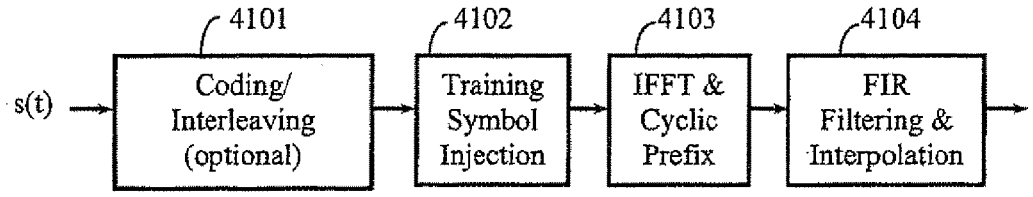


FIG. 41A

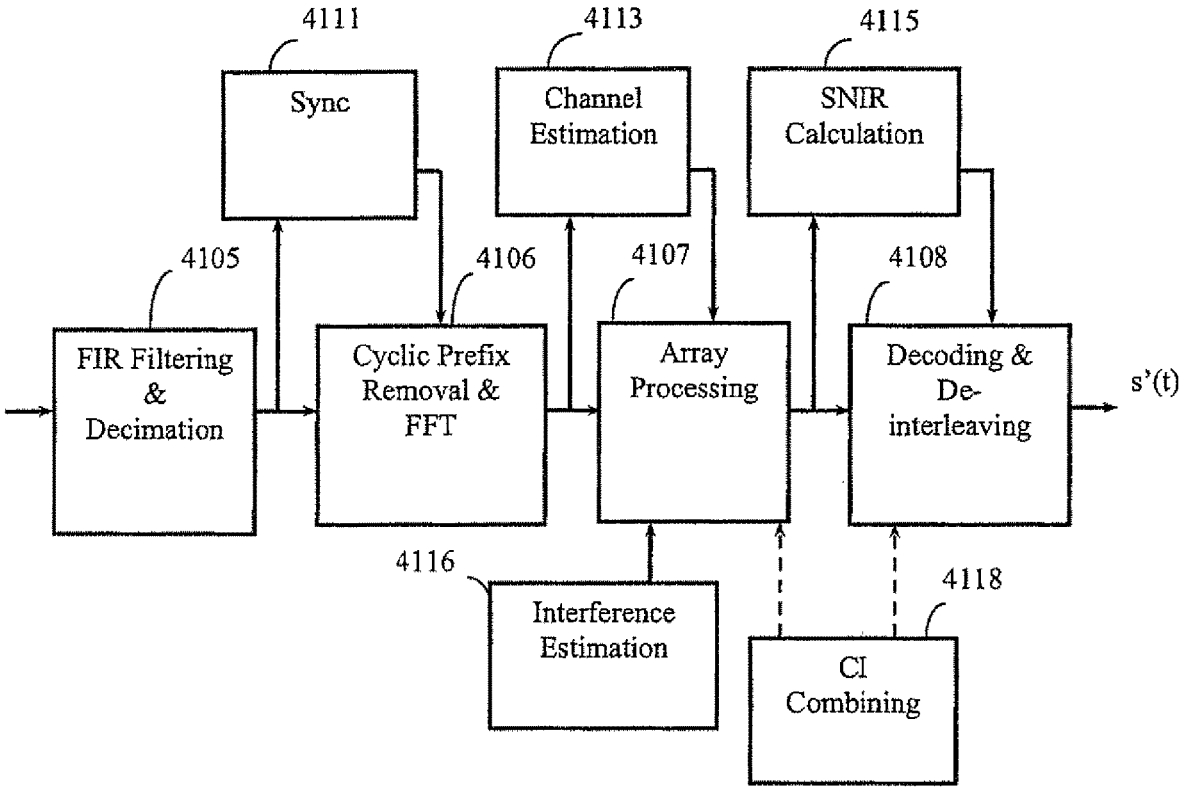


FIG. 41B

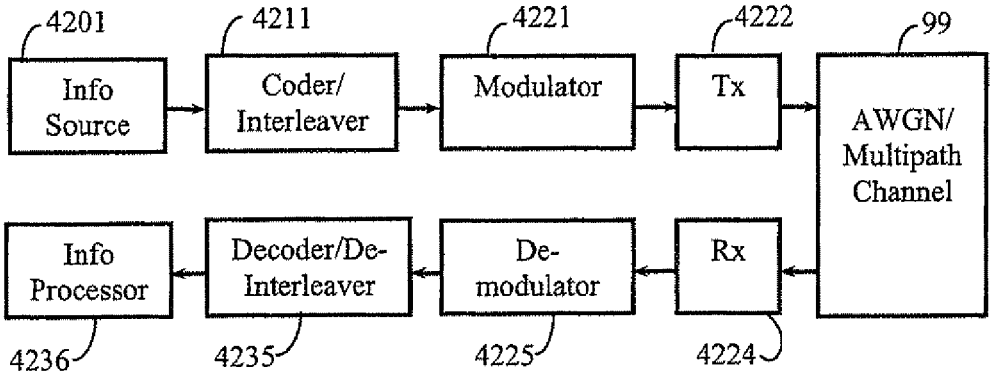


FIG. 42

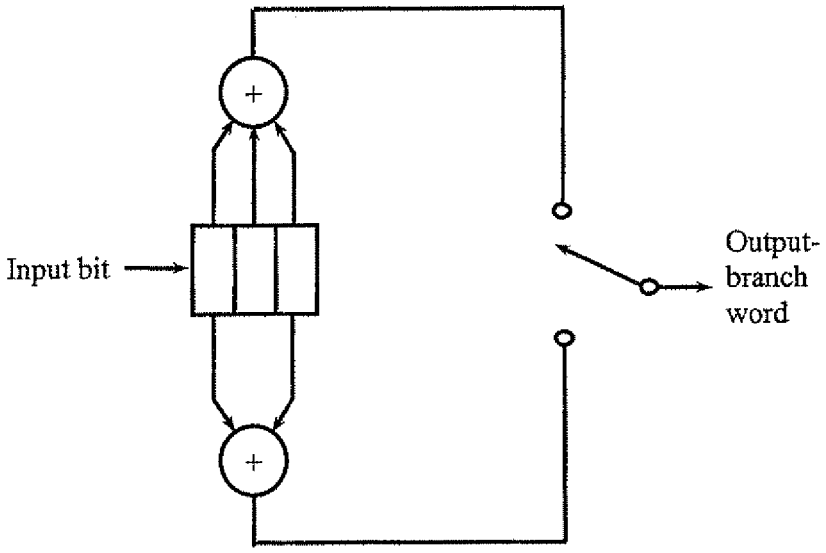


FIG. 43A

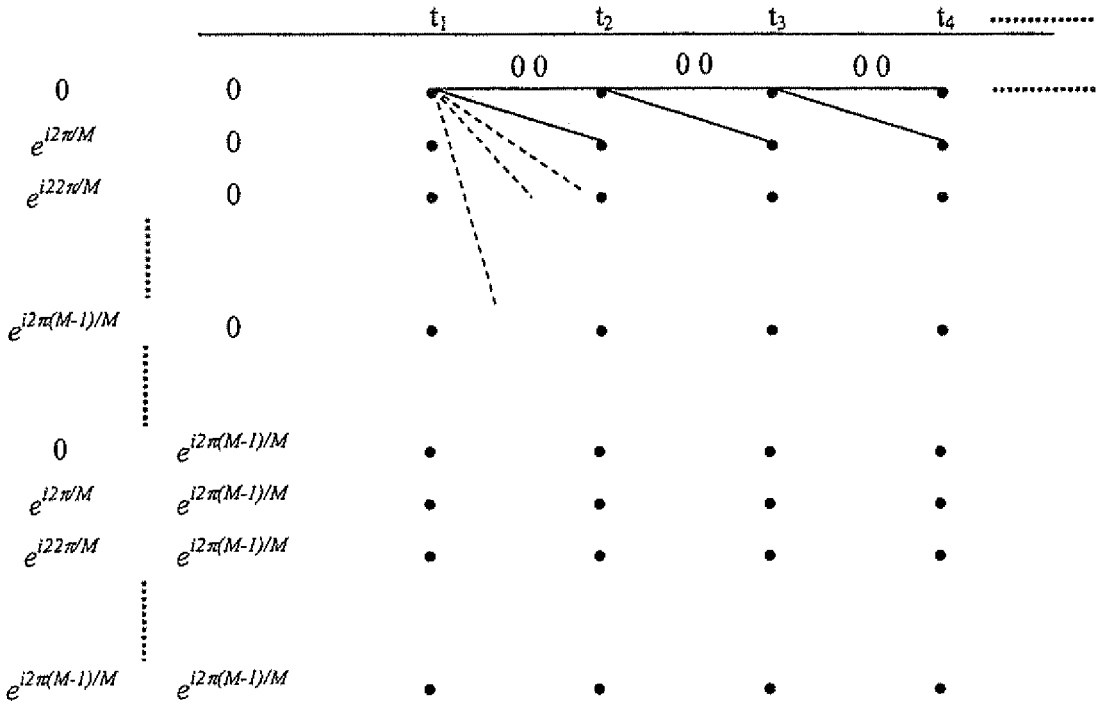
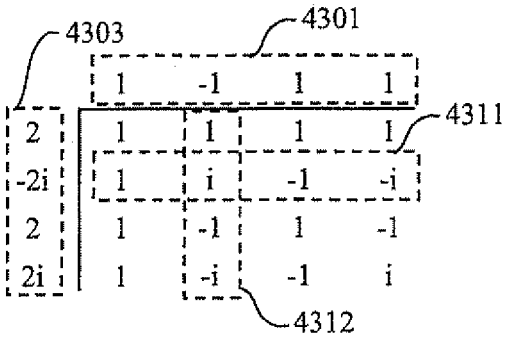


FIG. 43B

FIG. 43C



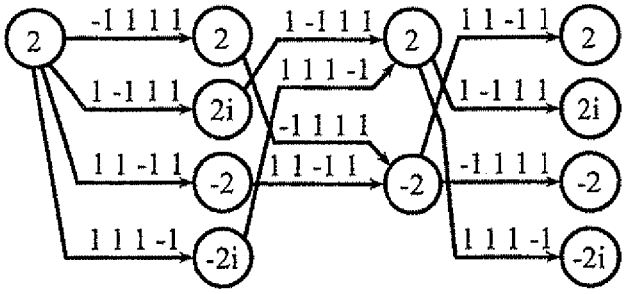


FIG. 43D

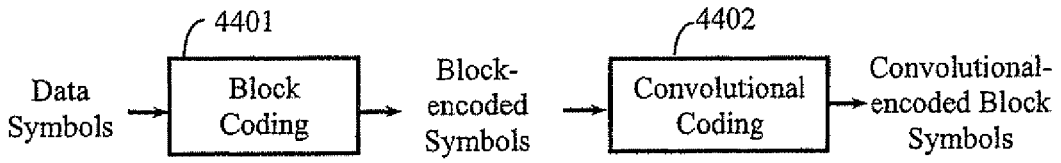


FIG. 44A

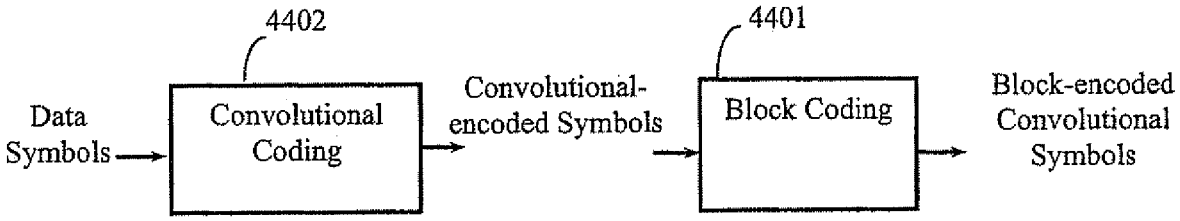


FIG. 44B

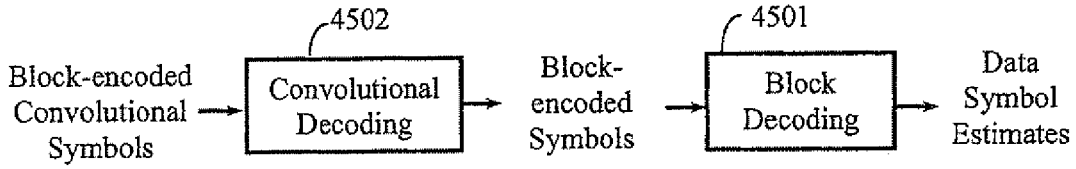


FIG. 45A

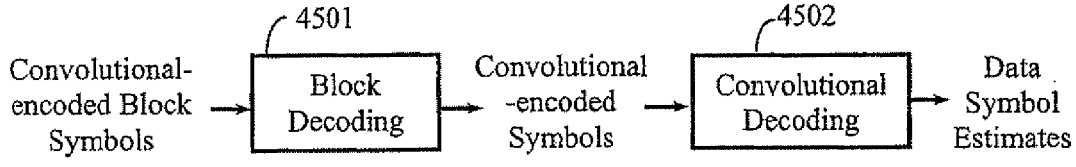


FIG. 45B

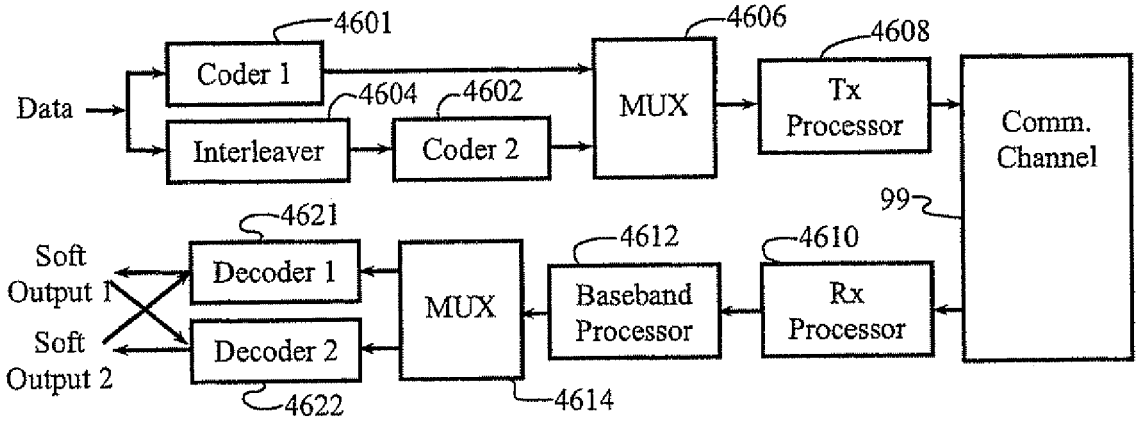

4601
Coder 1
Data
4604
4602
Interleaver
Coder 2
4606
MUX
4608
Tx Processor
Comm. Channel
99
4621
Soft Output 1
Soft Output 2
Decoder 1
Decoder 2
4622
MUX
4614
4612
Baseband Processor
4610
Rx Processor

FIG. 46

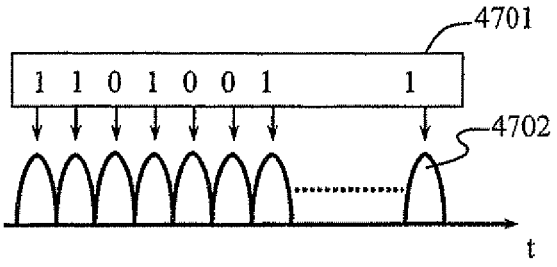


FIG. 47A

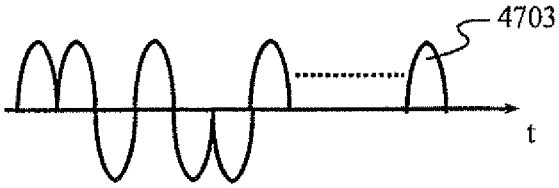


FIG. 47B

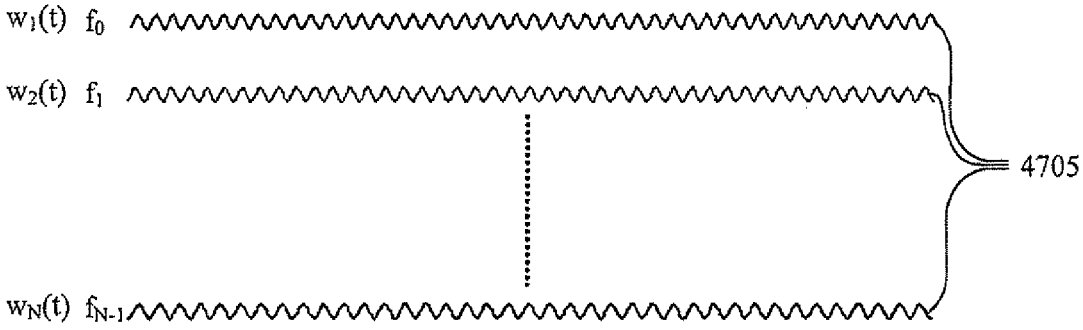


FIG. 47c

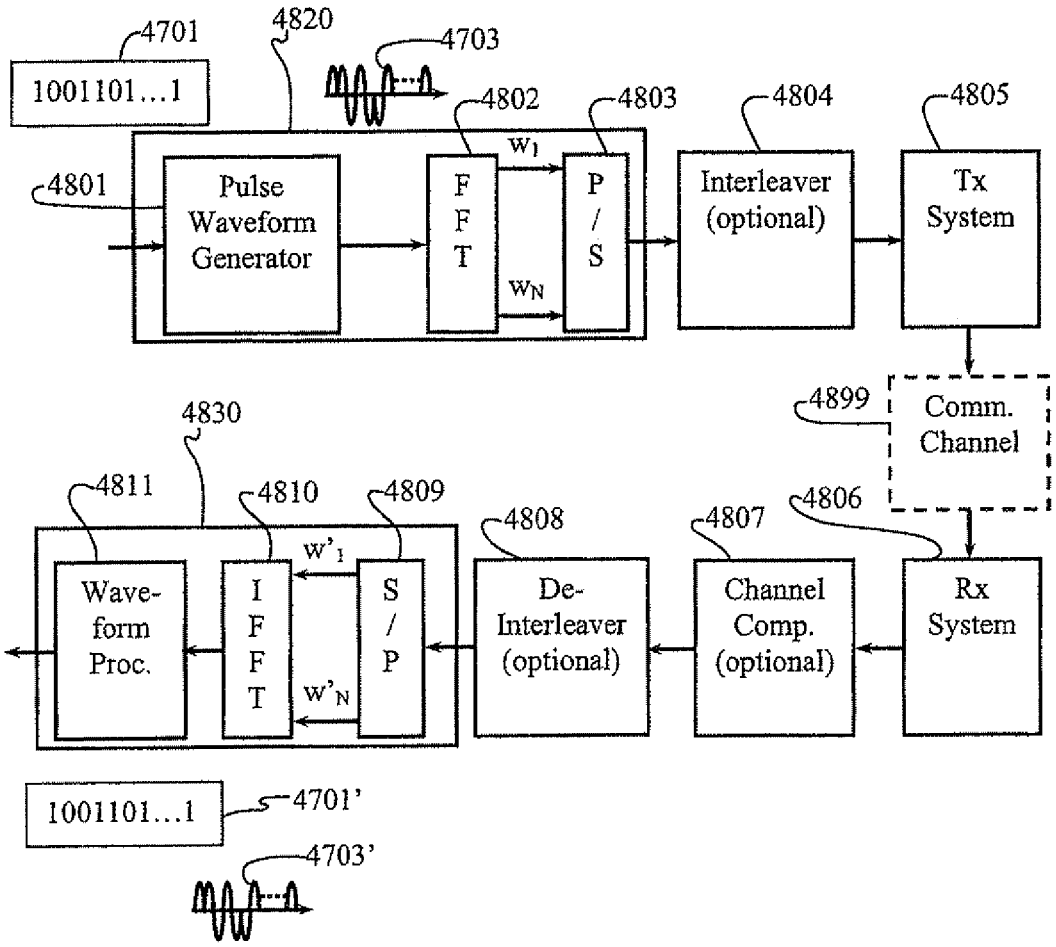

4701
1001101...1
4820
4703
4802
4803
4804
4805
4801
Pulse Waveform Generator
F F T
w_1
w_N
P / S
Interleaver (optional)
Tx System
4899
Comm. Channel
4830
4811
4810
4809
4808
4807
4806
w'_1
w'_N
Wave-form Proc.
I F F T
S / P
De-Interleaver (optional)
Channel Comp. (optional)
Rx System
1001101...1
4701'
4703'

FIG. 48

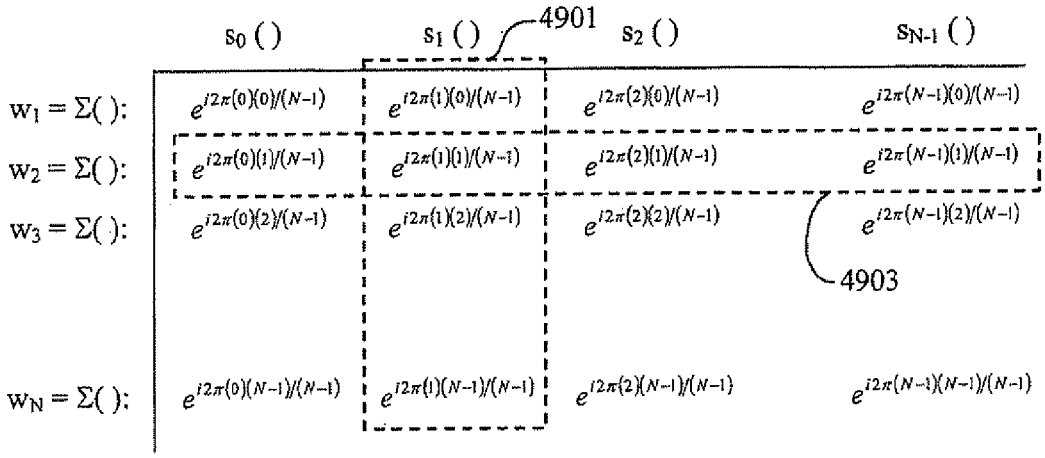

s0 ( )
s1 ( )
4901
s2 ( )
sN-1 ( )
w1 = Σ( ):
w2 = Σ( ):
w3 = Σ( ):
wN = Σ( ):
4903

FIG. 49

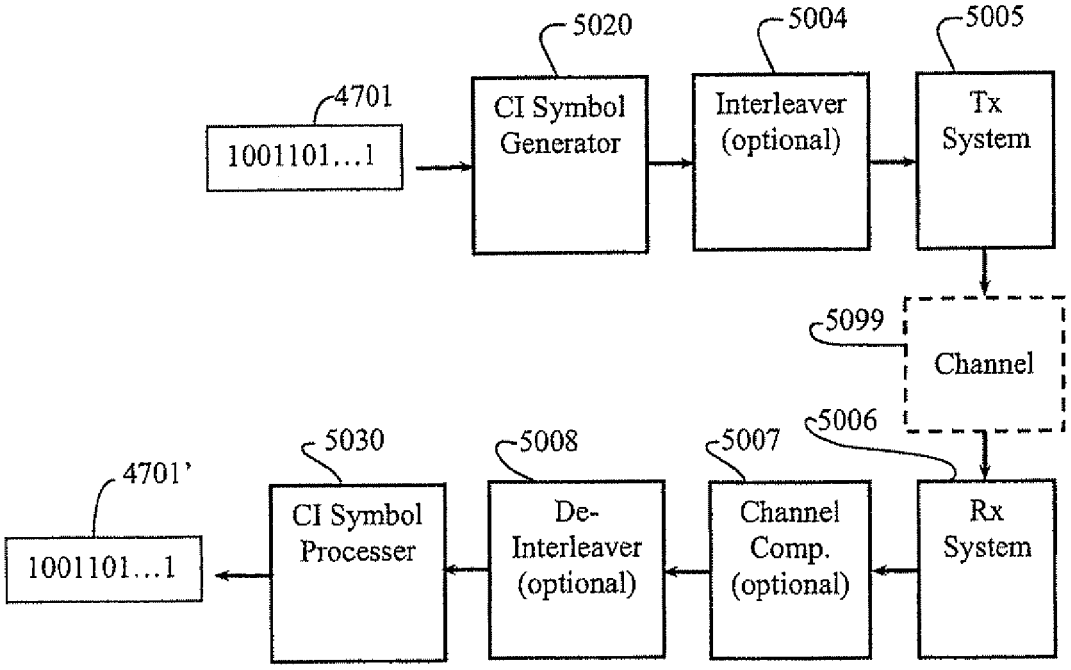

5020
5004
5005
4701
1001101…1
CI Symbol Generator
Interleaver (optional)
Tx System
5099
Channel
5006
5030
5008
5007
4701'
1001101…1
CI Symbol Processer
De-Interleaver (optional)
Channel Comp. (optional)
Rx System

FIG. 50

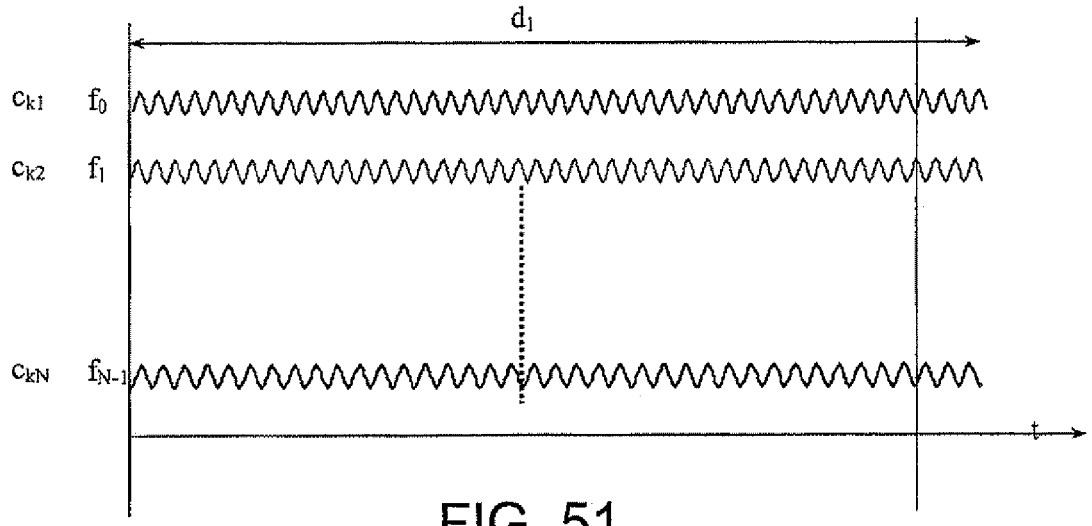

d_1
c_{k1} f_0
c_{k2} f_1
c_{kN} f_{N-1}
t

FIG. 51

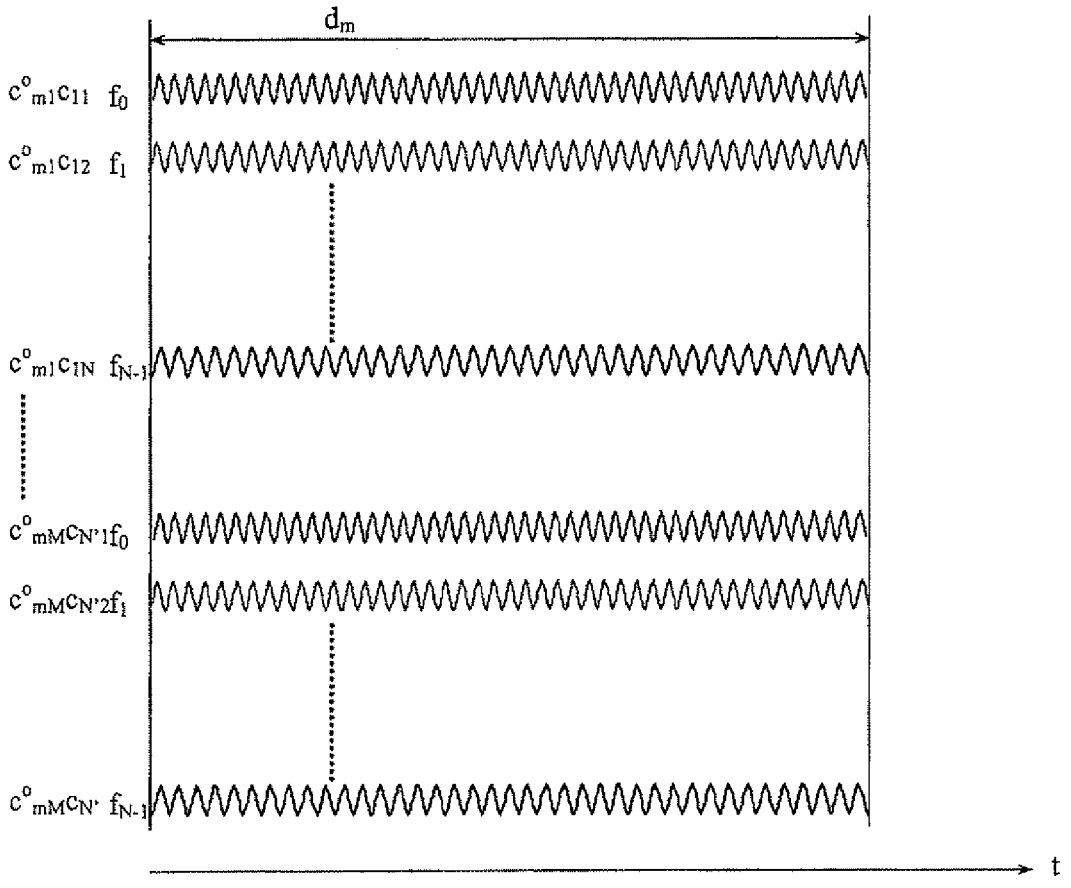

d_m
$c^o_{m1}c_{11}$ f_0
$c^o_{m1}c_{12}$ f_1
$c^o_{m1}c_{1N}$ f_{N-1}
$c^o_{mM}c_{N'1}f_0$
$c^o_{mM}c_{N'2}f_1$
$c^o_{mM}c_{N'}$ f_{N-1}
t

FIG. 52

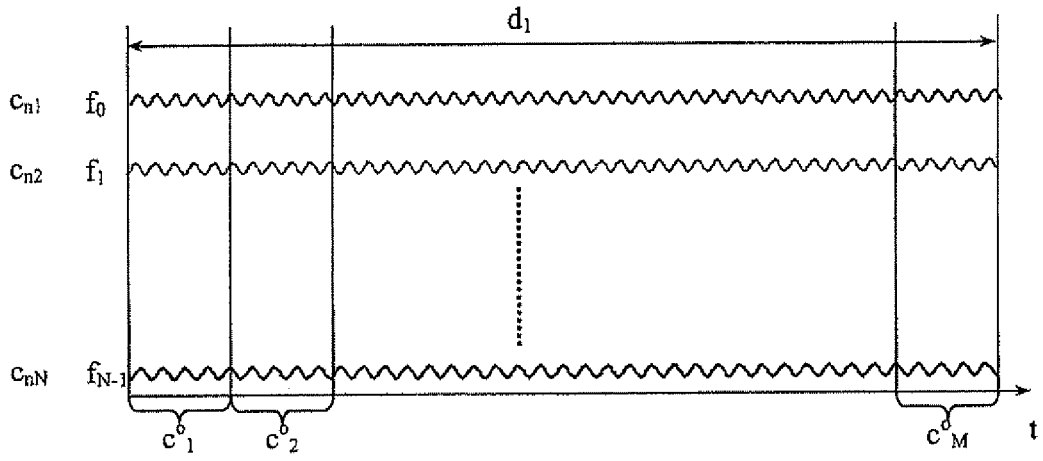


FIG. 53

	Spatial Sub-channel #1	Spatial Sub-channel #2	.....	Spatial Sub-channel #N
Code #1:	c_{11}	c_{12}	.....	c_{1N}
Code #2:	c_{21}	c_{22}	.....	c_{2N}
⋮	⋮	⋮		⋮
Code #n:	c_{n1}	c_{n2}	.....	c_{nN}
⋮	⋮	⋮		⋮
Code #N'	$c_{N'1}$	$c_{N'2}$	.....	$c_{N'N}$

FIG. 54A

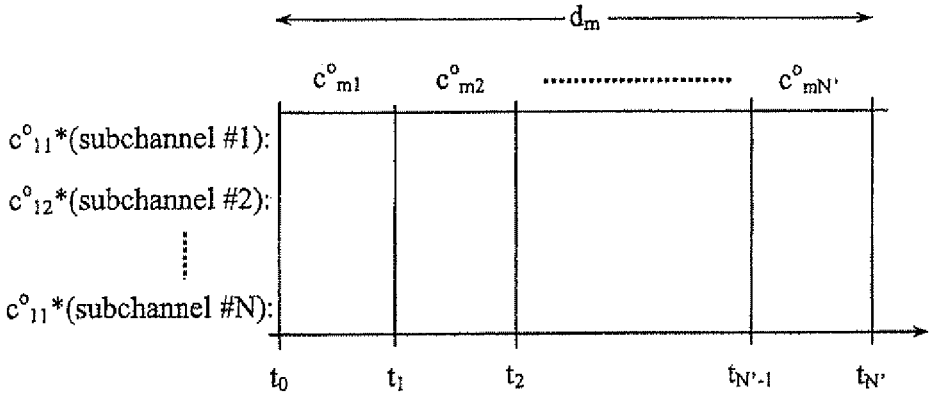


FIG. 54B

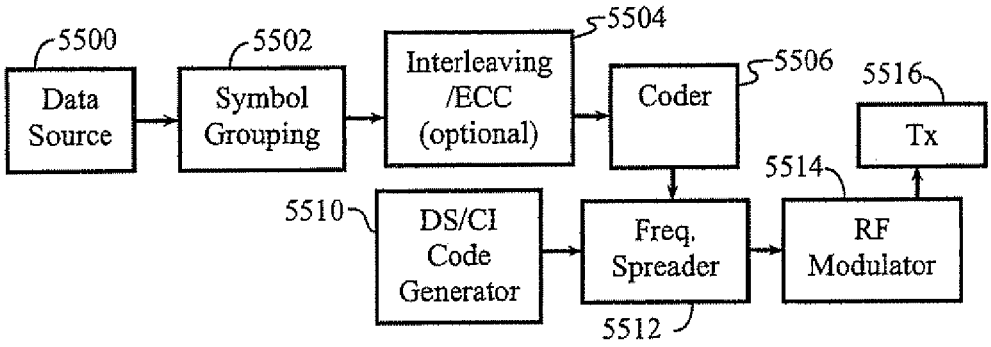


FIG. 55

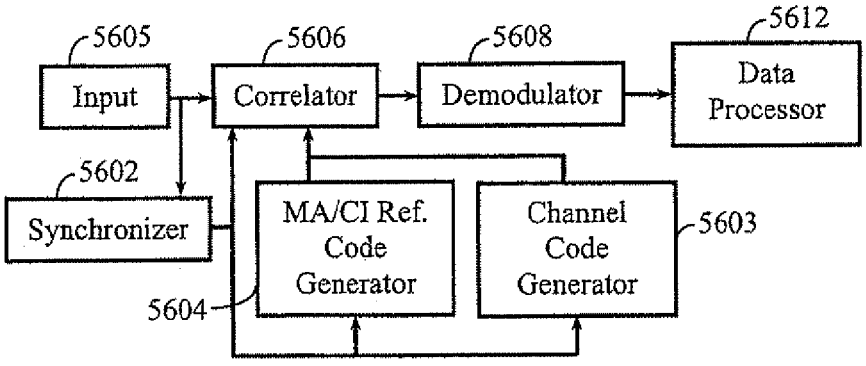


FIG. 56

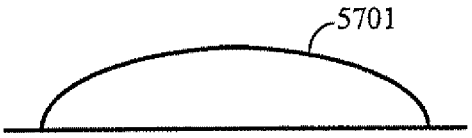


FIG. 57A

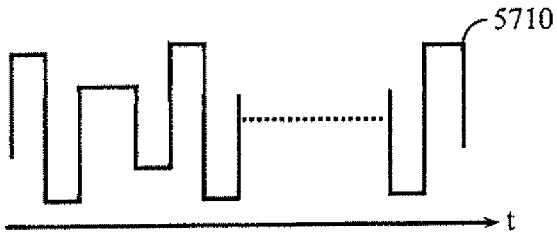


FIG. 57B

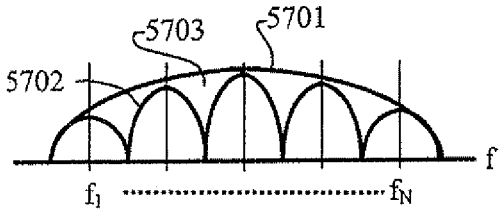


FIG. 57C

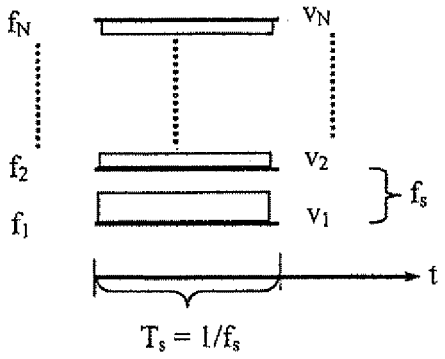


FIG. 58a

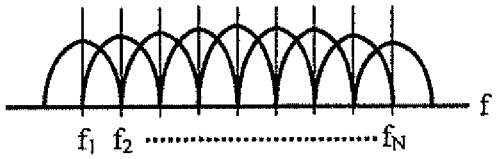


FIG. 58b

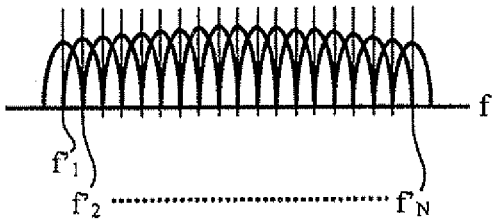


FIG. 58d

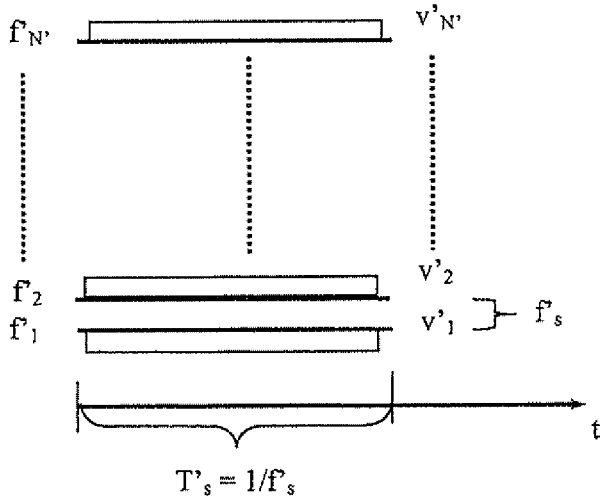


FIG. 58c

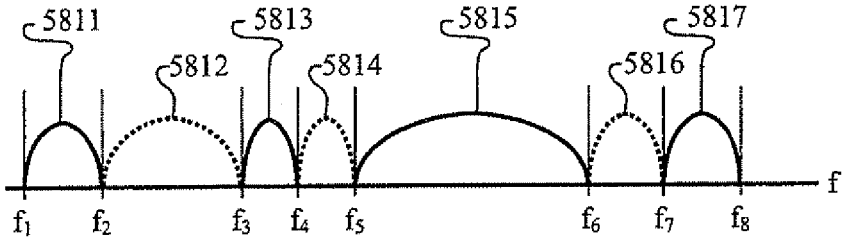


FIG. 58e

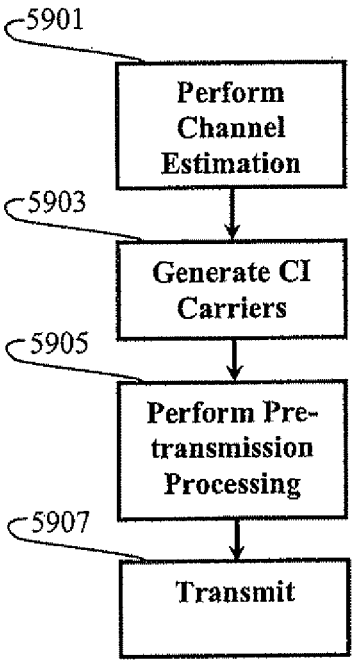


FIG. 59A

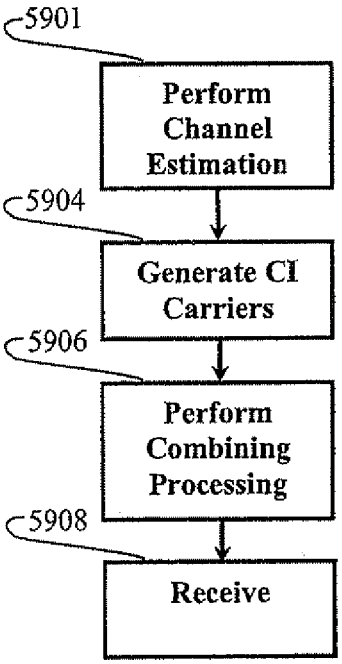


FIG. 59B

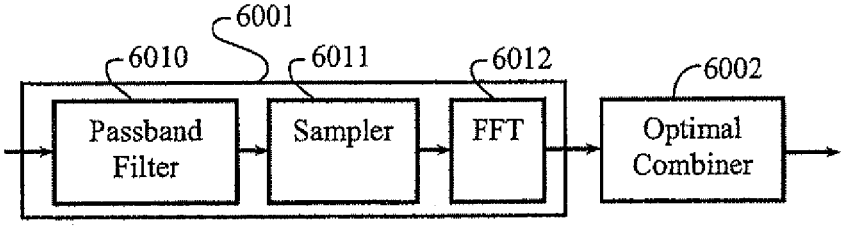


FIG. 60A

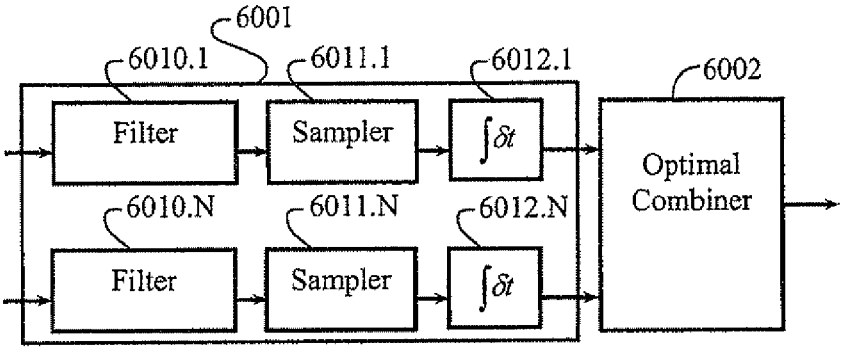


FIG. 60B

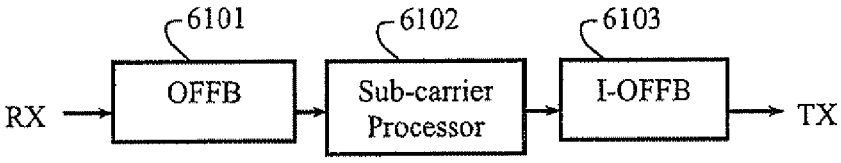


FIG. 61

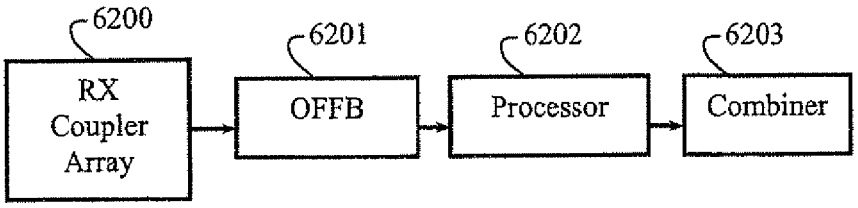

6200
RX Coupler Array
6201
OFFB
6202
Processor
6203
Combiner

FIG. 62

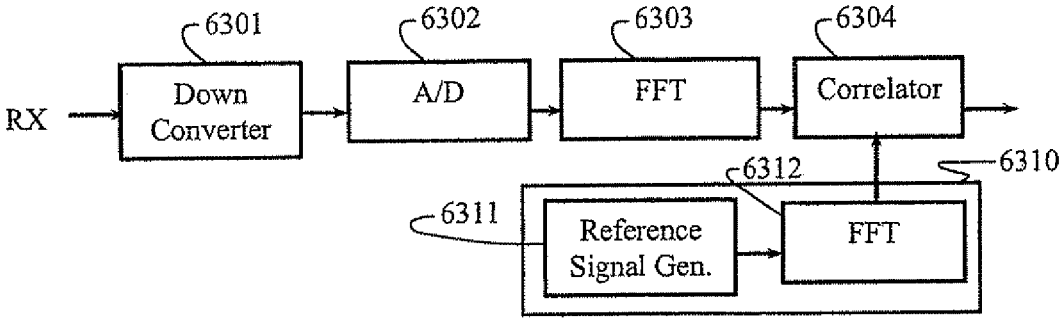

RX
6301
Down Converter
6302
A/D
6303
FFT
6304
Correlator
6310
6312
6311
Reference Signal Gen.
FFT

FIG. 63

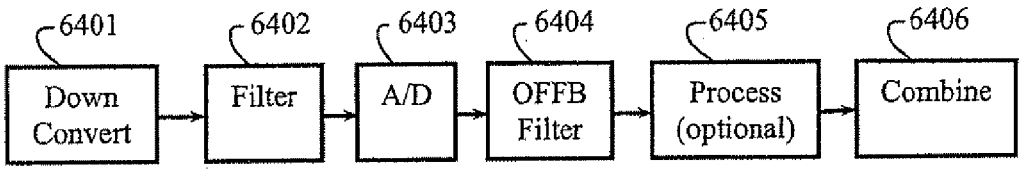


FIG. 64A

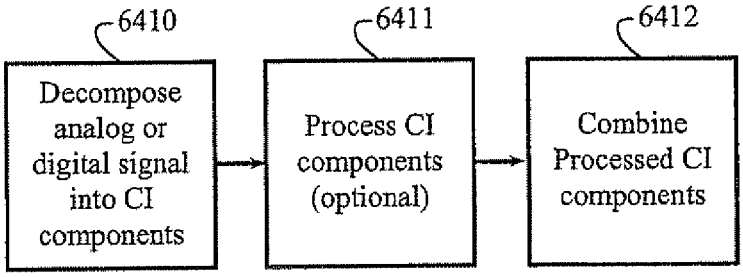


FIG. 64B

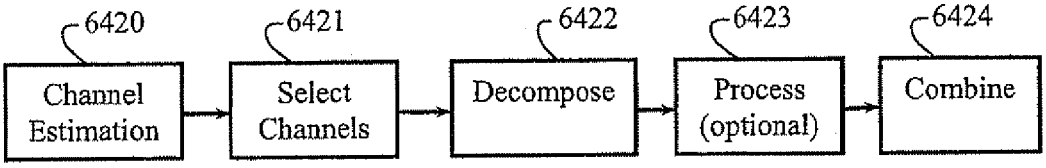


FIG. 64C

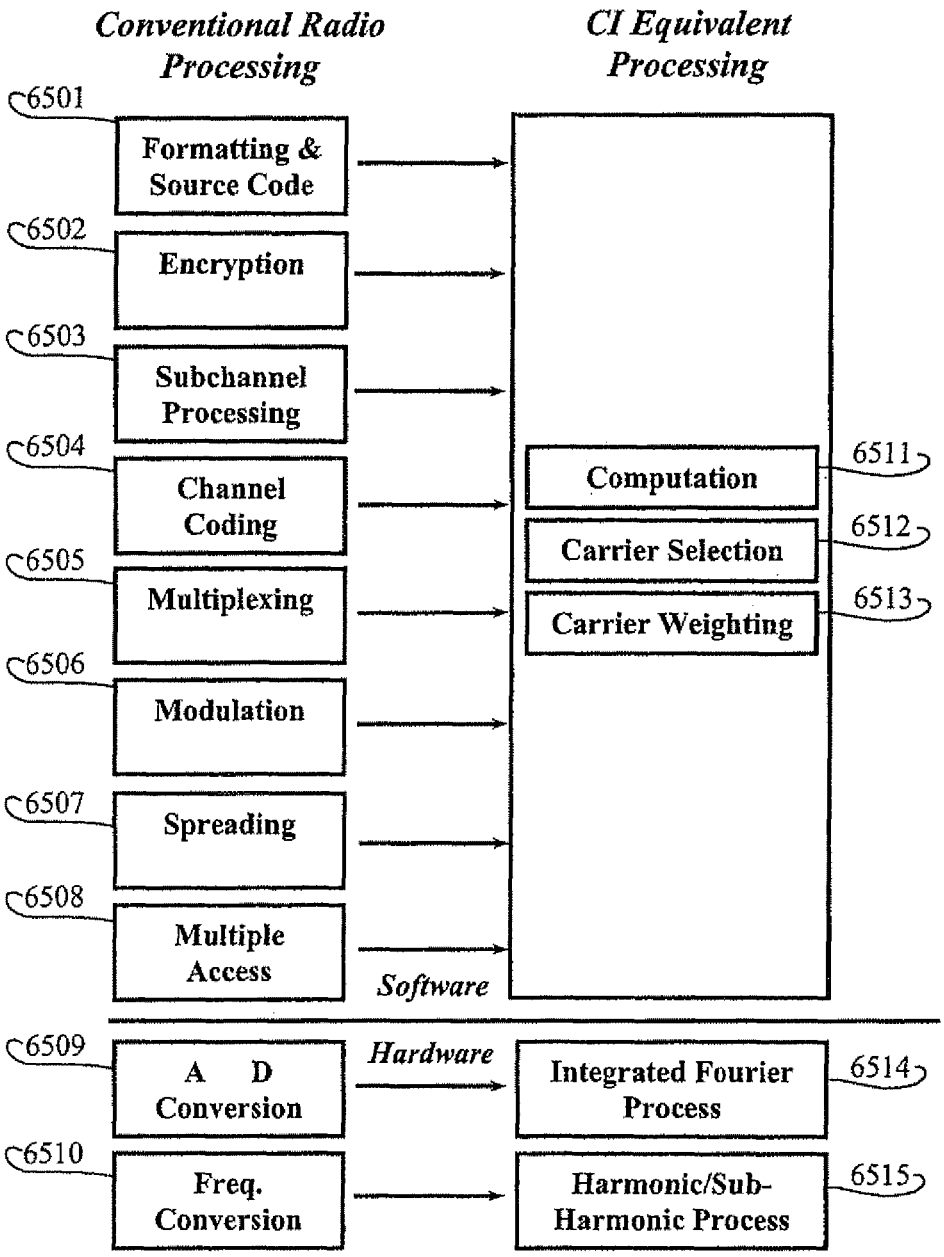

Conventional Radio Processing
CI Equivalent Processing
6501
Formatting & Source Code
6502
Encryption
6503
Subchannel Processing
6504
Channel Coding
6505
Multiplexing
6506
Modulation
6507
Spreading
6508
Multiple Access
Software
Computation
6511
Carrier Selection
6512
Carrier Weighting
6513
6509
A D Conversion
Hardware
Integrated Fourier Process
6514
6510
Freq. Conversion
Harmonic/Sub-Harmonic Process
6515

FIG. 65

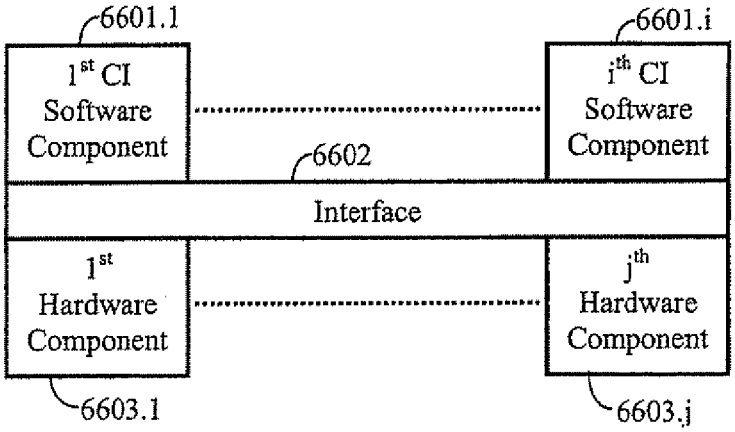

6601.1
1st CI Software Component
6601.i
ith CI Software Component
6602
Interface
1st Hardware Component
jth Hardware Component
6603.1
6603.j

FIG. 66

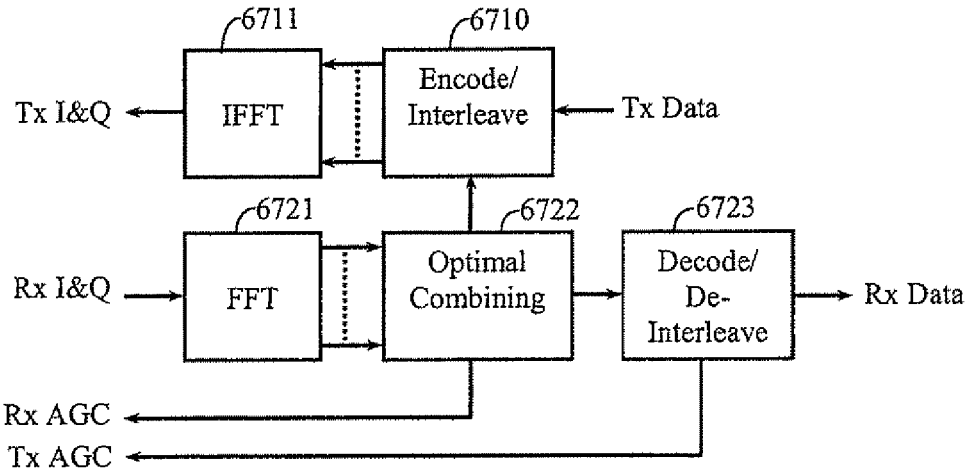

6711
6710
Tx I&Q
IFFT
Encode/ Interleave
Tx Data
6721
6722
6723
Rx I&Q
FFT
Optimal Combining
Decode/ De-Interleave
Rx Data
Rx AGC
Tx AGC

FIG. 67

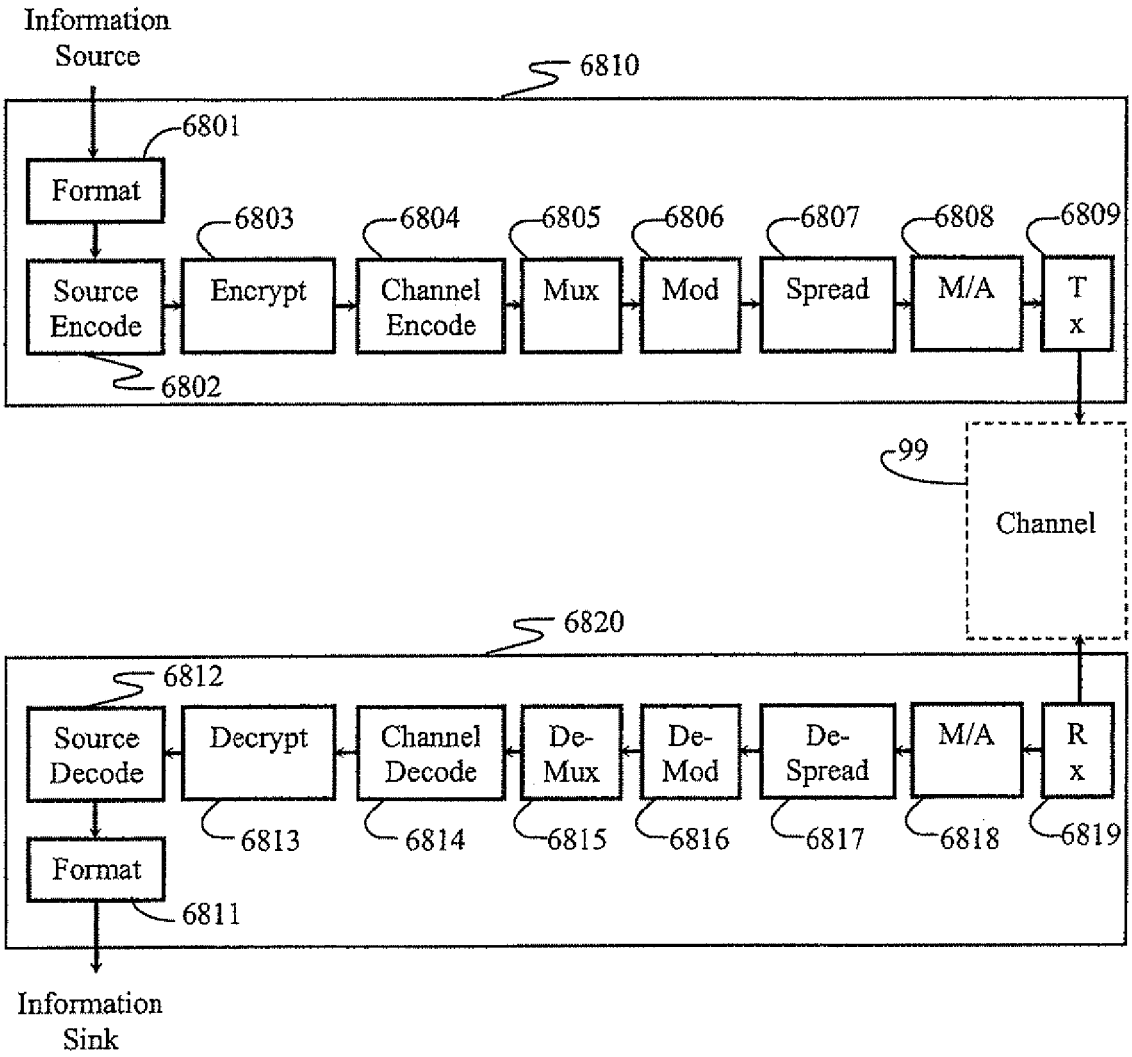

Information Source
6810
6801
Format
6803
6804
6805
6806
6807
6808
6809
Source Encode
Encrypt
Channel Encode
Mux
Mod
Spread
M/A
T x
6802
99
Channel
6820
6812
Source Decode
Decrypt
Channel Decode
De-Mux
De-Mod
De-Spread
M/A
R x
6813
6814
6815
6816
6817
6818
6819
Format
6811
Information Sink

FIG. 68

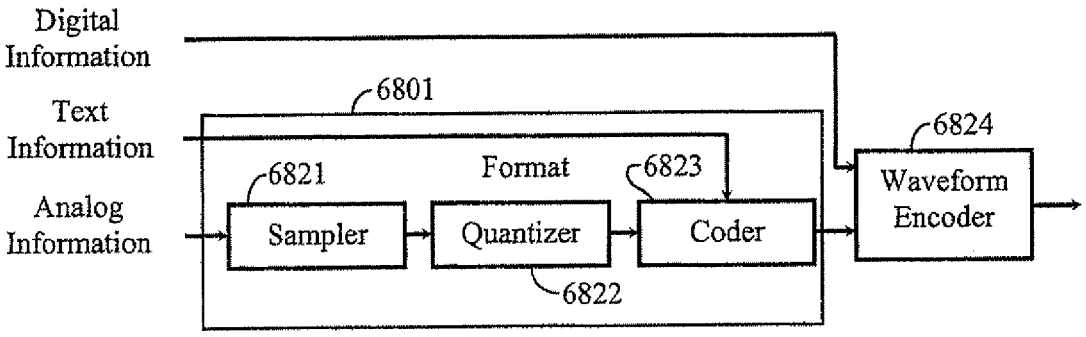


FIG. 69A

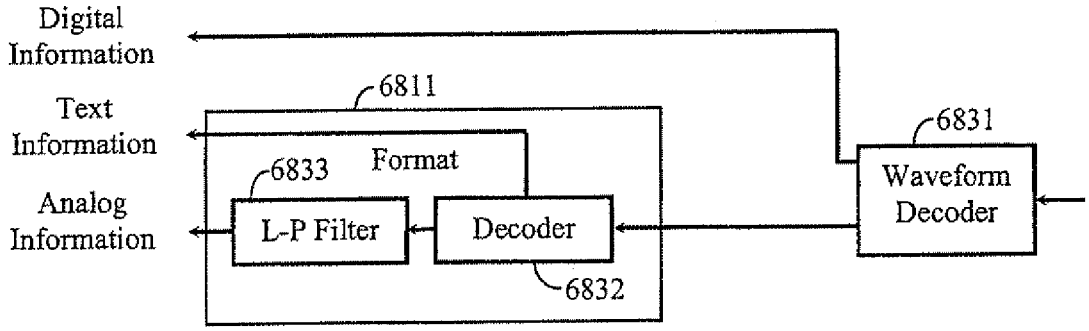


FIG. 69B

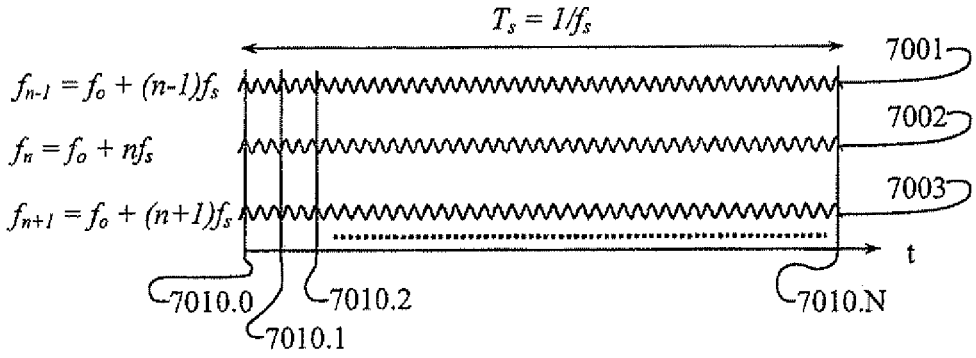


FIG. 70

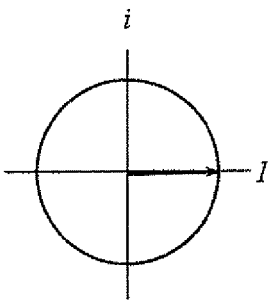


FIG. 71A

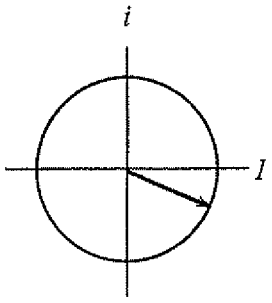


FIG. 71B

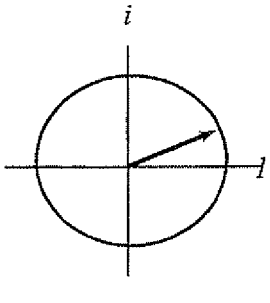


FIG. 71C

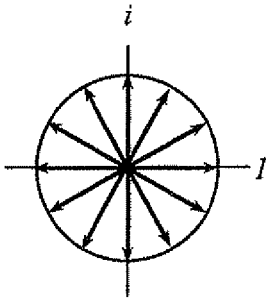

i
1

FIG. 72

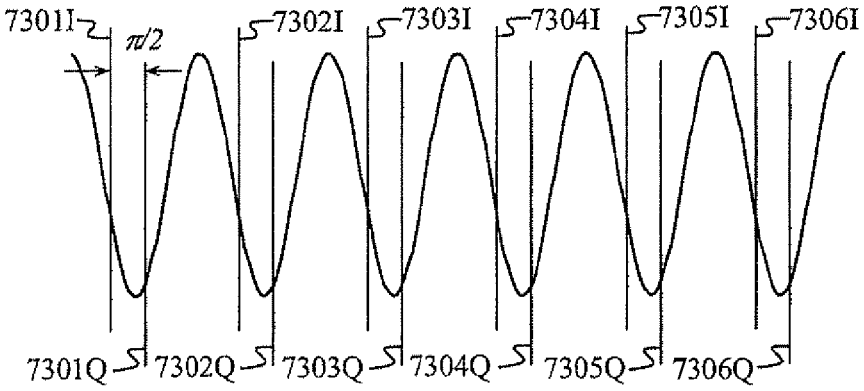

7301I
π/2
7302I
7303I
7304I
7305I
7306I
7301Q
7302Q
7303Q
7304Q
7305Q
7306Q

FIG. 73

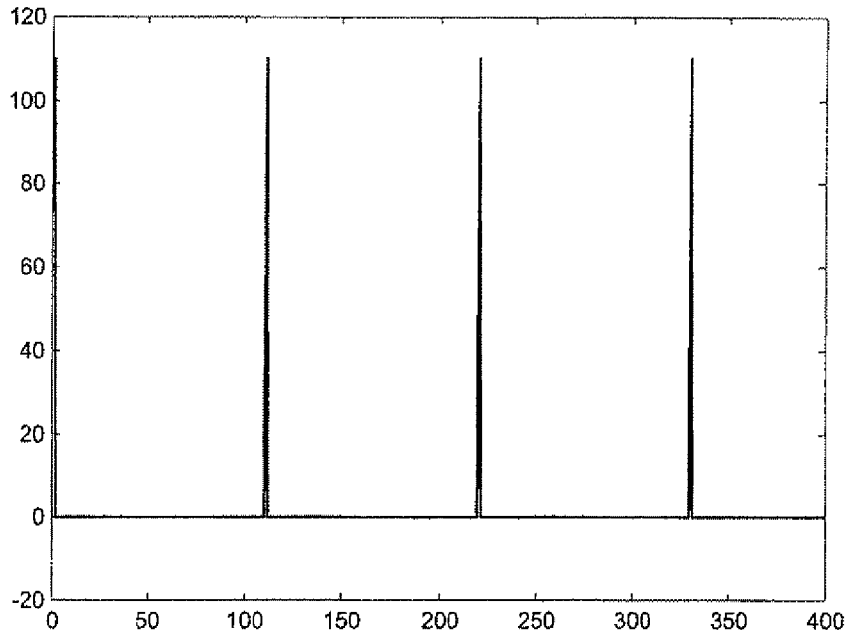


FIG. 74A

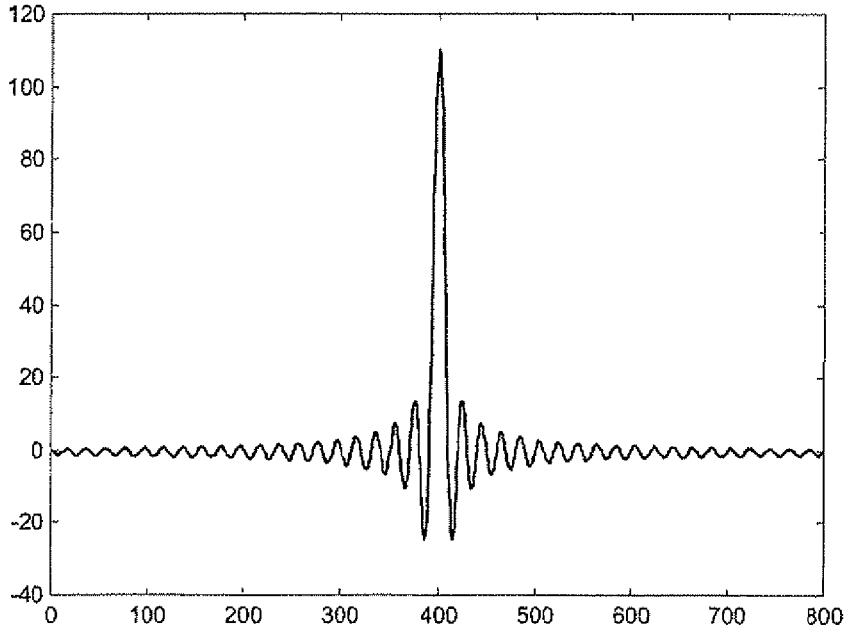


FIG. 74B

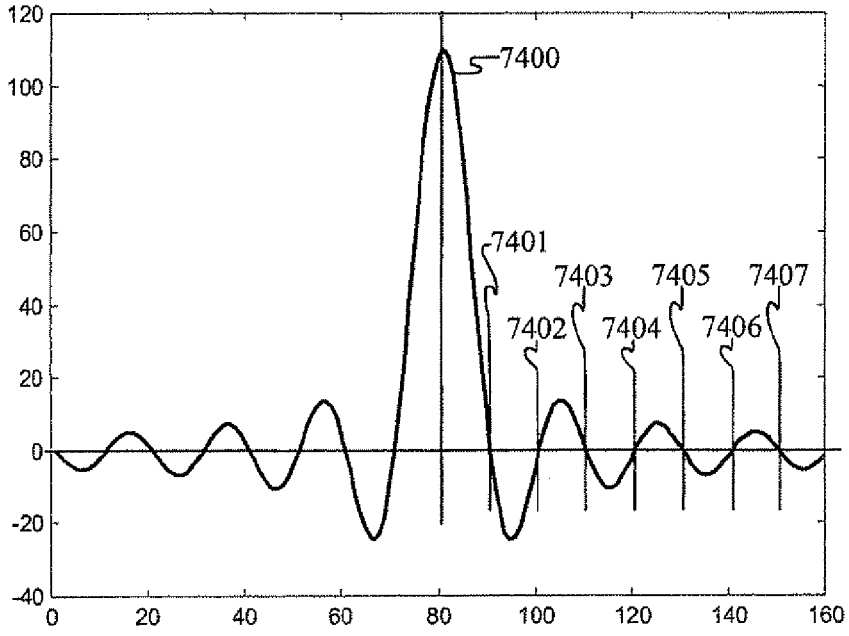


FIG. 74C

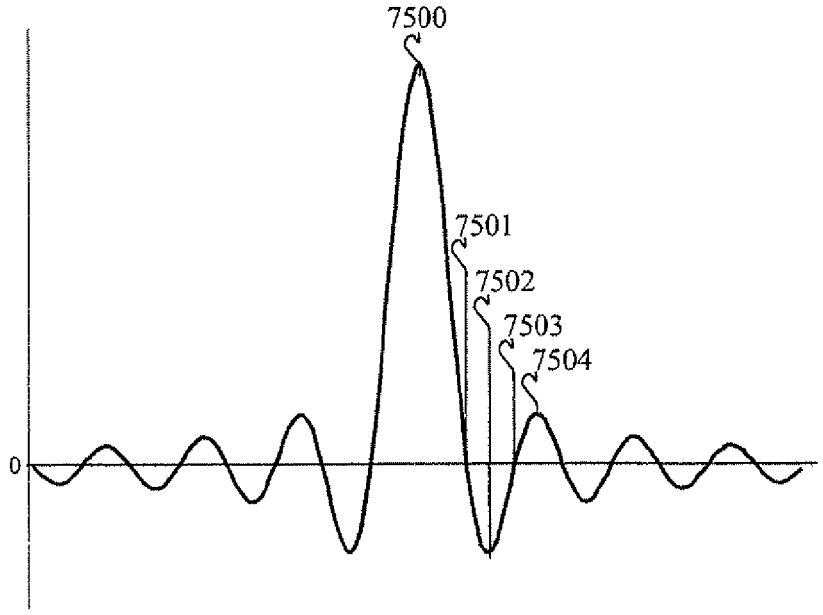
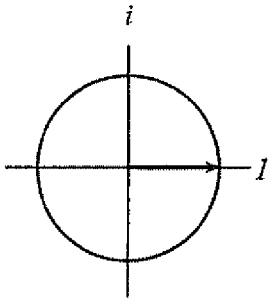
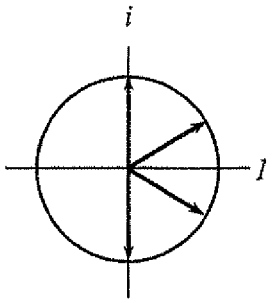


FIG. 75



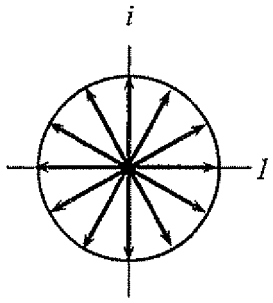
$f_n : f_n$

FIG. 76A



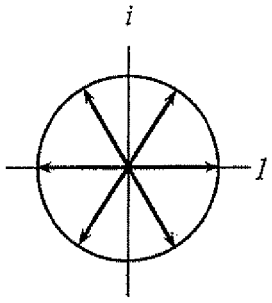
$f_n : f_{n+2.5}$

FIG. 76E



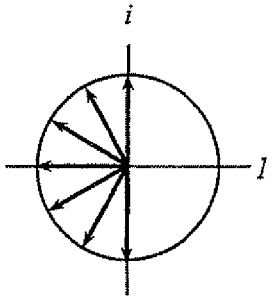
$f_n : f_{n+1}$

FIG. 76B



$f_n : f_{n+2}$

FIG. 76D



$f_n : f_{n+1.5}$

FIG. 76C

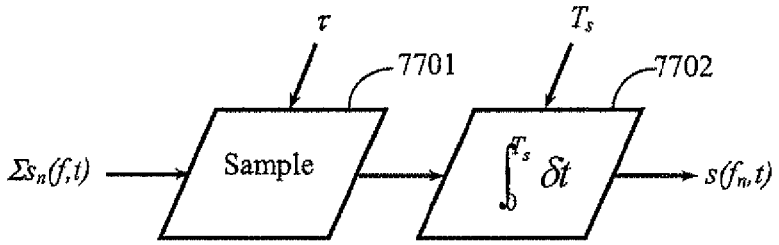


FIG. 77A

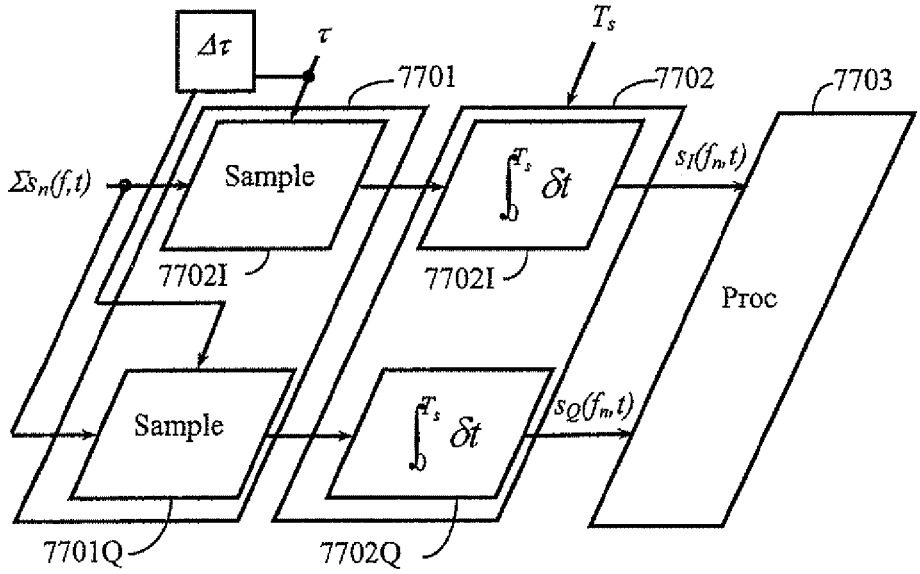


FIG. 77B

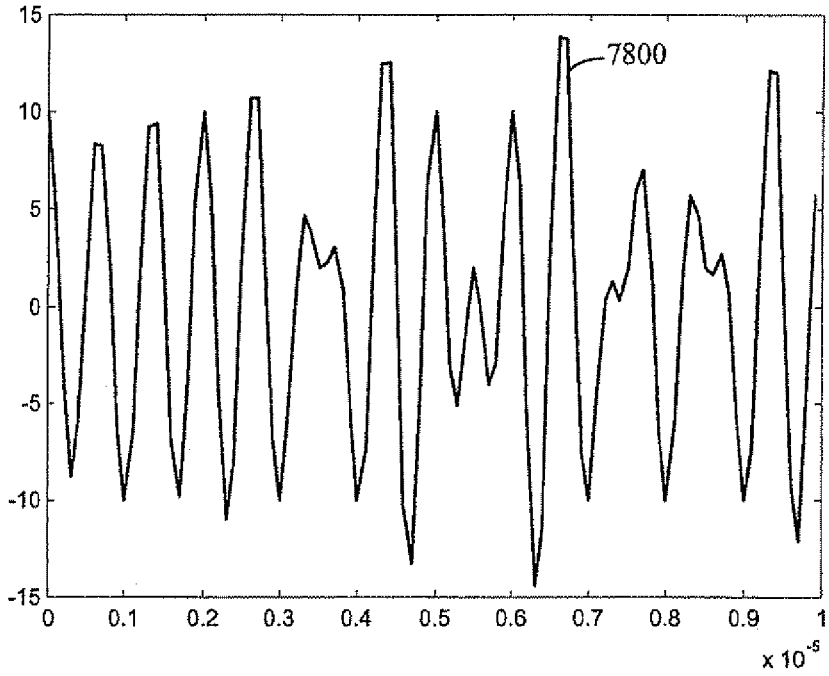


FIG. 78A

Phase Space	Tx Symbol	Rx Value
1	+1	+180.3291
2	-1	-167.5694
3	+1	+171.4620
4	-1	-137.1841
5	-1	-131.6329
6	+1	+134.0128
7	+1	+120.8614
8	-1	-116.9687
9	-1	-105.6389
10	-1	-169.7778

FIG. 78B

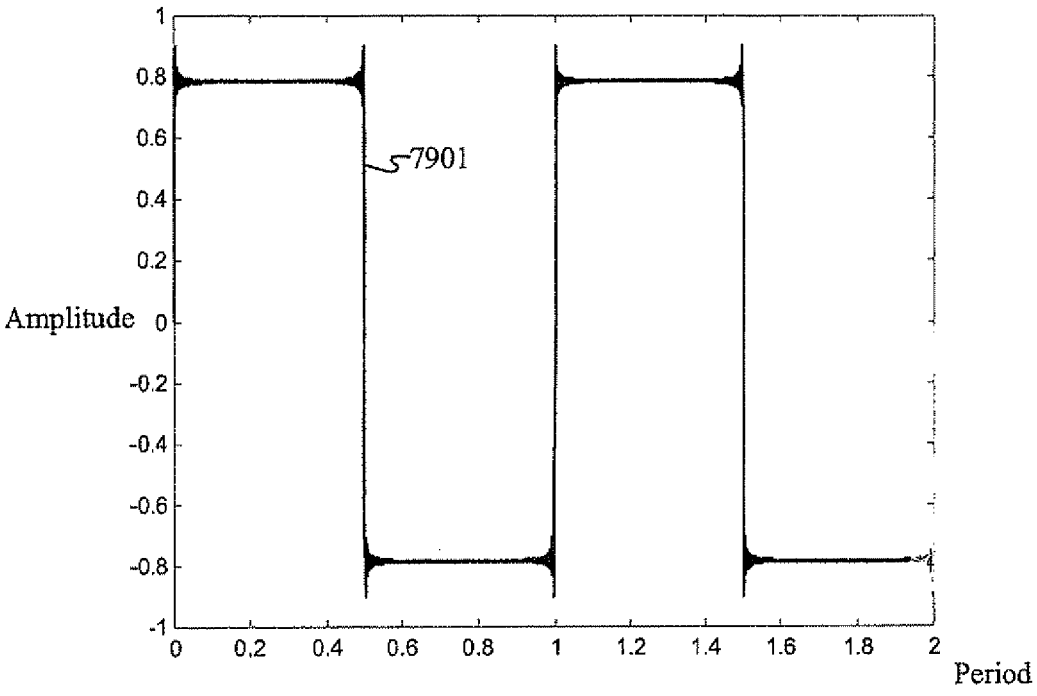


FIG. 79A

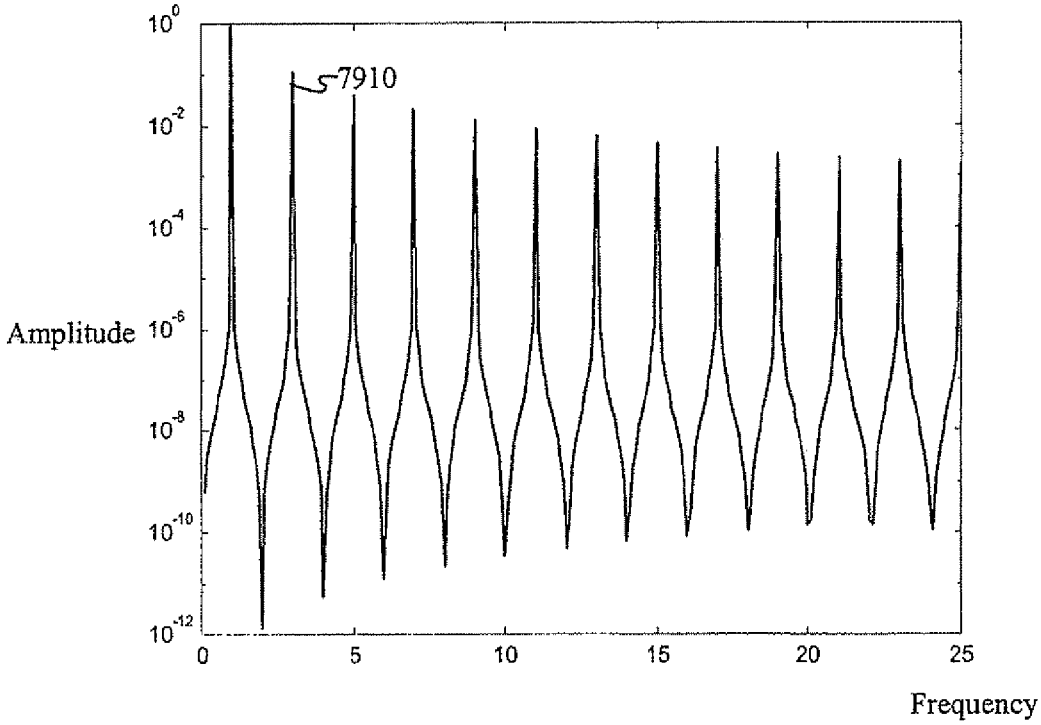


FIG. 79B

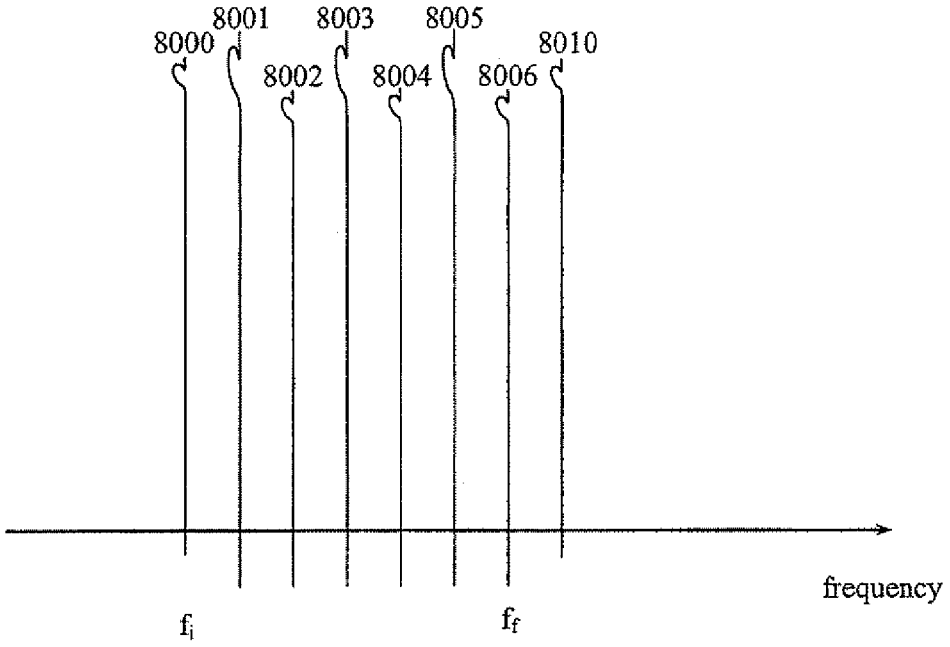


FIG. 80A

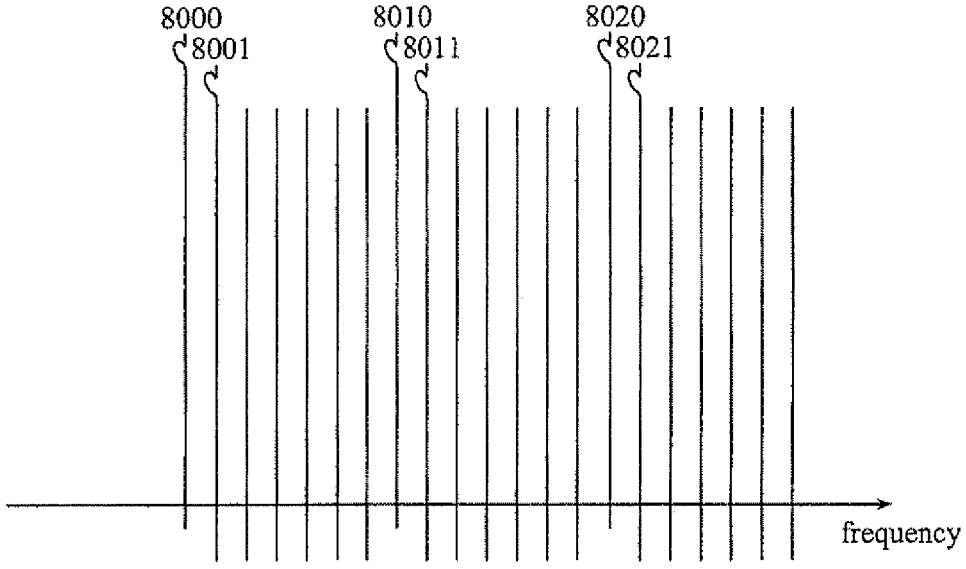


FIG. 80B

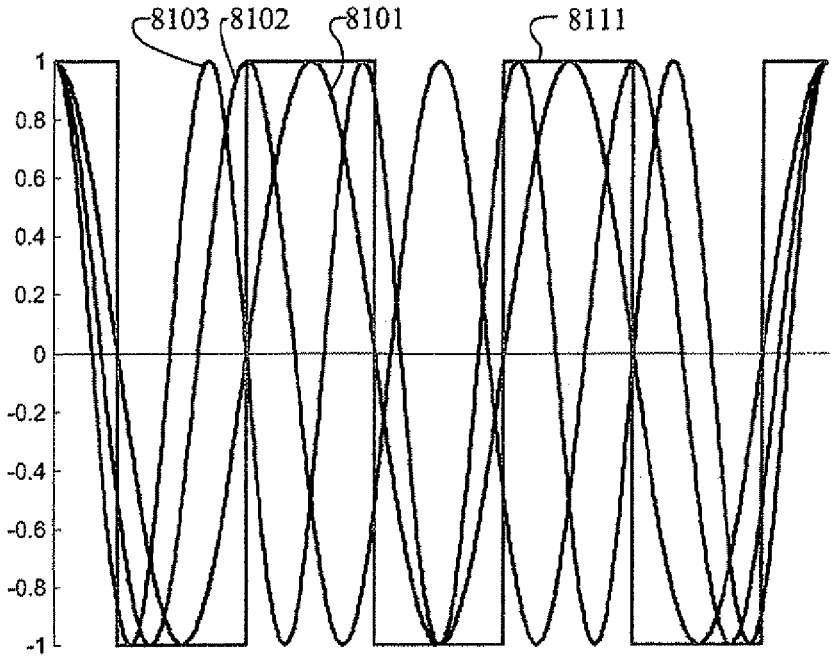

8103
8102
8101
8111
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

FIG. 81

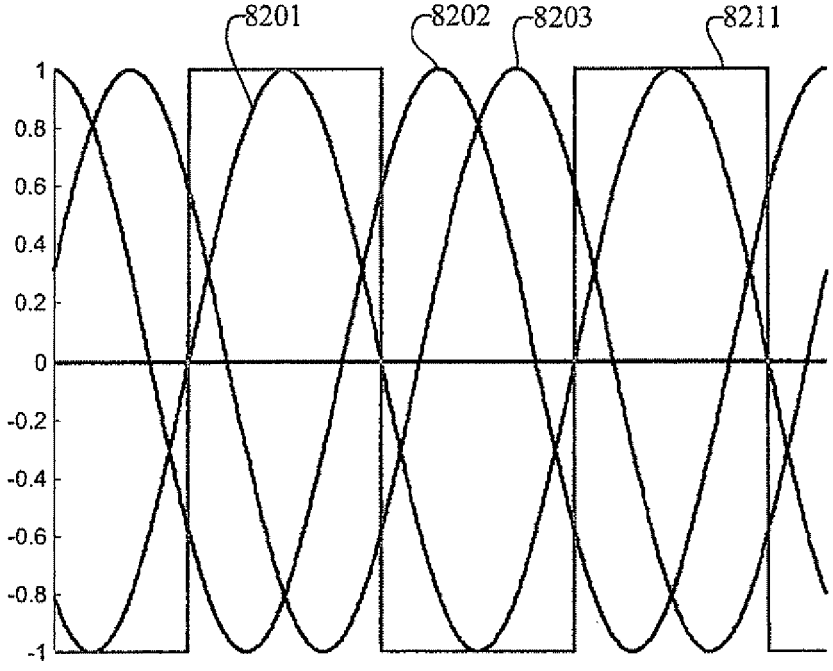

8201
8202
8203
8211
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

FIG. 82

Phase Space	Centered at PS 1	Centered at PS 2	Centered at PS 3
PS 1	**1.9128e+003**	3.0039	-3.9450
PS 2	-1.8043	**1.9117e+003**	4.8284
PS 3	1.6598	-2.0786	**1.9117e+003**

FIG. 83

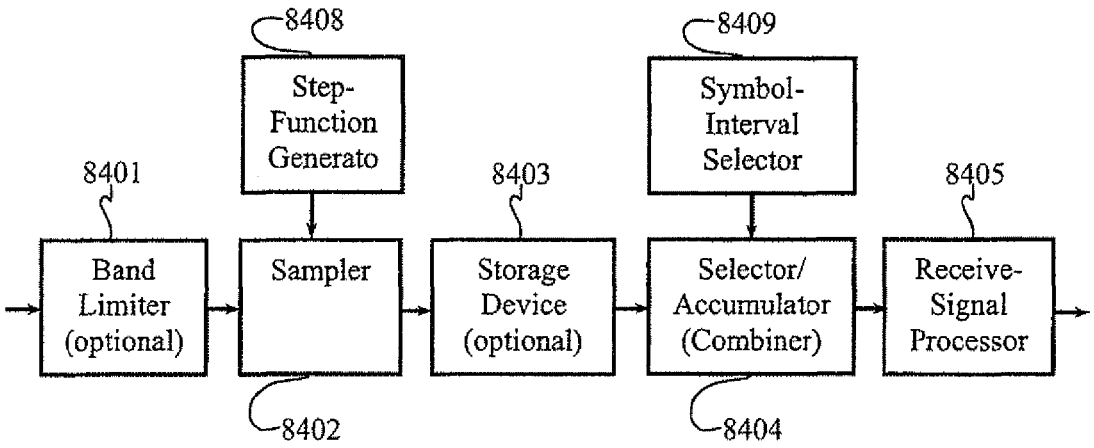


FIG. 84

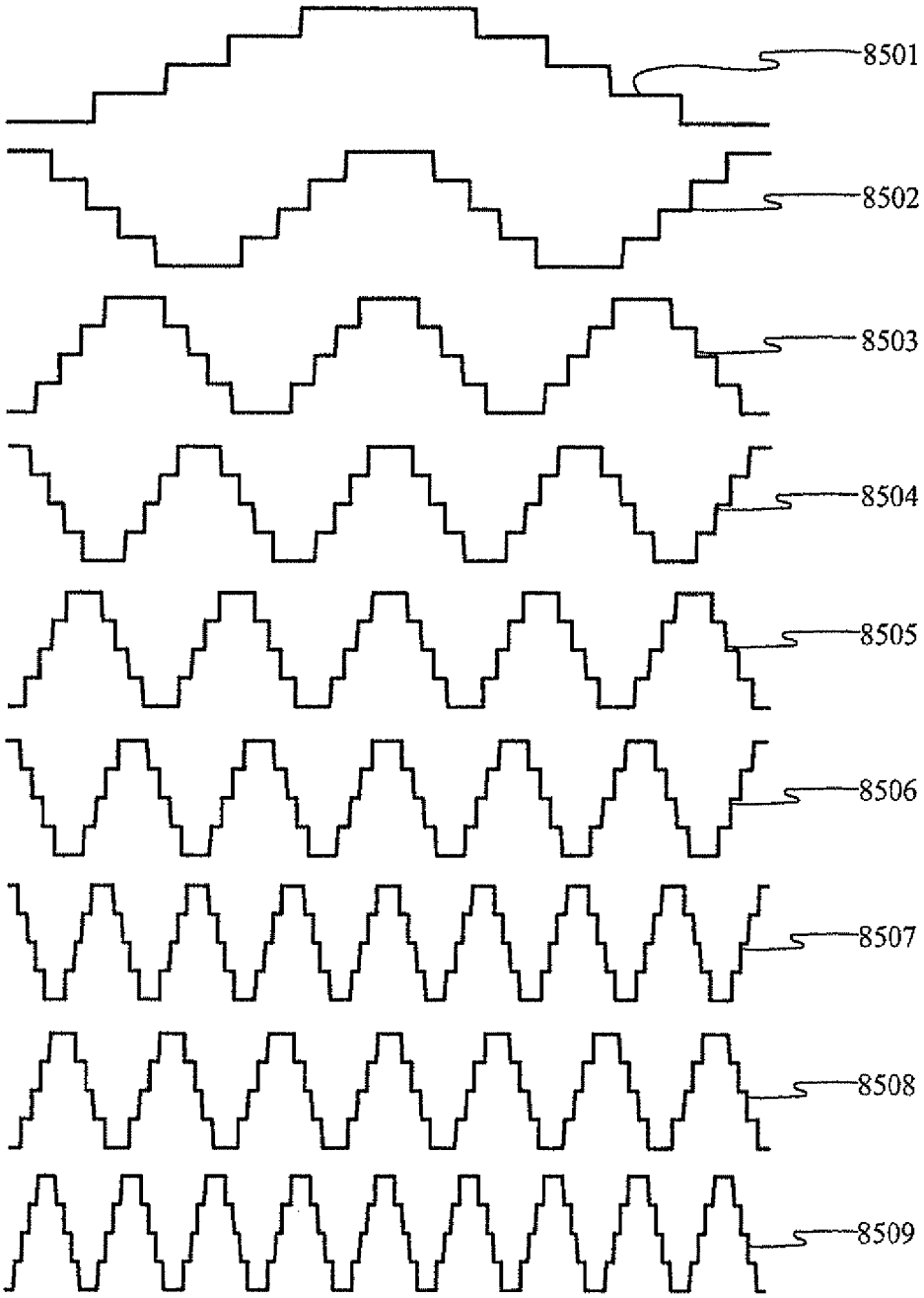


FIG. 85

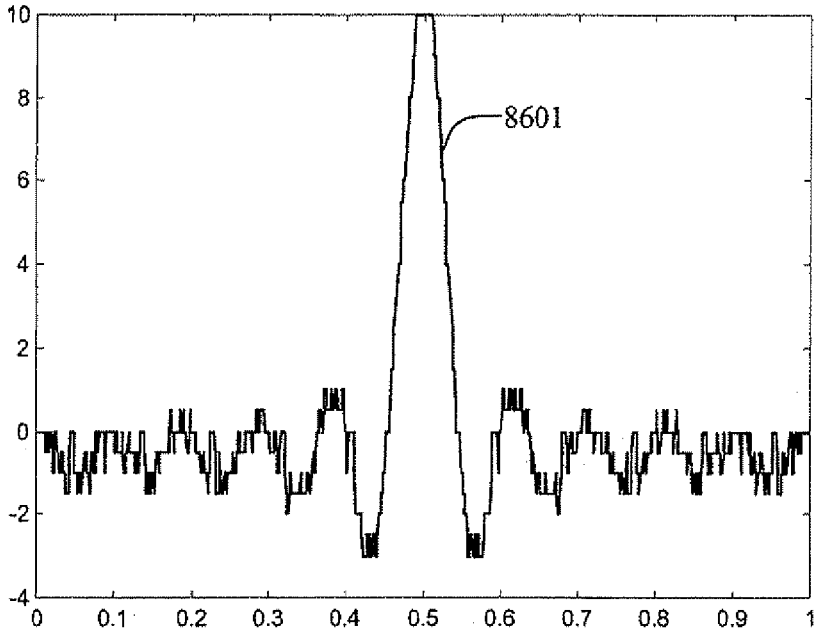


FIG. 86A

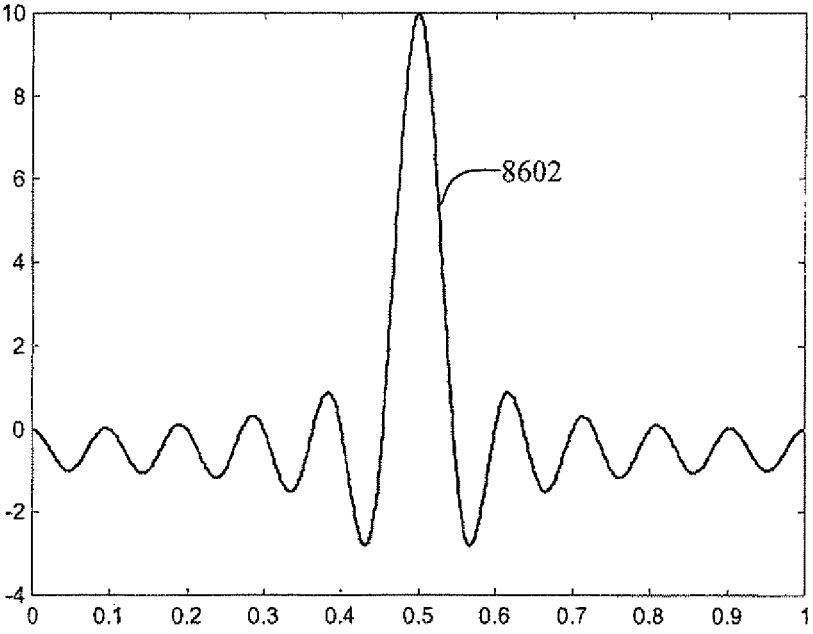


FIG. 86B

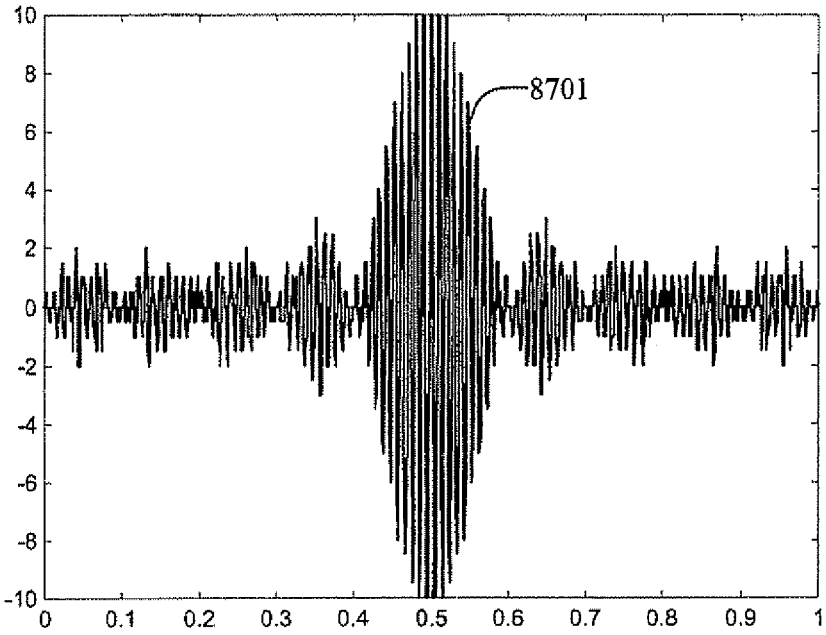


FIG. 87A

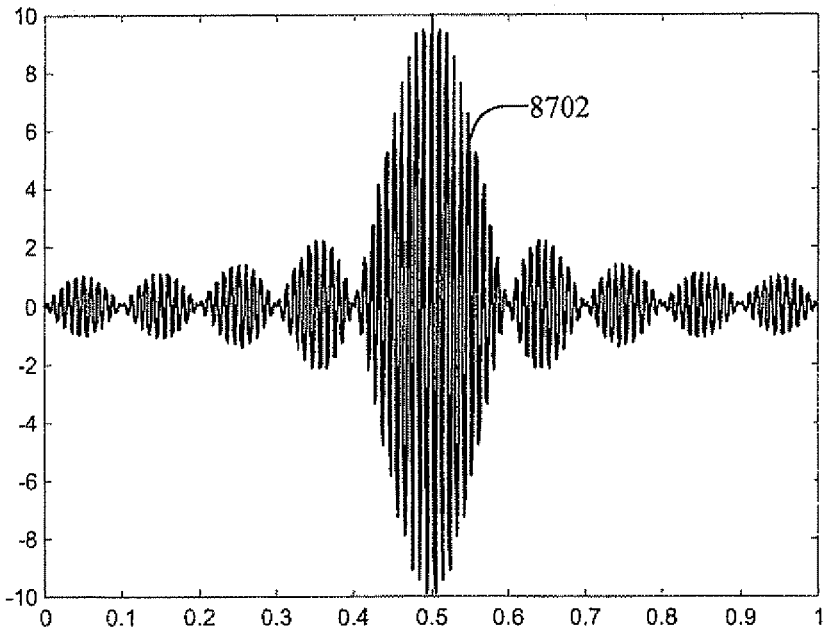


FIG. 87B

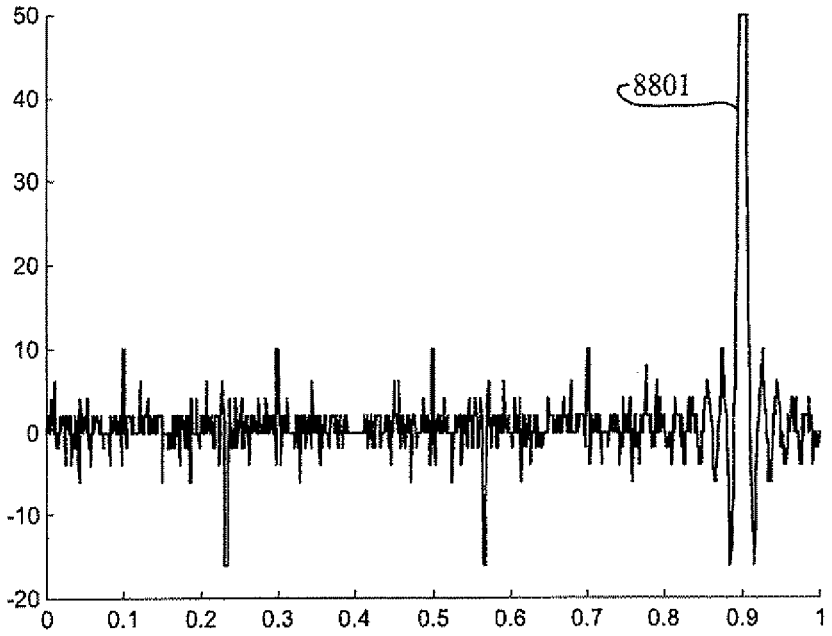


FIG. 88A

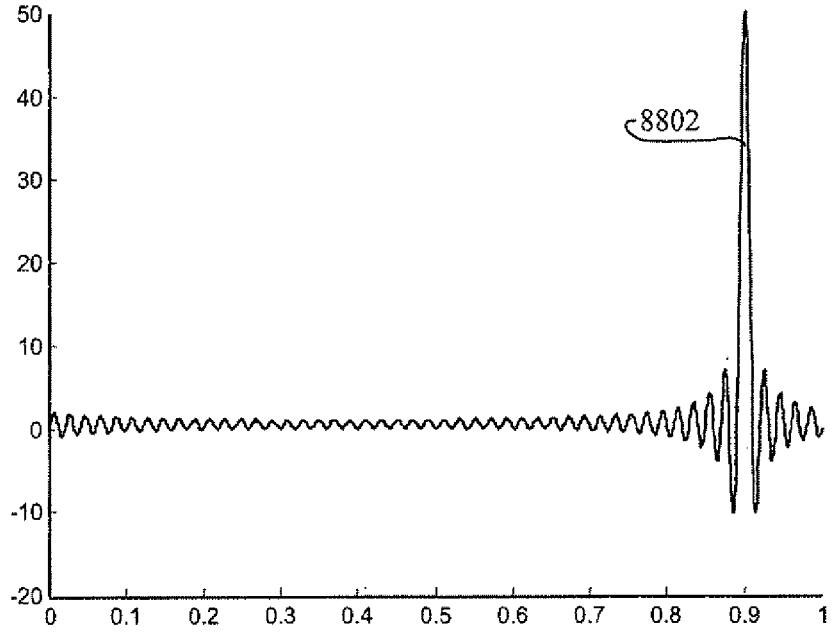


FIG. 88B

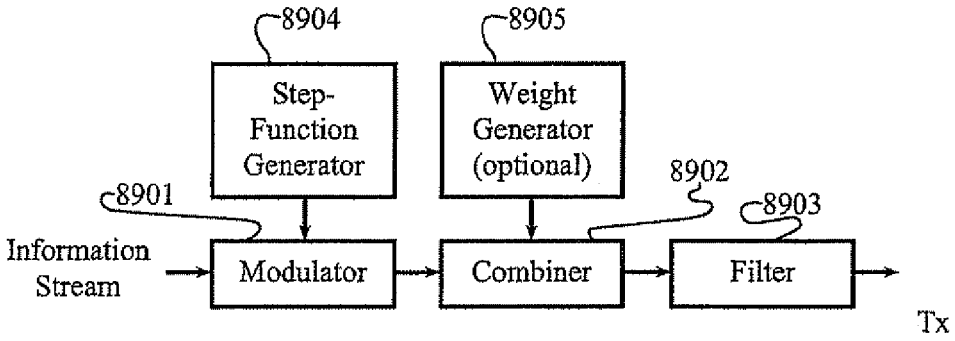


FIG. 89A

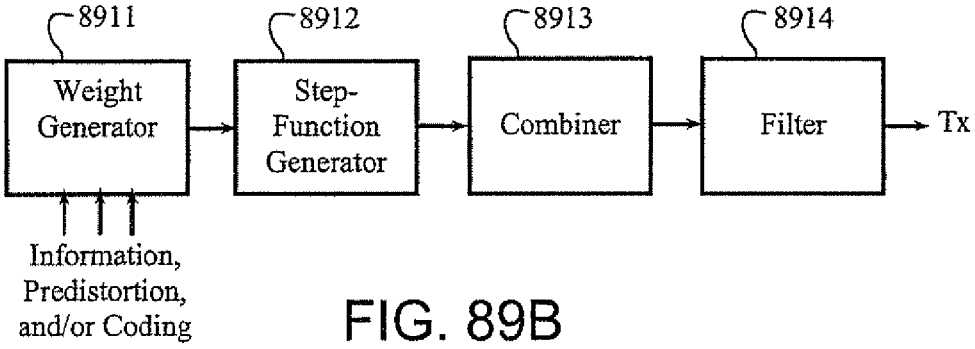


FIG. 89B

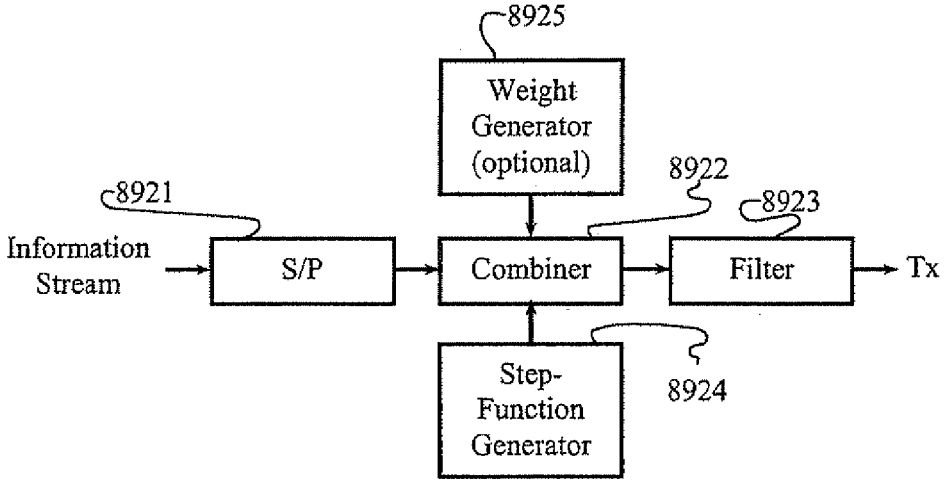


FIG. 89C

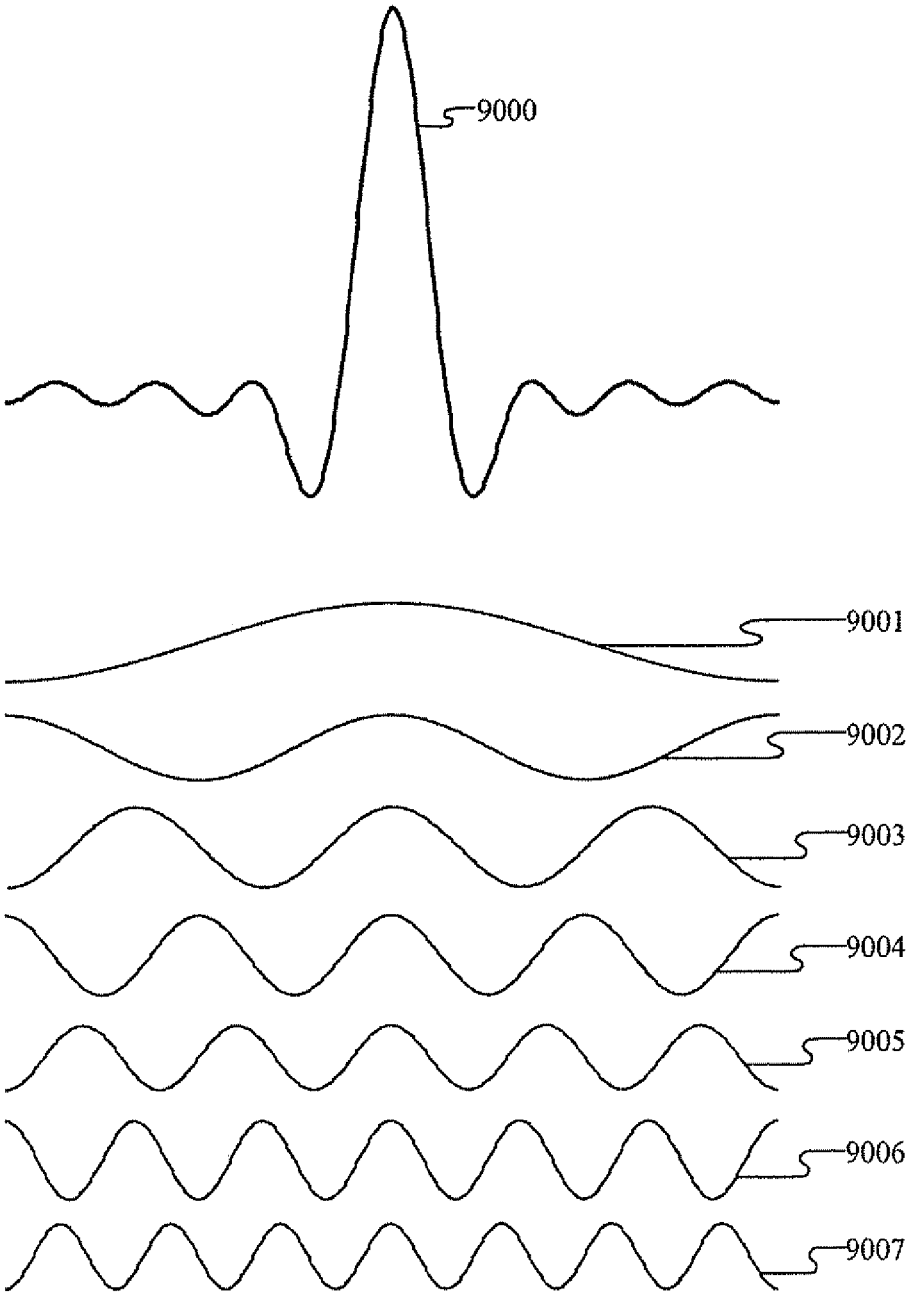


FIG. 90

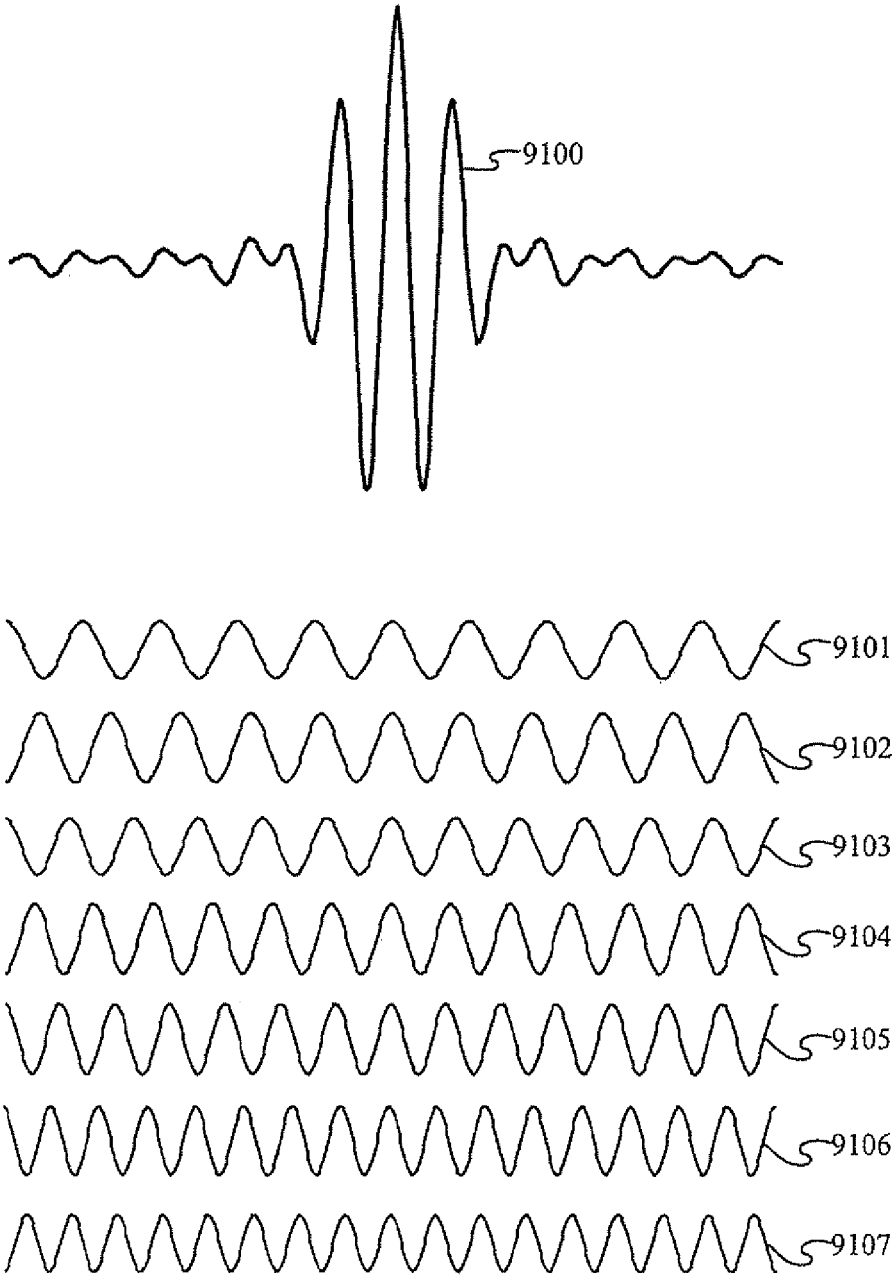


FIG. 91

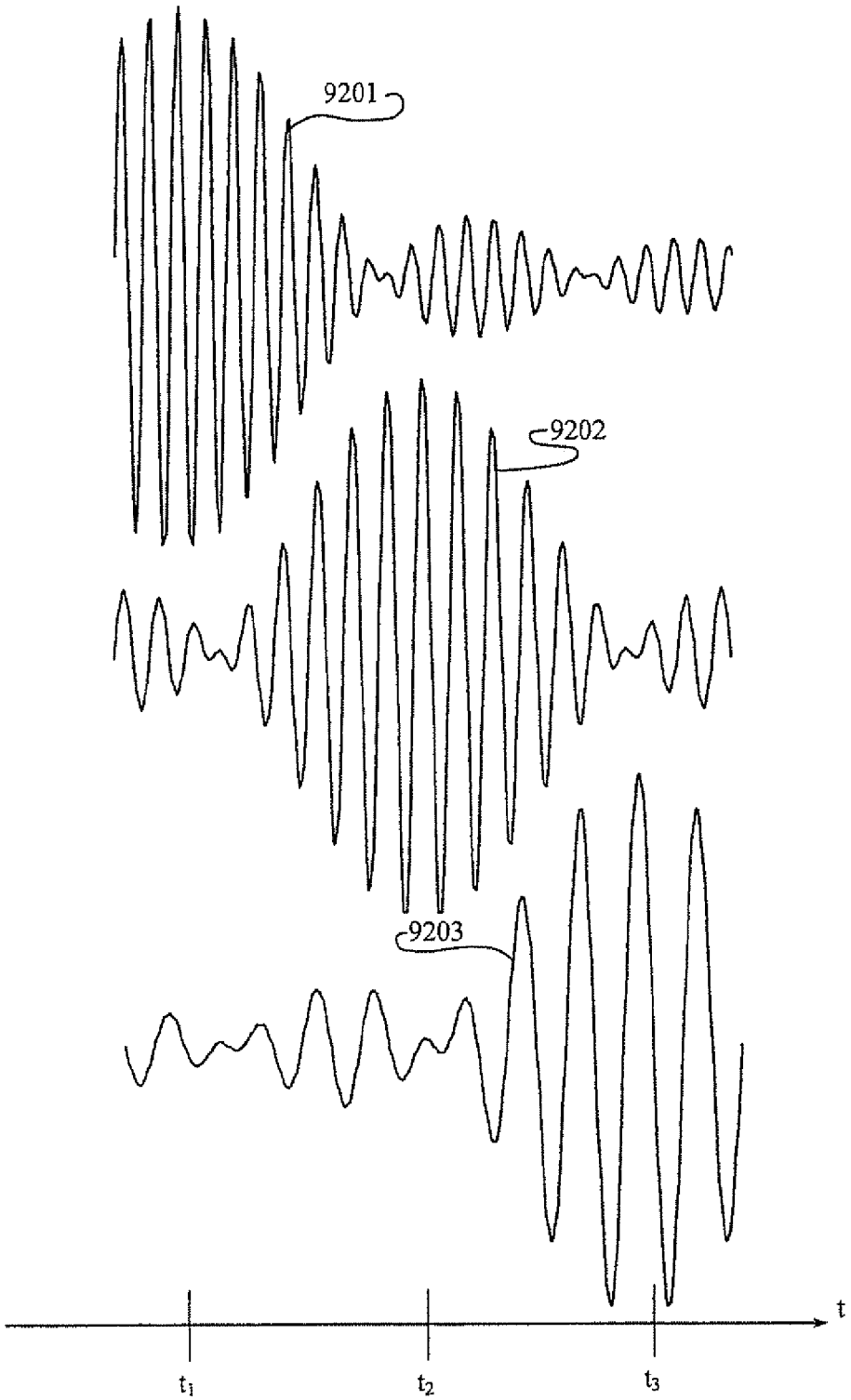


FIG. 92A

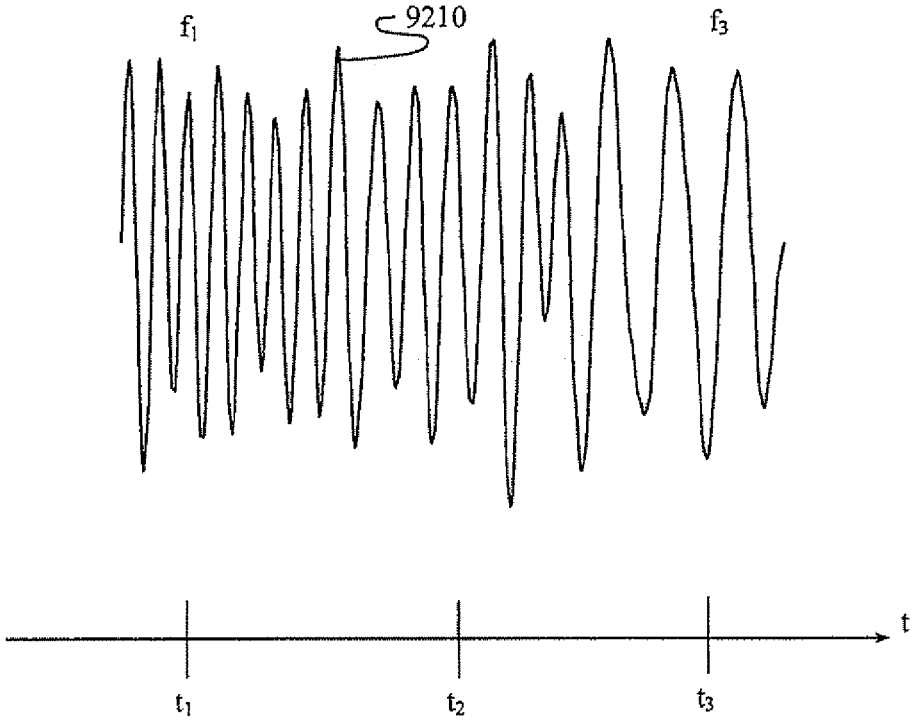


FIG. 92B

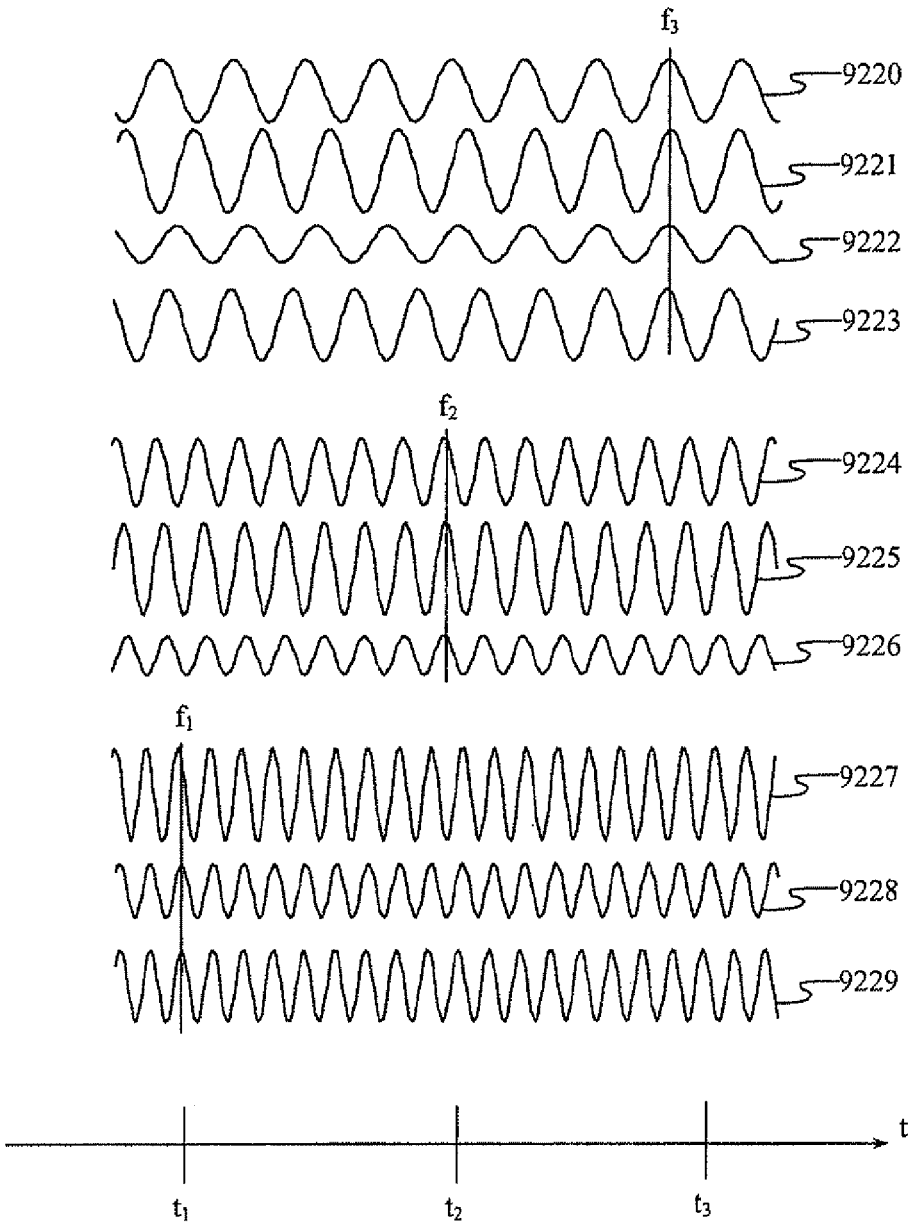

f3
9220
9221
9222
9223
f2
9224
9225
9226
f1
9227
9228
9229
t
t1
t2
t3

FIG. 92C

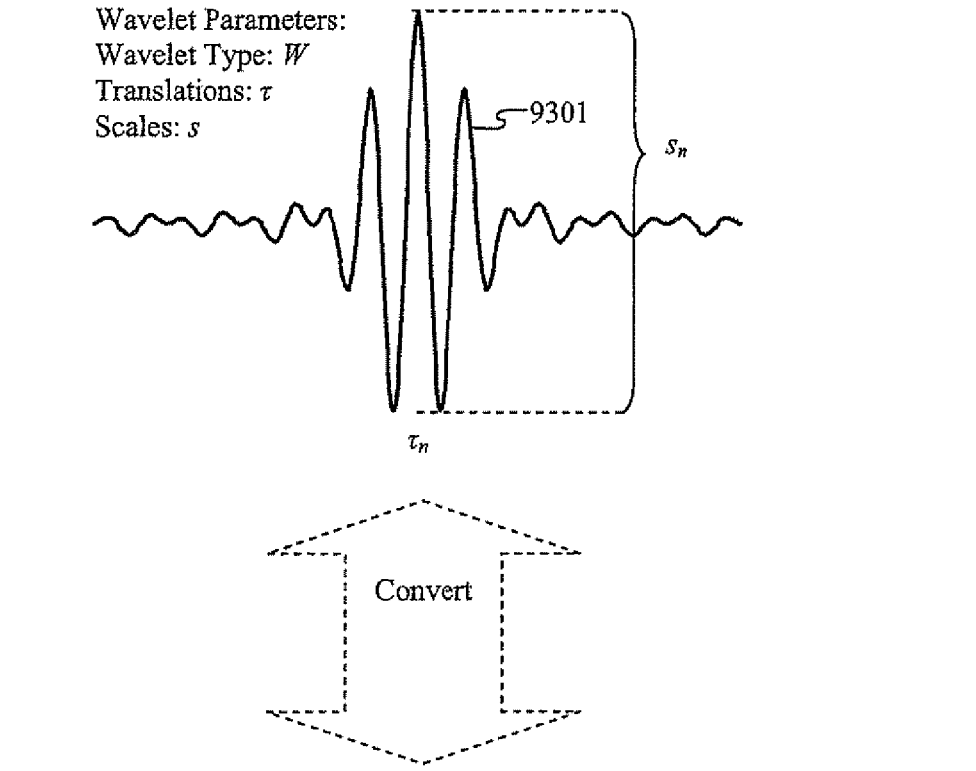

Wavelet Parameters:
Wavelet Type: W
Translations: τ
Scales: s
9301
s_n
τ_n
Convert
Frequency-Domain CI
Waveform Parameters:
Carrier Frequencies f_n
Carrier Weights: w_n
f_1:w_1
f_2:w_2
f_3:w_3
f_4:w_4
f_5:w_5
f_6:w_6
f_7:w_7
9302

FIG. 93

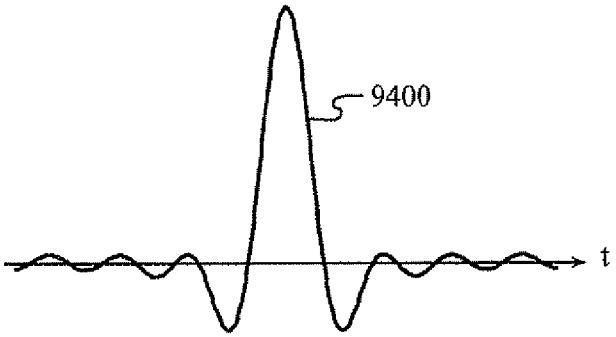


FIG. 94A

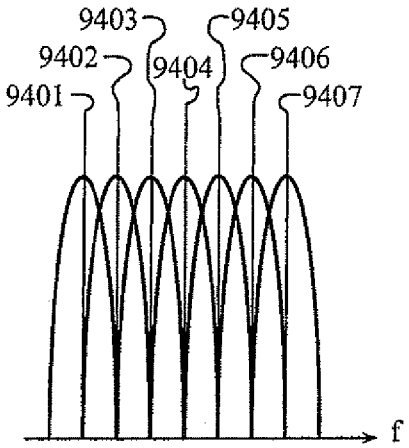


FIG. 94C

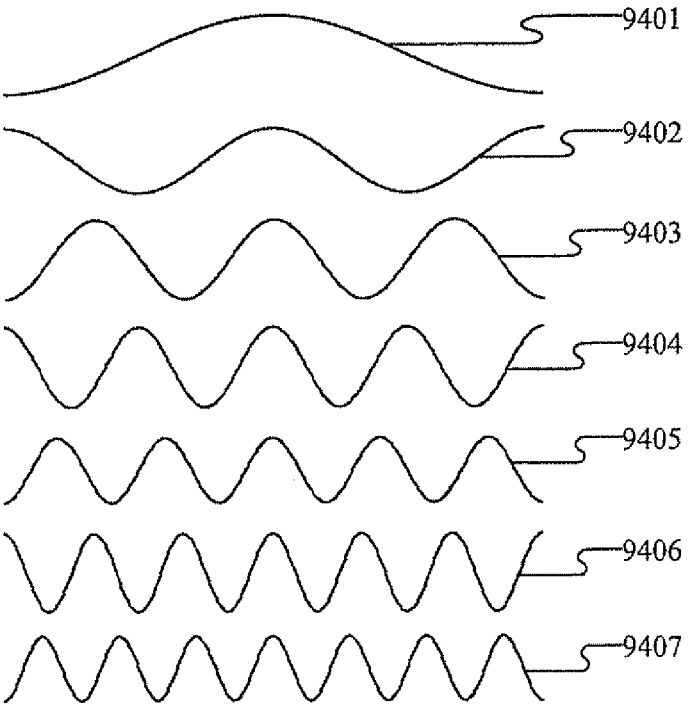


FIG. 94B

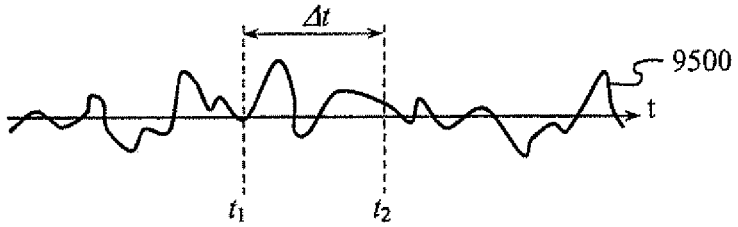


FIG. 95A

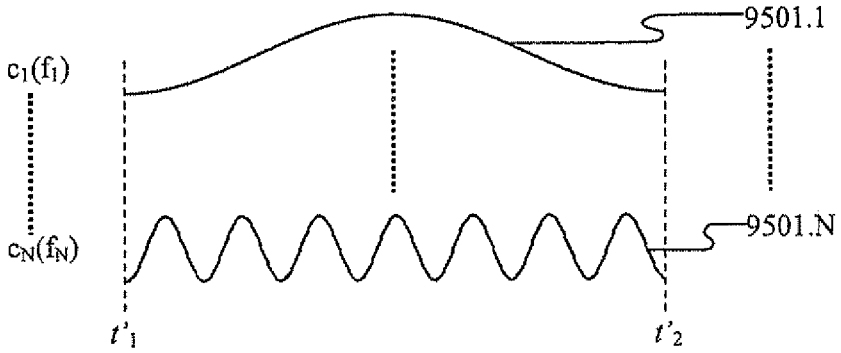


FIG. 95B

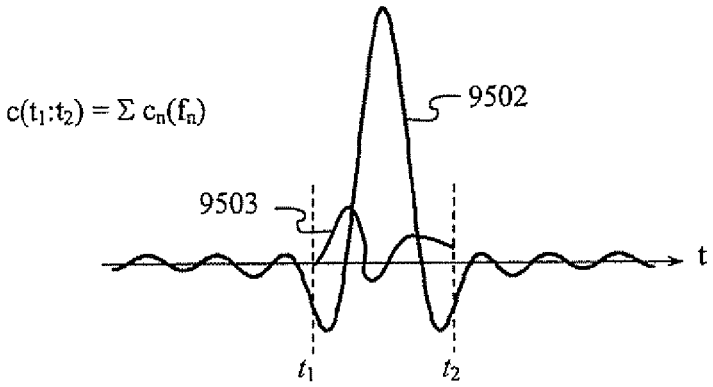


FIG. 95C

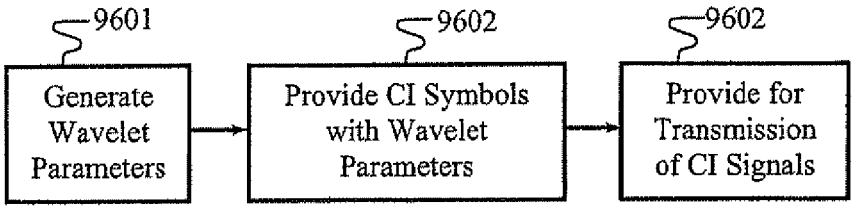


FIG. 96A

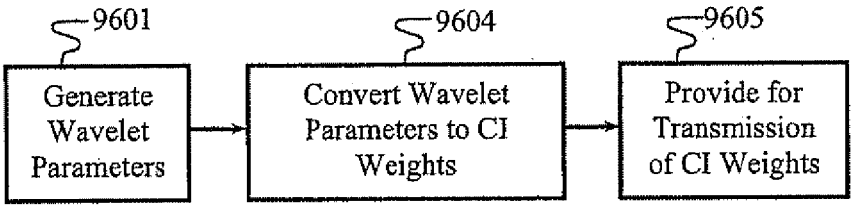


FIG. 96B

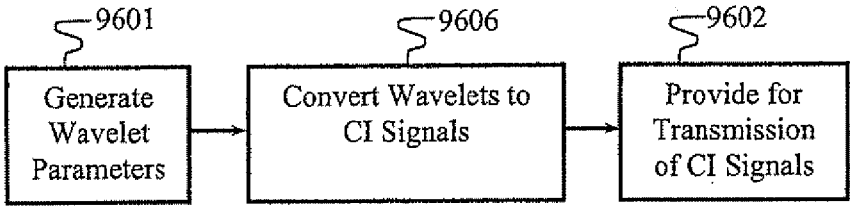


FIG. 96C

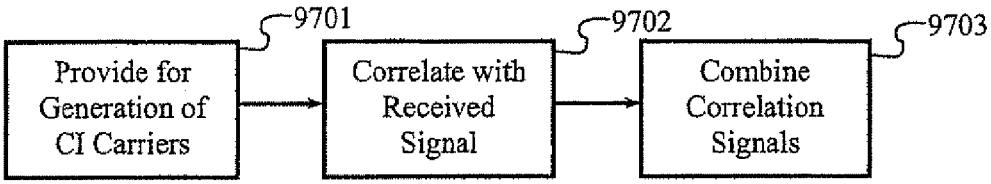


FIG. 97A

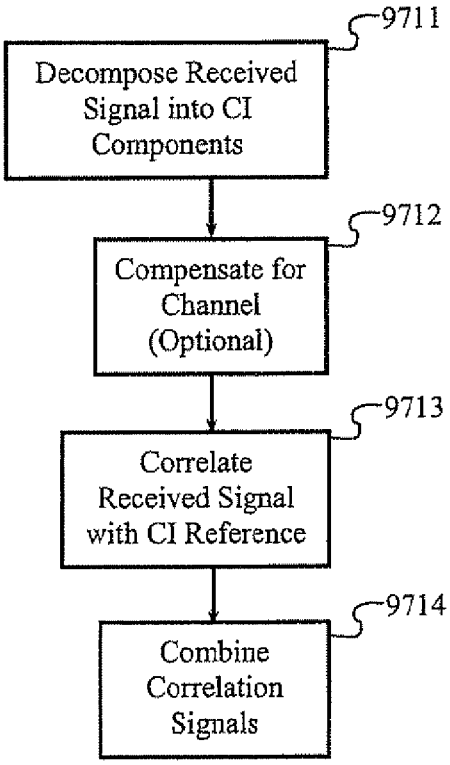


FIG. 97B

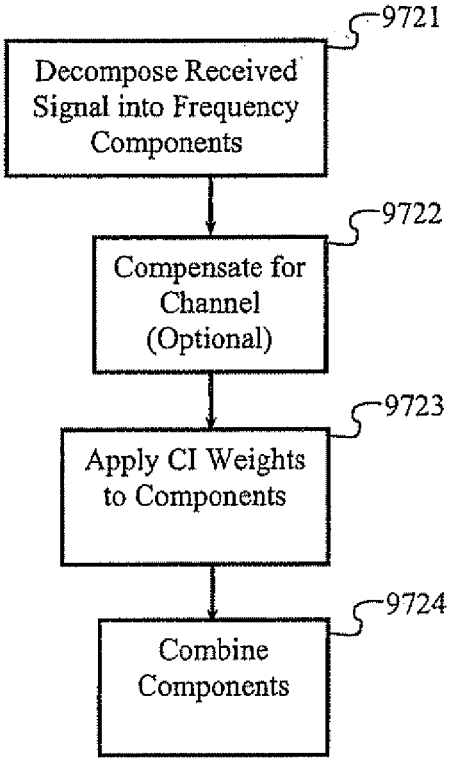


FIG. 97C

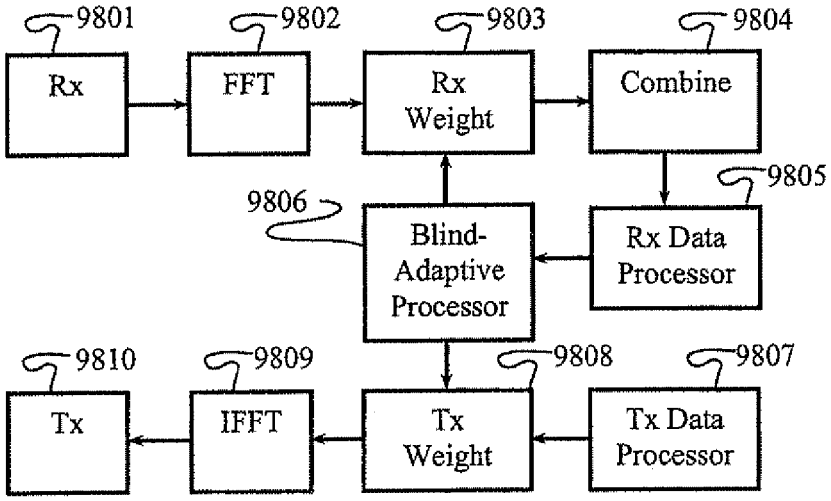

9801
Rx
9802
FFT
9803
Rx Weight
9804
Combine
9805
Rx Data Processor
9806
Blind-Adaptive Processor
9807
Tx Data Processor
9808
Tx Weight
9809
IFFT
9810
Tx

FIG. 98

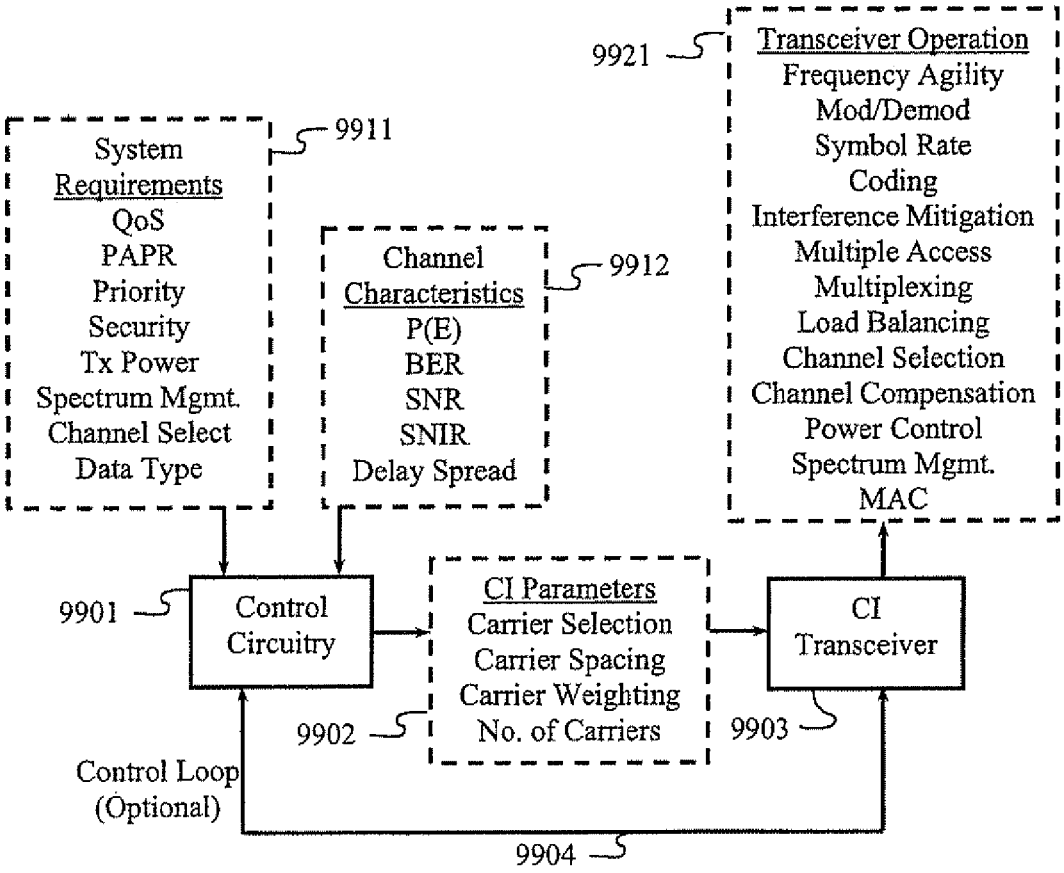

9921
Transceiver Operation
Frequency Agility
Mod/Demod
Symbol Rate
Coding
Interference Mitigation
Multiple Access
Multiplexing
Load Balancing
Channel Selection
Channel Compensation
Power Control
Spectrum Mgmt.
MAC
9911
System
Requirements
QoS
PAPR
Priority
Security
Tx Power
Spectrum Mgmt.
Channel Select
Data Type
9912
Channel
Characteristics
P(E)
BER
SNR
SNIR
Delay Spread
9901
Control
Circuitry
CI Parameters
Carrier Selection
Carrier Spacing
Carrier Weighting
No. of Carriers
9902
CI
Transceiver
9903
Control Loop
(Optional)
9904

FIG. 99

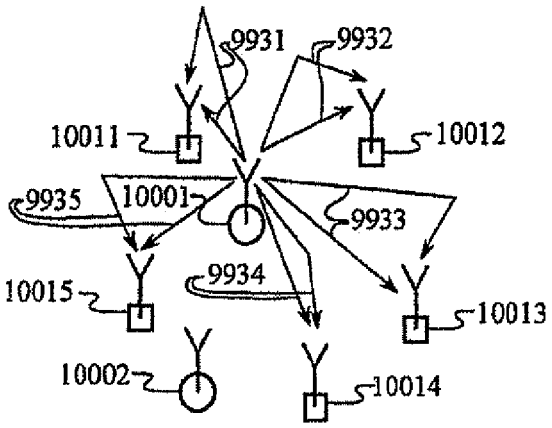


FIG. 100A

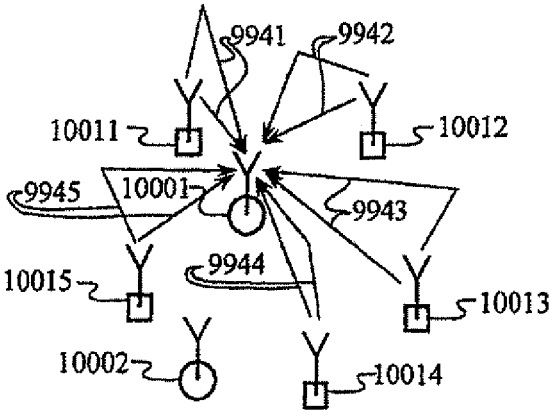


FIG. 100B

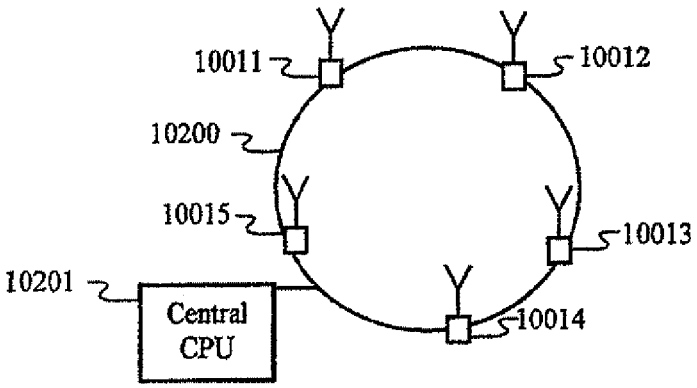


FIG. 101

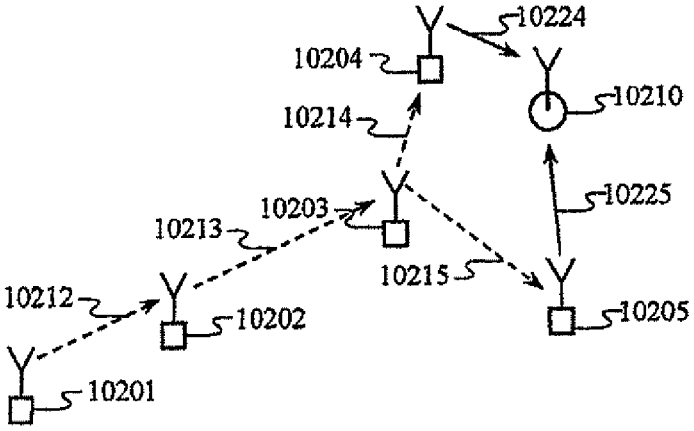


FIG. 102

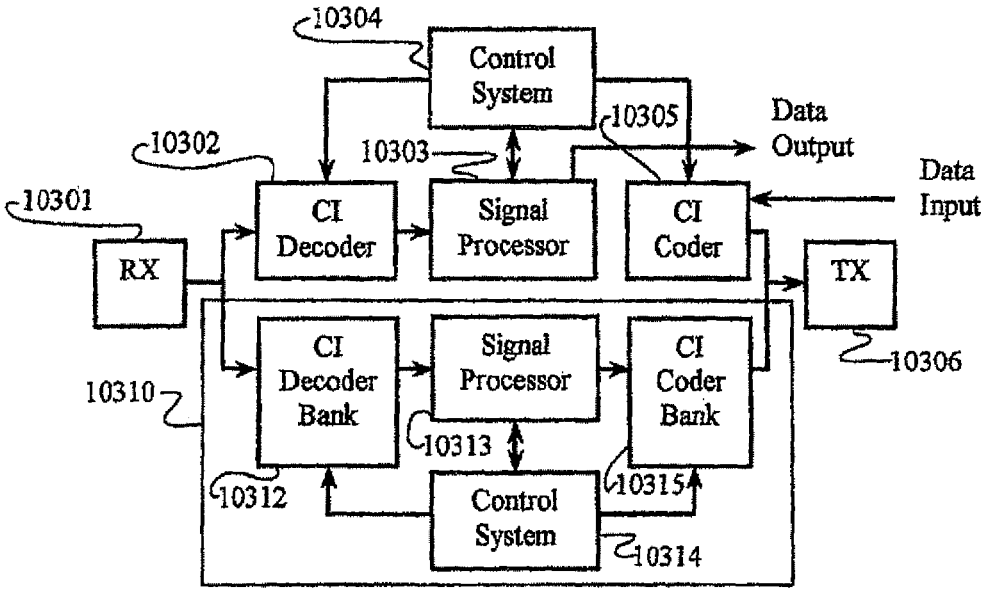


FIG. 103A

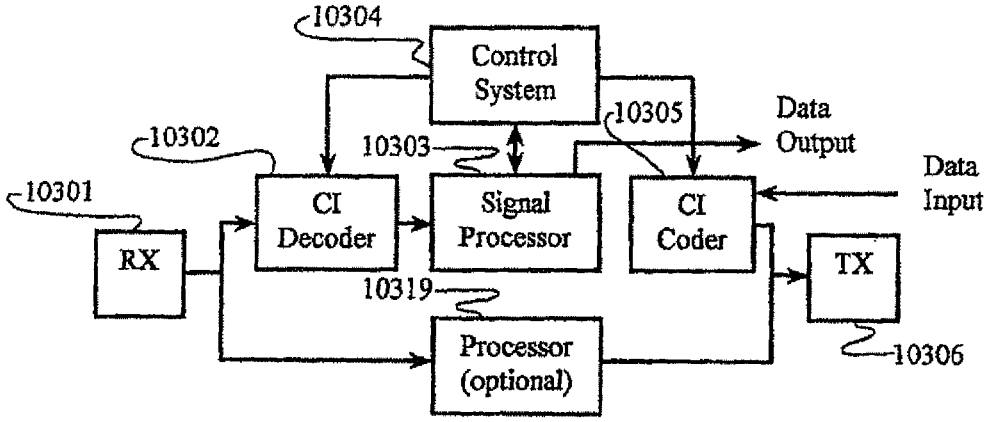


FIG. 103B

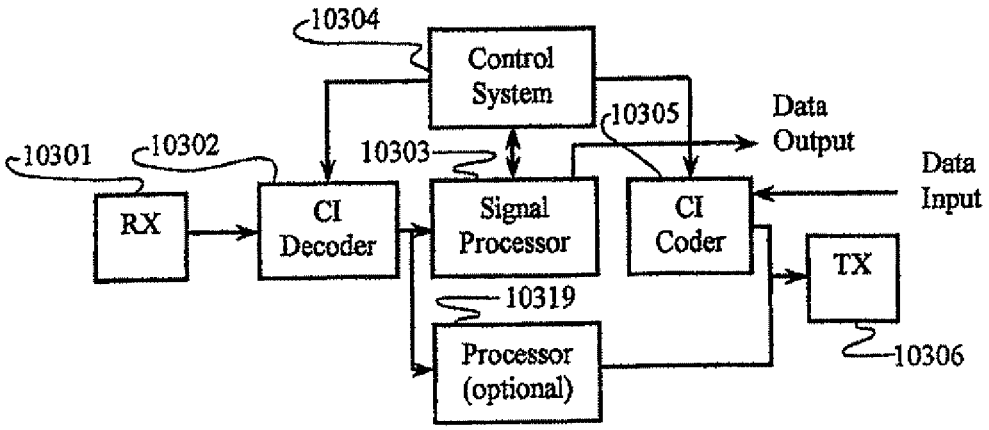

10304
Control System
10305
Data Output
10301
10302
10303
Data Input
RX
CI Decoder
Signal Processor
CI Coder
TX
10319
Processor (optional)
10306

FIG. 103C

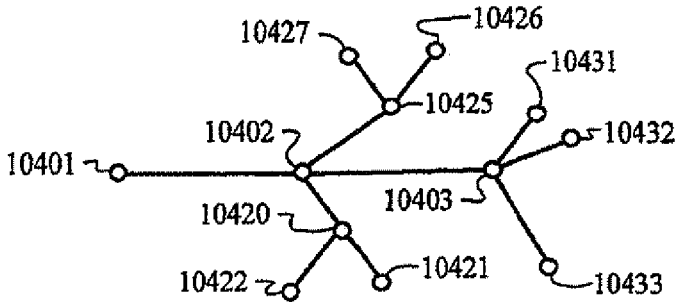


FIG. 104A

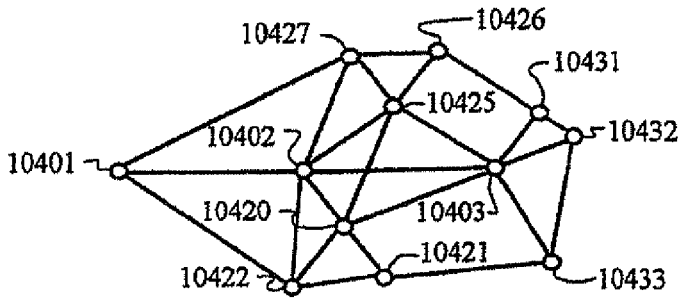


FIG. 104B

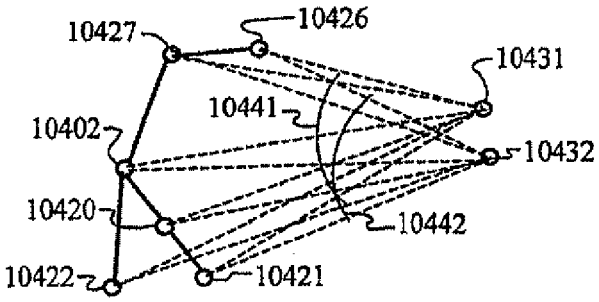


FIG. 104C

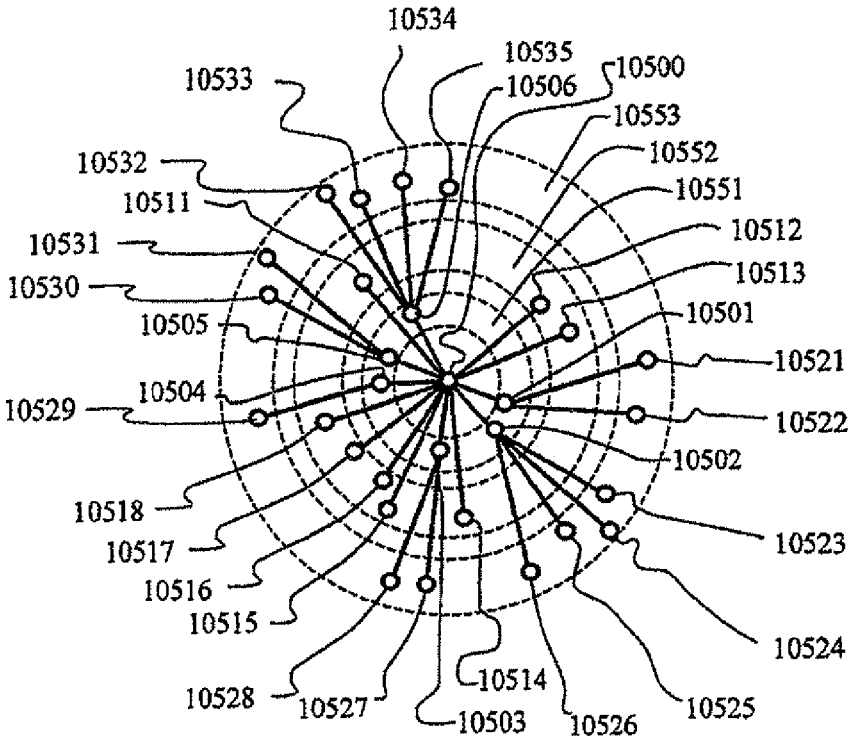


FIG. 105A

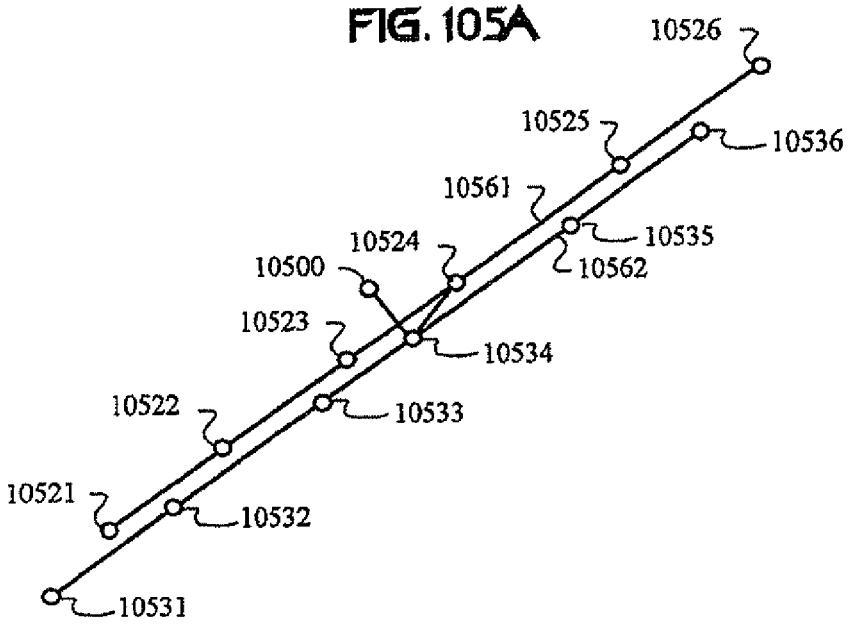


FIG. 105B

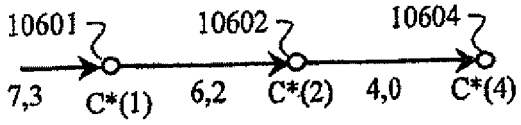


FIG. 106A

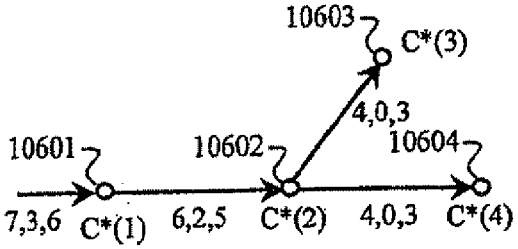


FIG. 106B

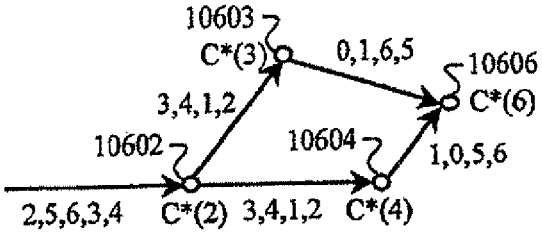


FIG. 106C

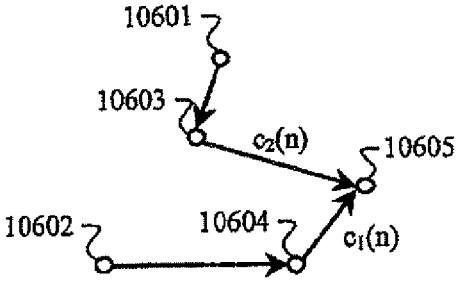


FIG. 106D

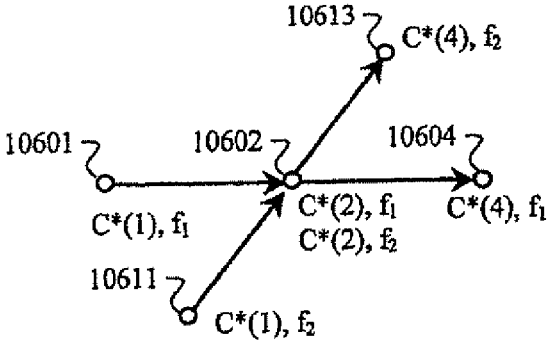


FIG. 106E

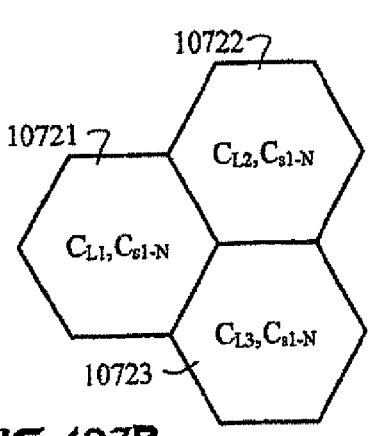


FIG. 107B

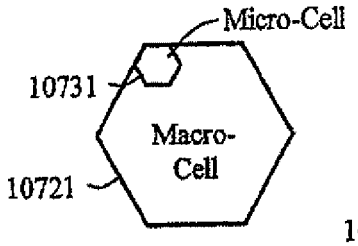


FIG. 107A

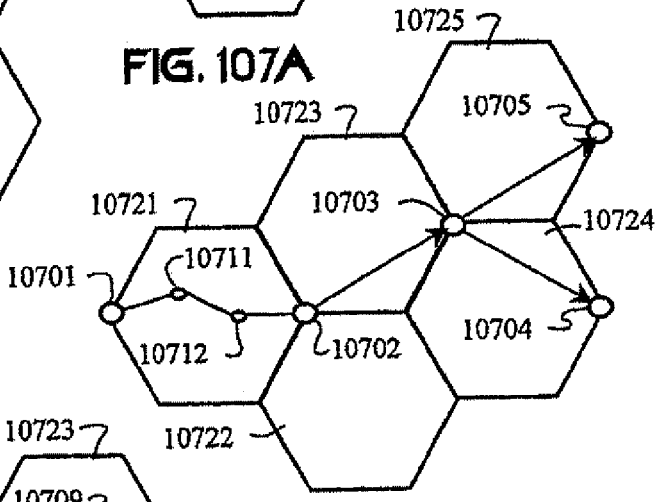


FIG. 107C

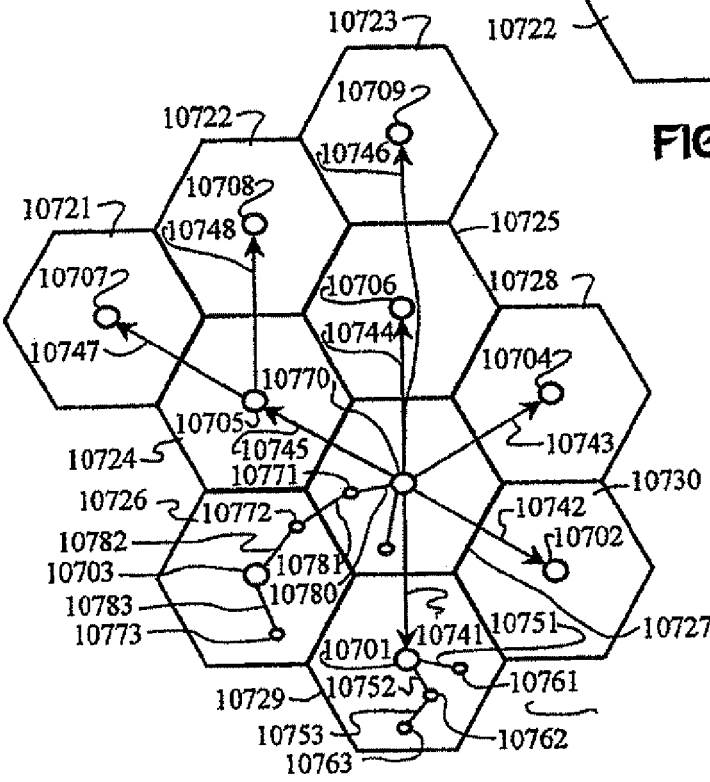


FIG. 107D

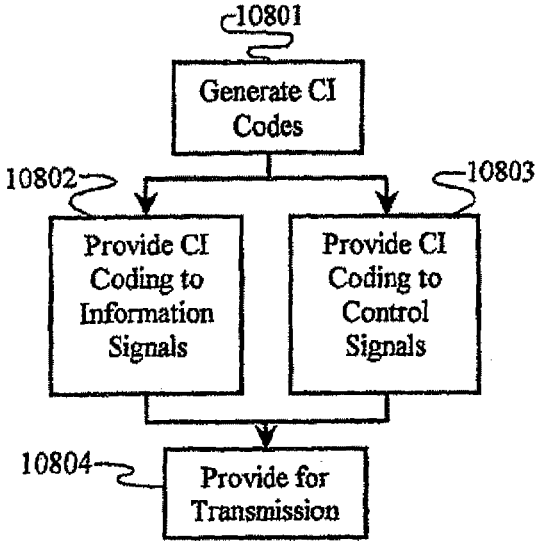


FIG. 108A

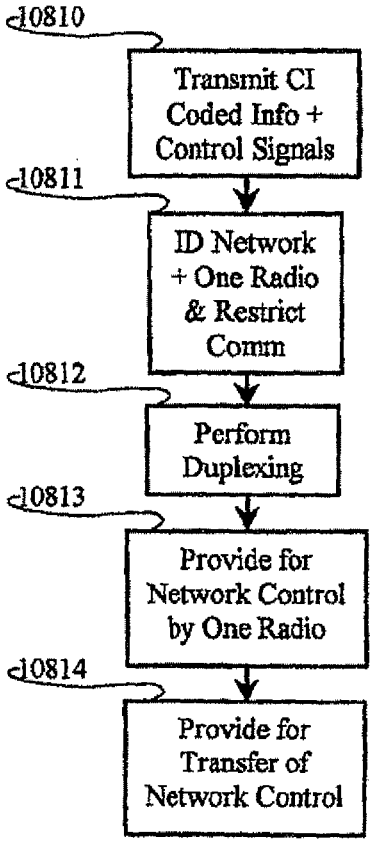


FIG. 108B

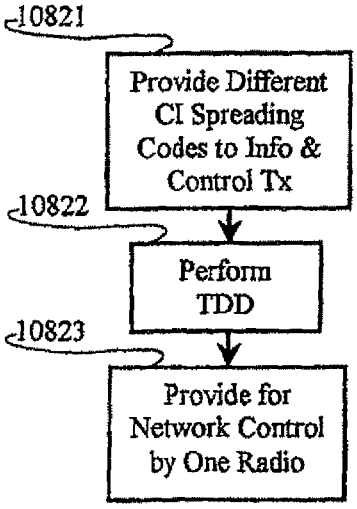


FIG. 108C

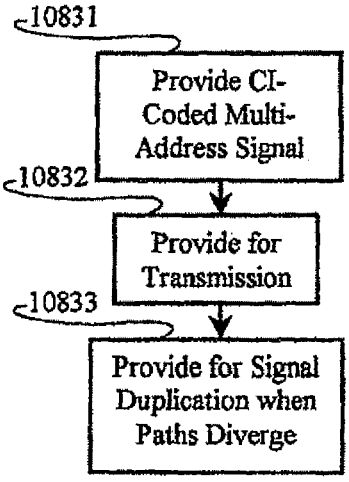


FIG. 108D

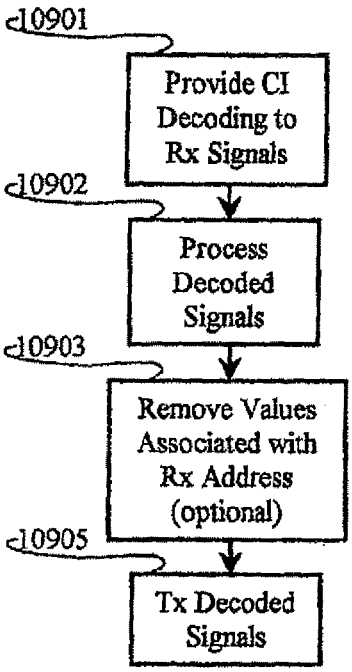


FIG. 109A

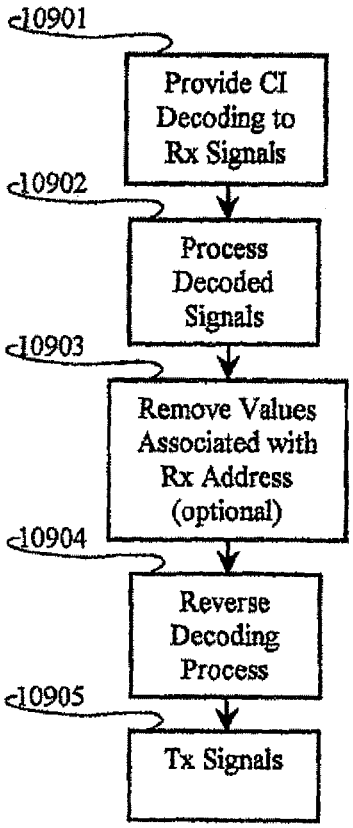


FIG. 109B

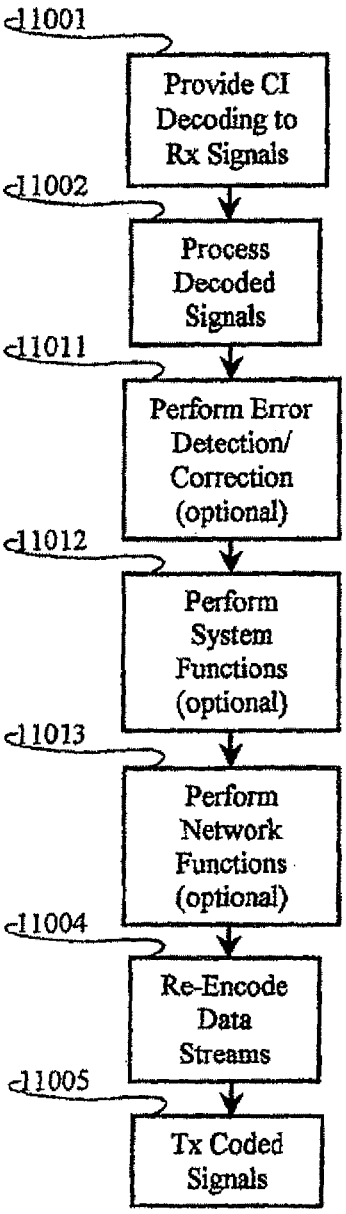


FIG. 110A

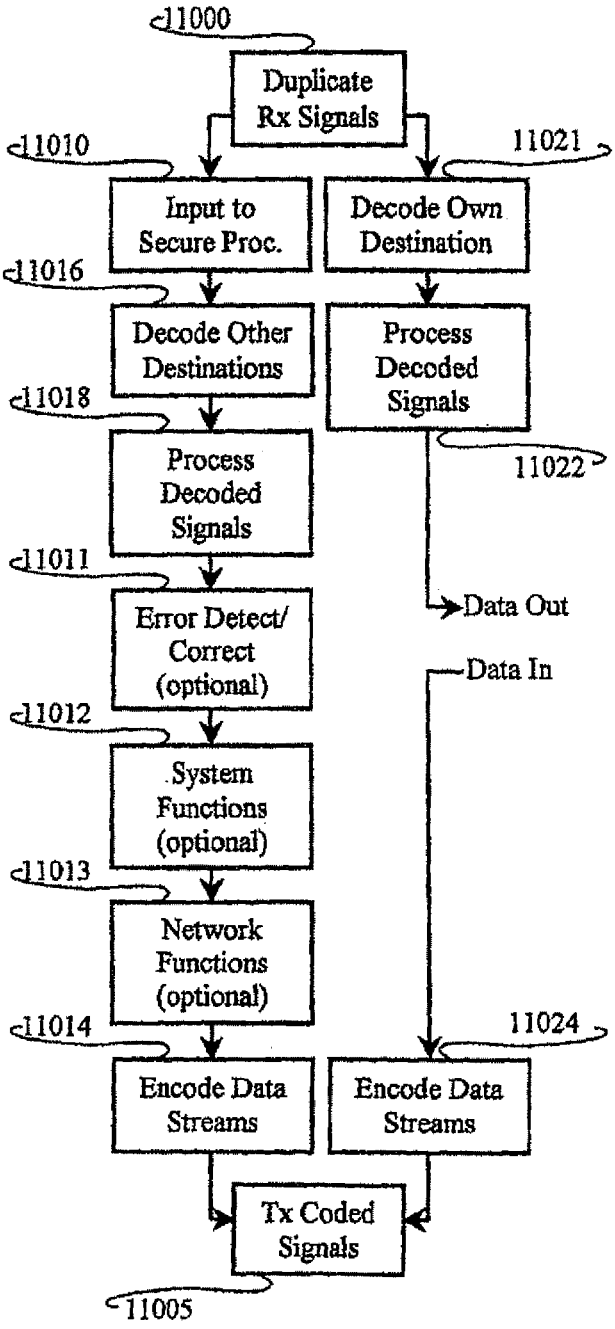


FIG. 110B

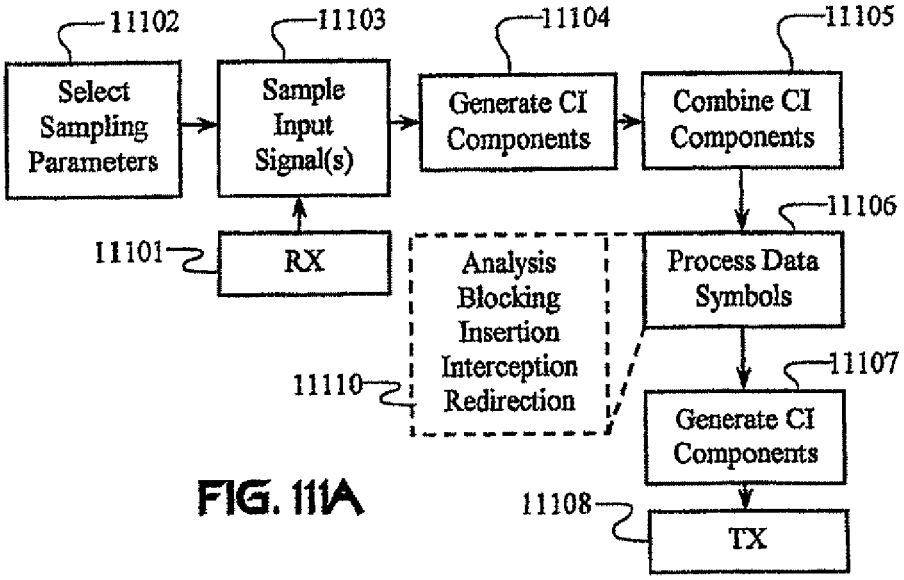


FIG. 111A

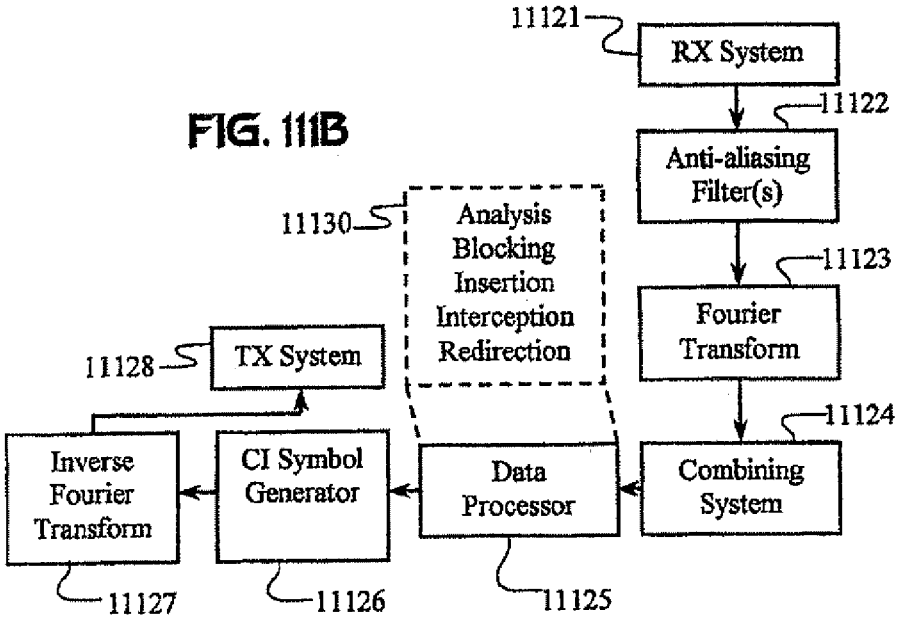


FIG. 111B

MULTICARRIER SUB-LAYER FOR DIRECT SEQUENCE CHANNEL AND MULTIPLE-ACCESS CODING

CROSS REFERENCE TO PRIOR RELATED APPLICATIONS

This application is a Continuation of U.S. patent application Ser. No. 16/199,221, filed Nov. 26, 2018, now U.S. Pat. No. 10,644,916, which is a Continuation of U.S. patent application Ser. No. 16/027,191, filed Jul. 3, 2018, now U.S. patent Ser. No. 10/574,497, which is a Continuation of U.S. patent application Ser. No. 15/489,664, filed Apr. 17, 2017, now U.S. Pat. No. 9,800,448, which is a Continuation of U.S. patent application Ser. No. 15/149,382, filed May 9, 2016, now U.S. Pat. No. 9,628,231, which is a Continuation-in-Part of U.S. patent application Ser. No. 14/727,769, filed Jun. 1, 2015, which is a Continuation of U.S. patent application Ser. No. 14/276,309, filed May 13, 2014, now U.S. Pat. No. 9,048,897, which is a Continuation of U.S. patent application Ser. No. 12/545,572, filed Aug. 21, 2009, now U.S. Pat. No. 9,042,333, which is a Divisional of U.S. patent application Ser. No. 11/187,107, filed on Jul. 22, 2005, now U.S. Pat. No. 8,670,390, which claims priority to Provisional Appl. No. 60/598,187, filed Aug. 2, 2004, all of which are hereby incorporated by reference in their entireties and all of which this application claims priority under at least 35 U.S.C. 120 and/or any other applicable provision in Title 35 of the United States Code.

BACKGROUND OF THE INVENTION

I. Field of the Invention

The present invention relates to direct-sequence code division multiple access (DS-CDMA), direct sequence spread spectrum (DSSS), and multicarrier spread spectrum communications. More specifically, the invention relates to adaptations of Carrier Interferometry (CI) that generate CDMA-like and DSSS-like signals.

II. Description of the Related Art

A wideband signal (such as a DS-CDMA signal) transmitted in a multipath environment experiences a frequency-selective fade. If the duration of the data bits is smaller than the multipath delay, the received signals experience inter-symbol interference resulting from delayed replicas of earlier bits arriving at the receiver. Improved DS-CDMA systems use interference cancellation to increase capacity; however, the required signal-processing effort is proportional to at least the cube of the bandwidth. Furthermore, DS-CDMA is susceptible to near-far interference, and its long pseudo-noise (PN) codes require long acquisition times. For these reasons, Orthogonal Frequency Division Multiplexing (OFDM) has been merged with DS-CDMA.

An OFDM system using fast Fourier transforms to generate orthogonal wave forms is described in an article by S. B. Weinstein and P. M. Ebert entitled "Data Transmission by Frequency Division Multiplexing Using the Discrete Fourier Transform," IEEE Transactions on Communication Technology, Vol. COM-19, No. 5, pp. 628-634, October 1971. In this OFDM system, the data symbols are processed in the transmitter by an inverse fast Fourier transform and in the receiver by a fast Fourier transform. The symbols are time-limited and the subcarriers overlap in the frequency domain.

OFDM has a high spectral efficiency (the spectrum of the subcarriers overlap) and combats frequency-selective fading. However, the amplitude of each carrier is affected by the Rayleigh law, hence flat fading occurs. Therefore, good channel estimation with an appropriate detection algorithm and channel coding is essential to compensate for fading. Coded OFDM provides data redundancy to reduce probability of error, but at the expense of reduced bandwidth efficiency.

Because frequency diversity is inherent in OFDM, it is much simpler to achieve than in a DS-CDMA system (which requires a Rake receiver to achieve diversity in the time domain). Frequency diversity can exploit all of the reflected energy in a multipath environment whereas a time-diversity (i.e., a Rake) receiver typically combines only a small fraction of the energy. OFDM systems benefit from a lower speed, parallel type of signal processing. A Rake receiver in a DS-CDMA system uses a fast, serial type of signal processing, which results in greater power consumption. In addition, OFDM simplifies the channel estimation problem, thus simplifying the receiver design.

In multicarrier CDMA (MC-CDMA), a spreading sequence is converted from serial to parallel. Each chip in the sequence modulates a different carrier frequency. Thus, the resulting signal has a PN-coded structure in the frequency domain, and the processing gain is equal to the number of carriers.

In multi-tone CDMA, or multicarrier DS-CDMA, the available spectrum is divided into a number of equal-width frequency bands used to transmit a narrowband direct-sequence waveform. In U.S. Pat. No. 5,504,775, binary CDMA code symbols are applied to individual carriers in an OFDM system. U.S. Pat. Nos. 5,521,937, 5,960,032, and 6,097,712 describe multicarrier DSSS systems having direct-sequence coding on each subcarrier.

U.S. Pat. Nos. 5,519,692 and 5,563,906 describe geometric harmonic modulation (GHM) in which preamble and traffic waveforms are created from multiple carrier frequencies (tones). The waveforms comprise tones incorporating a binary phase code where signal phases are 0 or $-\pi/2$. The binary phase offsets, which are applied to the tones, provide the spreading codes. The traffic waveforms are products of the tones. Orthogonality of GHM signals is realized upon correlation with a reference signal at a receiver. A preamble carrier waveform is constructed by summing the tones. Therefore, the preamble signals are similar to MC-CDMA signals.

GHM uses binary-phase offsets instead of polyphase offsets. Thus, GHM does not provide carriers with phase relationships that enable orthogonal superpositions of the carriers. Received GHM signals require processing by a correlator, whereas CI-based signals that are orthogonal in time can be processed using simpler signal-processing techniques, such as time sampling and weight-and-sum. Furthermore, GHM does not achieve the throughput, performance, and adaptability benefits enabled by orthogonal interferometry signals.

U.S. Pat. No. 4,901,307 describes processes of creating marginal isolation, which enhances in frequency reuse in DS-CDMA systems. In DS-CDMA, even small reductions in the overall power level of the system allow for increased system capacity. One particularly effective method for creating isolation and improving frequency reuse is spatial division multiple access (SDMA). SDMA applications to multiple access communications, including adaptive array processing, are discussed in U.S. Pat. Nos. 5,642,353, 5,592,490, 5,515,378, and 5,471,647. In addition to frequency

reuse, antenna arrays also provide increased processing gain and improved interference rejection.

Adaptive antenna arrays may be implemented with DS-CDMA communications to provide significant improvements in range extension, interference reduction, and system capacity. To identify a particular user, a DS-CDMA system demodulates Walsh codes after converting the received signal from RF to digital. Therefore, an adaptive antenna array requires information about the user codes, or it needs to demodulate many different incoming RF signals to track mobile users. These methods are complex processes that are more difficult to implement than tracking users in non-CDMA systems. Furthermore, the wideband nature of DS-CDMA signals restricts the effectiveness of beam forming, interference nulling, spatial interferometry multiplexing, and other techniques employed by adaptive antenna arrays.

U.S. Pat. No. 6,211,671 is one of the earliest references that describe interference cancellation in a non-beamforming type of array processor. A wideband signal is separated into narrowband signal components to optimize cancellation efficiency. This decomposition also reduces computational complexity. Interference cancellation compensates for propagation-path differences and differences in receiver responses to interfering multi-frequency signals.

U.S. Pat. No. 6,008,760, which is assigned to the same entity as the '671 patent, illustrates this cancellation method in a communication system that uses multi-element transmitters and receivers to create a plurality of same-frequency spatial subchannels.

U.S. Pat. Nos. 5,671,168 and 5,528,581 describe the application of well-known beam-forming processes to OFDM. U.S. Pat. No. 6,144,711 describes a simple combination of well-known OFDM and array-processing techniques.

U.S. Pat. No. 6,128,276 describes an application of antenna-array processing to well-known "stacked-carrier" spread spectrum communications in which duplicates of a data sequence are transmitted over different frequencies to achieve frequency diversity. Random or pseudorandom spreading weights are applied to each frequency band to facilitate multiple access. These spreading weights, unlike MC-CDMA weights, may provide both amplitude and phase adjustment. However, like MC-CDMA and other redundantly modulated multicarrier protocols, the spreading weights described in '276 do not enable carrier interferometry nor do they achieve the enormous throughput and performance improvements enabled by carrier interferometry.

In conventional multicarrier protocols, such as OFDM, DMT, and MC-CDMA, spreading is performed by energizing bins of a fast Fourier transform (FFT). U.S. Pat. Nos. 5,282,222, 6,175,550, and 5,608,764 illustrate exemplary OFDM transceivers. Blocks of coded data bits are serial-to-parallel converted and input into an N-point inverse-FFT (IFFT) operation. The output of the IFFT is parallel-to-serial converted to produce an OFDM signal having N frequency components. Time-domain samples of a received OFDM signal are serial-to-parallel converted and operated upon with an N-point FFT before being parallel-to-serial converted into a recovered data stream.

The N-point transforms used in OFDM essentially map one set of data symbols onto another set of data symbols. Each transform of a transform pair provides the basis for mixing symbols together to form a code that can be reversed by the complementary transform. In addition to Fourier transforms, other transform pairs are described in U.S. Pat. Nos. 5,282,222 and 6,192,068. This type of coding enables an overlay of multiple codes, which is referred to as "multi-code" spread spectrum.

One technique for implementing a Fourier transform includes filtering a time-domain sequence of input symbols. A polyphase FIR filter bank can be implemented equivalently with an N-point discreet Fourier transform (DFT) or inverse DFT (as illustrated by J. G. Proakis in "Digital Signal Processing," 3rd edition, p 825-831). Linear FIR filtering performed via the DFT typically involves segmenting the input symbols into blocks. The blocks are processed via the DFT and/or the IDFT to produce a block of output data. Common filtering techniques include the overlap-save method and the overlap-add method. The resulting output symbols are complex-weighted sums of the input symbols.

Various techniques have been developed to efficiently process Fourier transform algorithms, such as described in U.S. Pat. Nos. 6,169,723, 6,137,839, 5,987,005, 5,297,236, and 5,365,470. However, none of the prior-art Fourier transform techniques provide a means to replace direct-sequence processing with Fourier transforms or equivalent frequency-domain operations.

More recently, wavelet theory developed in response to perceived limitations to Fourier analysis and windowed Fourier techniques. Like string theory in quantum mechanics, wavelets provide an effective microscopic basis for describing macroscopic phenomena. However, one of the problems with conventional wavelet theory is that it relies on an abstraction with no physical basis to describe physical phenomena. In Hubbard's *The World According to Wavelets*, Meyer states that a Fourier transform is real, whereas wavelets do not have a physical existence. J. C. Van den Berg states that "wavelets cannot be interpreted in physical terms as easily as sines and cosines and their frequencies." This causes a major disconnect between interpretation and reality. As a result, engineers who work with wavelet transforms often have difficulty with the interpretation. In contrast, the intuitive nature of Fourier transforms is due to their direct association with real phenomena.

None of the prior-art references implement frequency-domain reception for direct-sequence signals. The prior-art references do not enable orthogonal multicarrier processing to be applied to direct-sequence spread-spectrum signals. Conventional direct-sequence protocols are not compatible with many types of adaptive array processing. The prior-art references fail to provide simultaneous improvements of increased throughput and enhanced performance to DSSS and DS-CDMA systems. No prior-art references describe a wave-based signal-processing technology that radically improves coding, wavelet, and Fourier-transform operations. None of the prior-art communication and signal-processing algorithms are based on principles of wave mechanics and quantum interferometry that describe the fundamental nature of all matter and energy.

SUMMARY OF THE INVENTION

Carrier Interferometry (CI) is a class of multicarrier-processing techniques that use sets of phase shifts (i.e., phase spaces) to overlay and separate data streams that are redundantly modulated onto the same sets of carrier signals. Multiple carriers are redundantly modulated with data streams that are orthogonalized by virtue of the different sets of phase spaces encoding each data stream. Interference between the carriers provides the means to orthogonalize the data streams, whether the carriers are combined or processed separately.

CI achieves the benefits of both narrowband and wideband processing. Narrowband processing is simpler than wideband processing. For example, multipath distortions in a narrowband signal can be characterized by a single attenuation and phase offset. Array processing, such as phased-array, adaptive beam forming, space-time, space-frequency, and spatial-interferometry techniques, are more effective and more easily performed with narrowband signals. This is important because array processing enables frequency reuse via spatial division multiple access, which greatly improves system capacity.

Wideband processing can provide benefits of frequency diversity. Path diversity exploits the short symbol length of a wideband signal relative to multipath delay. Path-diversity processing, such as RAKE reception, coherently combines multiple reflections of a desired signal. Frequency-diversity combining processes the reflected energy more efficiently, thus increasing transmission range or reducing required transmission power.

CI avoids multipath-interference problems of both wideband and narrowband signals while appearing like a conventional transmission protocol, such as TDMA or DS-CDMA. Inter-symbol interference occurs when a reflected signal travels a distance sufficiently greater than the distance traversed by a line-of-sight signal so as to cause a delay greater than the duration of a data symbol. This causes an earlier transmitted data symbol to interfere with a later symbol at a receiver. CI avoids inter-symbol interference by transmitting data symbols on narrowband carriers. The long symbol duration associated with a narrowband carrier ensures that multipath delays do not exceed the symbol duration. However, multipath fading occurs when a narrowband signal traverses two paths having a half-cycle phase difference.

CI avoids the problem of multipath fading by redundantly modulating each data symbol onto multiple carriers that are adequately separated with respect to frequency. Data symbols will not be lost to multipath fading if the carriers fade independently. However, redundant modulation typically reduces bandwidth efficiency.

CI avoids the problem of reduced bandwidth efficiency by modulating up to 2N coded data symbols on each of N carriers. However, conventional information theory shows that multiple signals occupying the same frequency band and time interfere with each other. Increased interference on one or more carriers typically increases probability of error.

CI avoids the problem of increased interference and probability of error by exploiting interferometry to orthogonalize data symbols modulated on the same carriers. Interference on each carrier cancels when the carriers are combined. This allows desired signals to be separated from interfering signals via superposition. Thus, CI-based multiple-access protocols achieve higher throughput with better signal quality than any other multiple-access protocols.

CI is distinguishable from conventional multicarrier modulation (MCM) techniques because it achieves both frequency diversity and bandwidth efficiency. CI is distinguishable from OFDM in that CI orthogonalizes data symbols via interferometry in the frequency domain whereas OFDM merely separates data symbols onto non-interfering frequencies. CI differs from MC-CDMA in that polyphase CI codes replace Hadamard-Walsh or Gold codes typically used with MC-CDMA. This provides significant differences between signal and operational characteristics of CI-based and MC-CDMA systems. For example, in MC-CDMA, CI codes are capable of doubling network capacity with almost no performance degradation. Furthermore, CI signals are substantially insensitive to phase jitter and frequency offsets, which are recognized as the major disadvantage of conventional MCM.

CI codes may be employed in direct-sequence-like coding. Additionally, CI codes may be used for channel coding. CI codes and/or CI-based signaling may be used to encode data bits and/or data symbols. CI coding and CI-based codes may include interleaving.

CI enables the application of a redundantly modulated multicarrier architecture to conventional transmission protocols, such as TDMA, DS-CDMA, MC-CDMA, and OFDM. Specifically, CI carrier signals combine to generate a superposition signal having time-domain characteristics that can be controlled via selection of the CI carrier characteristics (such as phase, frequency, and amplitude). This enables CI to be compatible with legacy systems that use TDMA, DS-CDMA, pulse radio, etc. CI also improves existing multicarrier protocols (such as OFDM and MC-CDMA). Thus, CI creates a common multicarrier architecture for all conventional transmission protocols.

The application of CI to DSSS and DS-CDMA is referred to as CI/DS-CDMA.

At the transmit side, the usual sinc and raised cosine pulse shapes used with DS-CDMA are replaced by a CI signal. For example, a DS-CDMA chip-shaping filter at a code generator is replaced with a chip-shaping filter matched to the CI signal. At the receive side, a RAKE receiver in a typical DS-CDMA receiver is replaced by a receiver that performs frequency decomposition and recombining. Each chip is separated into its N frequency components and recombined in a manner that provides (1) optimal frequency-diversity benefits, (2) minimal inter-chip interference, and (3) a reduction in additive noise power. Possible combining techniques include equal-gain combining (EGC), orthogonal restoring combining (ORC), and minimum mean squared error combining (MMSEC). Upon recombining the chips, DS-CDMA spreading codes may be applied to separate data symbols and/or data streams from each other. Variations to these transmit and receive side processing techniques, as well as other types of processing, are described in the preferred embodiments.

Although the time-domain characteristics of CI/DS-CDMA signals are similar to DSSS and DS-CDMA signals (thus, making them compatible with conventional DS-CDMA networks), CI/DS-CDMA signals differ from DSSS and DS-CDMA signals. Instead of spreading information symbols over code chips (i.e., the time domain), CI spreads information symbols over interfering subcarriers (i.e., the frequency domain). Consequently, the frequency-domain characteristics of transmitted CI/DS-CDMA signals are fundamentally different than the frequency-domain characteristics of DSSS and DS-CDMA signals. Furthermore, received CI/DS-CDMA signals are processed in the frequency domain (e.g., via frequency decomposition and combining), whereas received DSSS and DS-CDMA signals are processed in the time domain (e.g., via RAKE receivers).

Frequency-domain selectivity enables independent provisioning of CI sub-carrier channels to users who may only need a fraction of the bandwidth of a communication channel. In optical-fiber systems, a CI signal is composed of multiple narrowband subcarriers that are less sensitive to channel impairments, such as delay mode distortion. Thus, CI eliminates the need for high-speed equalization. This significantly reduces transceiver complexity and can increase the range of optical communication systems. The CI signal architecture, as well as efficient modulation (e.g.,

phase-shift modulation, polarization-shift modulation) achieves higher data rates with lower-frequency optoelectronics.

The frequency profile of a CI superposition signal can be controlled by adjusting weights of CI carriers and/or selecting CI carrier frequencies. This enables conventional single-carrier protocols, such as TDMA and DS-CDMA, to be implemented with a CI carrier architecture distributed across non-continuous frequency bands. CI is also complementary to SONET and wavelength-division multiplexing in optical fiber.

Carrier-weight adjustment facilitates adaptation to multipath and jamming environments. Carrier weights may be used by either or both a transmitter and a receiver to compensate for fading and/or other forms of signal degradation, avoid deep fades and/or interference, and/or optimize transmission power efficiency. A CI signal may be frequency hopped to avoid interference and/or fading. Frequency hopping may be employed to enhance security or frequency diversity.

CI allows network providers to deliver signals that are data rate and protocol independent. This allows rapid, independent provisioning of sub-carrier channels. Scalability is provided by adding CI sub-carriers, thus allowing a "pay as you grow" approach. Additionally, only one network element needs to be provisioned in order to reconfigure the network.

Frequency-domain and time-domain adjustments of CI superposition signals may be employed to generate wavelets. This link between CI and wavelets enables a simple conversion between CI carrier selection and weight adjustment and wavelet scaling and shifting. CI also provides a multicarrier architecture for encoding, transmitting, and receiving wavelets.

It is an object of the present invention to provide all types of communication signals with immunity to fading, inter-symbol interference, and other forms of channel distortion.

An advantage of the present invention is that it provides a common multicarrier platform that can be designed for TDMA, DS-CDMA, MC-CDMA, pulse radio, and OFDM. This can be implemented as a software-defined radio system that uses simple algorithms combined with CI to select different multiple-access protocols.

An advantage of the present invention is that a radio communication method is provided that is compatible with high-order digital modulations.

An advantage of the present invention is that a CDMA radio communication method is provided that can be used with transceiver arrays.

An advantage of the present invention is that a CDMA radio communication method is provided that is compatible with advanced array adaptation techniques and thereby separates signals based on spatial diversity, frequency diversity, and combined spatial/spectral diversity.

CI signals enable antenna arrays to achieve directionality and spatial diversity simultaneously. This reduces the cost of antenna infrastructure deployment and improves system performance. Thus, the invention allows concentration of complex operations at base stations in point-to-multipoint communication links, greatly reducing the cost of the overall system.

An advantage of the present invention is that a radio communication method is provided that has space division multiple access, interference excision, and channel equalization capability.

An advantage of the invention is that it increases throughput of wireless and guided-wave communications. CI-based protocols are highly bandwidth efficient, allowing higher data throughput in a given amount of spectrum than any other transmission protocol. CI provides higher data rates and supports more users than any other transmission protocol.

An advantage of the invention is that it enables improved signal quality. CI signals are highly resistant to interference and distortion.

An advantage of the invention is that it greatly reduces transmit power requirements. Received CI signals can be combined to use all of the transmitted signal energy that gets reflected on the way to the receiver. Other technologies make little or no use of reflected energy.

Some of the many wireless applications of the invention include local-area networks, cellular communications, personal communication systems, broadband wireless services, data link, voice radio, satellite links, tagging and identification, wireless optical links, campus-area communications, wide-area networks, last-mile communication links, and broadcast systems. The invention may be used in non-wireless communication systems, such as guided wave, cable, wire, twisted pair, optical fiber, and any networks connected via conducting elements.

Various aspects of the invention are applicable to many types of signal processing. Some of these types of processing include, but are not limited to, transducer-array processing, space-time processing, space-frequency processing, interferometry, filtering, wavelet processing, transform operations, frequency conversion, diversity processing, correlation, channel coding, error-correction coding, multiple-access coding, spread-spectrum coding, channel compensation, correlation, transmission-protocol conversion, and security coding and authentication. Other applications and embodiments of the invention are apparent from the description of preferred embodiments and the claims that follow.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A illustrates CI carriers having phase fronts that are aligned at a specific time. The CI carriers combine to generate a plurality of superposition signals that are orthogonal to each other in time.

FIG. **1**B illustrates an in-phase superposition of CI carriers of a carrier set that produces a superposition signal corresponding to a sum of the superposition signals shown in FIG. **1**A

FIG. **1**C illustrates two sets of orthogonal superposition signals. The signals in each set are orthogonal to each other. However, signals in a first set are quasi-orthogonal to signals in a second set.

FIG. **1**D shows a summation of two orthogonal sets of CI signals wherein signals in a first set are quasi-orthogonal to signals in a second set.

FIG. **2**A shows a plurality of carrier signals defined by a range of carrier frequencies and sets of phase offsets, such as phase offsets resulting in a particular time-domain characteristic of a superposition of the carriers.

FIG. **2**B shows a plurality of carrier signals defined by a range of carrier frequencies, sets of phase offsets, and sets of carrier amplitudes and a superposition of the carriers. Either or both the superposition signal and the set of carriers may be processed for transmission and/or reception.

FIG. **3** shows a plurality N of carrier signals that are redundantly modulated with a stream of data symbols $s_k(t)$ associated with a kth channel.

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FIG. **4**A illustrates the use of different phases and time intervals applied to one set of carrier frequencies to distinguish a kth channel.

FIG. **4**B represents a plurality of data symbols $s_1(t)$, $s_2(t)$, and $s_3(t)$ modulated onto the same carrier frequencies within the same time interval.

FIG. **5** illustrates a plurality of time-offset carrier signals having different initial time offsets t^o_{kn}.

FIG. **6**A shows a plurality of carriers corresponding to a plurality M of subchannels each having a plurality N of carriers.

FIG. **6**B illustrates a superposition of three subchannels that occupy the same time-domain space.

FIG. **7** illustrates a time-offset code used with carrier-defined subchannels.

FIG. **8** shows a plurality N of carrier frequencies wherein each carrier frequency f_n (n=1, . . . , N) has a plurality of phased subcarriers.

FIG. **9**A shows a plurality N of incrementally spaced-in-frequency carrier signals that may be used as an underlying architecture for transmission protocols. Users and/or data channels having symbols that are redundantly modulated on all N carriers can be provided with N orthogonal phase spaces.

FIG. **9**B shows an arrangement of N incrementally spaced-in-frequency carrier signals divided into M sets of carrier signals. Each set may include one or more users and/or data channels. Each set may or may not include a similar number of carriers. The carriers in each set may be incrementally spaced or non-incrementally spaced.

FIG. **10**A shows a single carrier frequency f_n having multiple quasi-orthogonal phases $\phi_{(mn)k}$ that can be used in a quasi-orthogonal phase-space division multiplexing technique.

FIG. **10**B shows a plurality of carrier frequencies wherein each frequency includes multiple quasi-orthogonal phases.

FIG. **11** shows a CI-OFDM signal architecture for a plurality M of users wherein each user is provided with a unique set of carriers.

FIG. **12** shows a CI/MC-CDMA architecture in which a kth user having a kth phase space ϕ_{kn} is provided with a spreading sequence c_{kn} assigned to each of a plurality N of carriers. The spreading sequence c_{kn} may include binary or polyphase values.

FIG. **13**A shows a time-domain representation of a plurality K of DS-CDMA codes generated from a CI architecture. Each chip of each CI/DS-CDMA code is generated from a CI superposition of carriers. Each chip is provided with a binary code value corresponding to a DS-CDMA code.

FIG. **13**B illustrates chip overlap, which can increase bandwidth efficiency and/or provide additional redundancy. Chip overlap introduces a quasi-orthogonal condition. In the example shown, chip overlap doubles the code length without increasing bandwidth.

FIG. **13**C shows one of many possible carrier architectures for a CI/DS-CDMA system.

FIG. **14**A shows an embodiment of a CI/DS-CDMA transmitter.

FIG. **14**B shows another embodiment of a CI/DS-CDMA transmitter.

FIG. **15**A illustrates a plurality of orthogonal phase spaces corresponding to a plurality of CI carrier frequencies.

FIG. **15**B shows a matrix of phase-shifted symbol values corresponding to carrier frequencies (rows) and phase spaces (columns).

FIG. **16**A illustrates at least some of the principle components of a CI transmission system.

FIG. **16**B illustrates another embodiment of a CI transmitter.

FIG. **16**C illustrates an alternative embodiment of a CI transmitter.

FIG. **16**D illustrates basic components of a particular set of embodiments of a CI transmitter.

FIG. **16**E illustrates generalized components of a broad class of CI transmitters.

FIG. **16**F illustrates basic components of a CI transmitter that impresses at least one data sequence, at least one channel code, and at least one multiple-access code onto a plurality of carriers.

FIG. **16**G illustrates a further embodiment of a transmitter.

FIG. **17**A illustrates how a CI/DS-CDMA signal can be characterized by both time-domain and frequency-domain codes. CI may be characterized by multi-dimensional codes with respect to other combinations of diversity parameters.

FIG. **17**B illustrates a multi-dimensional signal with CI coding.

FIG. **17**C illustrates a three-dimensional diversity-parameter space that can be modulated or impressed with CI codes.

FIG. **18**A is a functional representation of one set of embodiments of a CI receiver.

FIG. **18**B is a general illustration of a CI receiver, such as a CI/DS-CDMA receiver.

FIG. **18**C illustrates one possible set of embodiments of a CI receiver.

FIG. **19**A illustrates an embodiment of a CI receiver array.

FIG. **19**B illustrates an alternative embodiment of a CI receiver array.

FIG. **19**C illustrates an embodiment of the combiner shown in FIG. **19**A.

FIG. **19**D illustrates an embodiment of the combiner shown in FIG. **19**B.

FIG. **20** illustrates a system adapted to transmit CI subspace coded data symbols into a multipath channel and a receiver adapted to process and decode the CI subspace coded data symbols.

FIG. **21**A illustrates an embodiment of a space-time matched-filter receiver of the present invention.

FIG. **21**B illustrates an embodiment of a space-frequency matched-filter receiver of the present invention.

FIG. **21**C illustrates a space-time receiver of the present invention.

FIG. **21**D illustrates a space-frequency receiver of the present invention.

FIG. **21**E shows a generalized illustration of a multi-element receiver of the present invention.

FIG. **21**F shows a multi-element receiver of the present invention.

FIG. **21**G is a functional illustration of a multi-element receiver of the present invention.

FIG. **22** illustrates an array-processor receiver of the invention that combines space-time processing with space coding.

FIG. **23**A illustrates one of many possible CI/DS-CDMA signal structures corresponding to a set of apparatus and method embodiments of the invention.

FIG. **23**B illustrates signal structures of one set of embodiments of a multi-dimensional CI/DS-CDMA method and apparatus of the invention.

FIG. **24** illustrates a signal structure derived from an alternate set of apparatus and method embodiments of the invention.

FIG. **25**A illustrates a subspace processing method of the present invention.

FIG. **25**B illustrates an alternative subspace processing method of the present invention.

FIG. **26**A shows a frequency-versus-magnitude plot of an alternative CI-based protocol.

FIG. **26**B shows a frequency-versus-magnitude plot of an associated conventional protocol.

FIG. **27** is a frequency-domain illustration of carrier placements for multiple CI channels. These carrier placements allow the CI channels to benefit from frequency diversity of nearly the entire frequency band.

FIG. **28**A illustrates a set of methods for generating CI-based signals.

FIG. **28**B illustrates a set of methods for receiving one or more CI-based signals.

FIG. **29**A shows a conventional 4×4 Hadamard-Walsh matrix that may be used in the invention.

FIG. **29**B shows a basic 4×4 CI matrix.

FIG. **30**A shows a 4×4 CI matrix multiplied by a first row of a Hadamard-Walsh matrix.

FIG. **30**B shows a 4×4 CI matrix multiplied by a second row of a Hadamard-Walsh matrix.

FIG. **30**C shows a 4×4 CI matrix multiplied by a third row of a Hadamard-Walsh matrix.

FIG. **30**D shows a 4×4 CI matrix multiplied by a fourth row of a Hadamard-Walsh matrix.

FIG. **31**A illustrates a selection of quaternary-phase vectors from the matrices shown in FIG. **30**A and FIG. **30**C.

FIG. **31**B illustrates a selection of binary-phase vectors from the matrices shown in FIG. **30**A and FIG. **30**C.

FIG. **31**C shows a 4×4 poly-phase code matrix.

FIG. **32**A shows an 8×8 Hadamard-Walsh matrix $HW_{8\times8}$ generated from a 4×4 Hadamard-Walsh matrix $HW_{4\times4}$ using the Hadamard-Walsh matrix-expansion technique.

FIG. **32**B shows an 8×8 CI matrix $PC4_{8\times8}$ generated from the 4×4 polyphase CI matrix shown in FIG. **31**C via Hadamard Walsh matrix expansion.

FIG. **32**C shows an 8×8 CI matrix $CI_{8\times8}$ generated from a 4×4 CI matrix $CI_{4\times4}$ via Hadamard Walsh matrix expansion.

FIG. **33**A shows an 8×8 CI matrix $HW_{8\times8}(1)\times CI_{8\times8}$ resulting from multiplication of the 8×8 CI matrix $CI_{8\times8}$ shown in FIG. **32**C by the first row vector $HW_{8\times8}(1)$ of the 8×8 Hadamard-Walsh matrix shown in FIG. **32**A.

FIG. **33**B shows an 8×8 CI matrix $HW_{8\times8}(2)\times CI_{8\times8}$ resulting from a multiplication of an 8×8 CI matrix $CI_{8\times8}$ by the second row vector $HW_{8\times8}(2)$ in an 8×8 Hadamard-Walsh matrix shown in FIG. **32**A.

FIG. **33**C shows an 8×8 CI matrix $HW_{8\times8}(3)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the third row $HW_{8\times8}(3)$ of the 8×8 Hadamard-Walsh matrix shown in FIG. **32**A.

FIG. **33**D shows an 8×8 CI matrix $HW_{8\times8}(4)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the fourth row $HW_{8\times8}(4)$ of the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$.

FIG. **33**E shows an 8×8 CI matrix $HW_{8\times8}(5)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the fifth row vector $HW_{8\times8}(5)$ of the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$.

FIG. **33**F shows an 8×8 CI matrix $HW_{8\times8}(6)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the sixth row $HW_{8\times8}(6)$ in the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$.

FIG. **33**G shows an 8×8 CI matrix $HW_{8\times8}(7)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the seventh row vector $HW_{8\times8}(7)$ of the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$.

FIG. **33**H shows an 8×8 CI matrix $HW_{8\times8}(8)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the eighth row $HW_{8\times8}(8)$ in the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$.

FIG. **34**A shows a set 16 octonary codes C(n) generated from multiplying an 8×8 CI matrix $CI_{8\times8}$ by rows $HW_{8\times8}(n)$ of the 8×8 Hadamard-Walsh matrix $HW_{8\times8}$.

FIG. **34**B shows auto correlations and cross correlations of the 16 octonary codes C(n) shown in FIG. **34**A.

FIG. **35** illustrates a decoding method of the invention in which data transmitted on two codes may be processed with a single despreading code.

FIG. **36**A shows a frequency-domain plot of a data symbol that is converted to a wideband spread-spectrum signal via direct-sequence processing.

FIG. **36**B shows a frequency-domain plot of the data symbol shown in FIG. **36**A that is converted to a CI signal having a plurality N of narrowband components.

FIG. **37** shows a time-domain plot of a plurality N of narrowband CI components and a data symbol, which can be represented by a superposition of the CI components.

FIG. **38** illustrates frequency-domain characteristics of a typical direct-sequence signal **3801** in comparison to frequency-domain characteristics of a plurality of different CI/DS-CDMA signal types.

FIG. **39**A illustrates a CI code mapped into a plurality of orthogonal diversity-parameter values.

FIG. **39**B illustrates a CI code mapped into a plurality of orthogonal time slots.

FIG. **39**C illustrates a CI code mapped into a set of orthogonal frequencies.

FIG. **39**D illustrates a plurality of CI code chips impressed onto a plurality of spatial directions.

FIG. **39**E illustrates CI coding used with a transmitter array such that each code chip corresponding to a multiple-access channel or channel code is applied to an individual spatially separated transmitter element.

FIG. **39**F illustrates CI coding applied to a plurality of linear polarized signals.

FIG. **39**G illustrates CI coding applied to a plurality of circular (or elliptical) polarized signals having different precession rates.

FIG. **40**A illustrates basic components of a CI transceiver.

FIG. **40**B illustrates basic components of a CI-code generator

FIG. **41**A illustrates general steps of a transmitting method of the present invention.

FIG. **41**B illustrates general steps of a receiving method that may be performed in conjunction with the transmitting method illustrated in FIG. **41**A.

FIG. **42** shows basic components of a CI transceiver.

FIG. **43**A shows a (2,1) polyphase (M-ary) convolutional encoder with constraint length K=3.

FIG. **43**B illustrates an M-ary trellis diagram that represents the function of the polyphase convolutional encoder shown in FIG. **43**A.

FIG. **43**C illustrates polyphase channel coding that may be provided by a CI channel coder coupled to a modulator adapted to perform M-ary modulation.

FIG. **43**D illustrates a CI Trellis decoding technique that may be used to decode CI-coded signals.

FIG. **44**A shows an embodiment of a CI coder that includes at least one block coder and at least one convolutional coder.

FIG. **44**B shows an alternative embodiment of a CI coder that includes at least one block coder and at least one convolutional coder.

FIG. **45**A shows a decoder corresponding to the coder shown in FIG. **44**A.

FIG. **45**B shows a decoder corresponding to the coder shown in FIG. **44**B.

FIG. **46** illustrates basic components of a turbo coder/decoder system that may be used to process CI codes.

FIG. **47**A illustrates a set of data symbols and a plurality of CI pulses that are adapted with respect to a plurality of data symbols.

FIG. **47**B illustrates a modulated CI pulse stream generated by impressing data symbols onto a CI pulse stream.

FIG. **47**C illustrates CI carrier components of the modulated CI pulse stream shown in FIG. **47**B.

FIG. **48** shows a CI encoding system coupled to a transmitter and a CI decoding system coupled to a receiver.

FIG. **49** illustrates relationships between basic CI symbol values w_n and data symbols s_n processed with CI code chips to produce the CI symbol values w_n.

FIG. **50** shows a block diagram of basic components used in a CI coding system and a CI decoding system.

FIG. **51** illustrates channel-code chips c_{nk} used to map a data symbol d_m to multiple carrier frequencies.

FIG. **52** illustrates an application of multi-level coding of the present invention.

FIG. **53** illustrates a multi-level coding method of the invention that spreads a data symbol over multiple frequencies and time intervals.

FIG. **54**A illustrates a method of sub-channel coding.

FIG. **54**B shows a subchannel coding technique combined with time-domain coding.

FIG. **55** shows an embodiment of a transmitter for combined channel coding and multiple access.

FIG. **56** illustrates a receiver associated with the transmitter shown in FIG. **55**.

FIG. **57**A shows a continuous frequency-domain profile of a single-carrier signal.

FIG. **57**B represents a simplified time-domain profile of a wideband digital signal.

FIG. **57**C is a frequency-domain illustration of an inefficient decomposition of the wideband signal into a plurality of narrowband components. The frequency spectra of the components do not overlap. The roll-off factor of an analog filter's frequency response causes some received energy (and thus, information) to be lost.

FIG. **58**A shows a decomposition of a single-carrier or multicarrier signal into N carrier-frequency components.

FIG. **58**B shows a frequency-domain plot of the signal shown in FIG. **58**A.

FIG. **58**C shows a decomposition of the signal shown in FIG. **58**A into N' carrier components where N'>N.

FIG. **58**D shows a frequency-domain plot of the signal shown in FIG. **58**C.

FIG. **58**E illustrates a spectral profile selected for transmission or reception in a particular communication channel. Frequency ranges characterized by interference, jamming, fading, and/or frequency allocations to other systems, applications, and/or users can selectively be avoided.

FIG. **59**A illustrates a method of generating CI carriers in a transmission system.

FIG. **59**B illustrates a method of generating CI carriers in a decomposition process in a receiver.

FIG. **60**A illustrates a CI receiver adapted to generate a plurality of CI component signals from a received single-carrier signal.

FIG. **60**B illustrates an alternative embodiment of a CI receiver adapted to process single-carrier signals.

FIG. **61** illustrates a repeater adapted to convert a received signal into overlapping, orthogonal CI sub-carrier components, process the components, and recombine the processed components prior to transmitting the combined components.

FIG. **62** illustrates a CI receiver coupled to an antenna array wherein the receiver is adapted to process a received single-carrier signal as a plurality of CI components.

FIG. **63** illustrates a CI-based matched-filter receiver adapted to process a single-carrier signal as a plurality of CI components.

FIG. **64**A illustrates a CI receiving method adapted to process a single-carrier signal.

FIG. **64**B illustrates basic steps of a CI reception method.

FIG. **64**C illustrates basic steps performed by a CI receiver.

FIG. **65** illustrates how conventional radio-processing techniques can be consolidated into simple CI transceiver processes.

FIG. **66** illustrates an embodiment of a CI-based software-defined radio.

FIG. **67** illustrates basic baseband-processing components of a CI transceiver.

FIG. **68** illustrates transmission methods **6810** and reception methods **6820** of the present invention.

FIG. **69**A illustrates how digital, text, and analog signals are formatted for different information signals.

FIG. **69**B illustrates a formatting step adapted to process received signals into different information signals.

FIG. **70** shows three orthogonal waveforms separated in frequency by integer multiples of a separation frequency.

FIG. **71**A is a normalized complex-plane representation of samples of a signal having a particular signal frequency collected at a sampling rate that equals, or is some sub-harmonic frequency of, the signal frequency. Each sample corresponds to an integer number of full rotations in the complex plane.

FIG. **71**B is a normalized complex-plane representation that illustrates a non-zero progressive phase offset for each sample of a signal having an orthogonal signal frequency (represented by frequency f_{n-1}) relative to a sampling rate $f_{sample}=f_n$. Each sample corresponds to less than a full rotation (i.e., f_{n-1}/f_n rotations) in the complex plane.

FIG. **71**C is a normalized complex-plane representation that illustrates a non-zero progressive phase offset for each sample of a signal having an orthogonal signal frequency (represented by frequency f_{n+1}) relative to a sampling rate $f_{sample}=f_n$. Each sample corresponds to a greater than full rotation (i.e., f_{n+1}/f_n rotations) in the complex plane.

FIG. **72** is a normalized complex-plane representation of samples collected over a symbol interval. In this case, samples of a signal having a signal frequency f_{signal} collected at a sampling rate $f_{sample}\neq f_{signal}$, where f_{sample} is orthogonal to f_{signal}, fill an integer number of full rotations in the normalized complex plane. The samples are uniformly spaced throughout the unit circle, and thus, cancel.

FIG. **73** illustrates in-phase and quadrature-phase samples collected at a particular sampling rate.

FIG. **74**A illustrates combined values of 110 CI samples for each of 400 frequencies in intervals of one cycle per symbol period T_s.

FIG. **74**B illustrates the combined values of 110 CI samples for each of 800 frequencies spaced at 0.05 cycles-per-period intervals and centered at 110 cycles per symbol period.

FIG. **74**C illustrates a plot of sums of samples collected at a particular sample frequency for a plurality of sampled signal frequencies.

FIG. **75** is a plot of sums of samples collected at a particular sample frequency for a plurality of sampled signal frequencies.

FIG. **76**A illustrates samples of a signal having a frequency f_n sampled at a sample frequency $f_{sample}=f_n$. The samples are represented as vectors in a normalized complex plane. Since $f_{sample}=f_n$, the vectors map onto the same position in the complex plane. Thus, the samples add constructively.

FIG. **76**B shows a representation of samples mapped as vectors in a normalized complex plane. The sample frequency is $f_{sample}=f_n$ and the sampled signal's frequency is $f_{signal}=f_{n+1}$. Since the sample and signal frequencies are orthogonal to each other and the samples are collected over a symbol interval $T_s=1/f_s$, the samples are uniformly distributed around a unit circle in the complex plane. The samples combine destructively to produce a zero value.

FIG. **76**C shows samples mapped on a unit circle in a complex plane. The samples correspond to a sample frequency of $f_{sample}=f_n$ and a sampled signal frequency of $f_{signal}=f_{n+1.5}$. The samples are collected over a symbol interval $T_s=1/f_s$. Since the sample and signal frequencies are not orthogonal, there is a non-uniform distribution of samples over the unit circle. Some of the samples combine constructively to produce a non-zero value.

FIG. **76**D illustrates a plurality of samples mapped onto a unit circle in a normalized complex plane. The samples correspond to a sample frequency of $f_{sample}=f_n$ and a sampled signal frequency of $f_{signal}=f_n+2$. The samples are collected over a symbol interval $T_s=1/f_s$. Since the sample and signal frequencies are orthogonal and not harmonically related, the samples are distributed uniformly around the unit circle. When the samples are summed, they cancel.

FIG. **76**E shows samples mapped on a unit circle in a complex plane. The samples correspond to a sample frequency of $f_{sample}=f_n$ and a sampled signal frequency of $f_{signal}=f_{n+2.5}$. The samples are collected over a symbol interval $T_s=1/f_s$. Since the sample and signal frequencies are not orthogonal, there is a non-uniform distribution of samples over the unit circle. The samples combine to produce a non-zero value.

FIG. **77**A is a functional diagram that illustrates apparatus and method embodiments of a coherent CI sampler.

FIG. **77**B shows an alternative functional diagram that illustrates apparatus and method embodiments of a coherent CI sampler.

FIG. **78**A shows part of a coded CI waveform that may be processed using a CI sampling algorithm.

FIG. **78**B shows a table that illustrates **10** transmitted data symbols and corresponding non-normalized received signal values for each of 10 phase spaces.

FIG. **79**A illustrates two periods of a step function constructed from a superposition of odd-numbered sinusoids.

FIG. **79**B illustrates a portion of a Fourier transform of the step function shown in FIG. **79**A.

FIG. **80**A is a frequency-domain representation showing a first frequency component of a sampling step function that equals a desired carrier frequency. A plurality of orthogonal frequencies is also shown that may correspond to undesired carrier frequencies. A second frequency component of the step function is also shown. The second frequency corresponds to a harmonic of the first frequency. If a carrier frequency equals the second frequency, then the sampling step function generates non-zero values for both carrier frequencies.

FIG. **80**B is a frequency-domain profile that shows a first plurality of harmonics corresponding to both a first plurality of carriers and a plurality of components of a first sampling step function. The frequency-domain profile also shows a second plurality of harmonics corresponding to both a second plurality of carriers and a plurality of components of a second sampling step function. The first and second pluralities of carriers are orthogonal to each other. Thus, the first sampling step function generates non-zero values for only the first set of carriers and the second sampling step function generates non-zero values for only the second set of carriers. Data symbols are advantageously modulated onto more than one carrier of each carrier set.

FIG. **81** shows three sinusoidal waves having uniformly spaced frequencies f_1, f_2, and f_3, and a step function **8111** having a frequency equal to frequency f_1.

FIG. **82** shows a step function having a particular phase and frequency f_n superimposed over three sinusoidal waves having the same frequency f_n, but different phases.

FIG. **83** is a table that illustrates summed values of three frequency bins of a three-carrier signal generated for each of three desired phase spaces and for the two remaining undesired phase spaces.

FIG. **84** illustrates basic components of a CI-OFFT receiver.

FIG. **85** illustrates a plurality of five-level step functions having orthogonal frequencies, which are shown over a partial symbol interval.

FIG. **86**A illustrates a pulse resulting from a superposition of the step functions shown in FIG. **85**.

FIG. **86**B illustrates a filtered superposition pulse generated by low-pass filtering the pulse shown in FIG. **86**A.

FIG. **87**A illustrates a combined signal resulting from a superposition of a plurality of step functions having a frequency offset f_o.

FIG. **87**B illustrates a low-pass filtered superposition signal in which high-frequency components have been removed from the combined signal shown in FIG. **87**A.

FIG. **88**A illustrates a superposition pulse generated from a plurality of binary step functions.

FIG. **88**B illustrates a filtered superposition pulse generated by low-pass filtering the pulse shown in FIG. **88**A.

FIG. **89**A illustrates a functional embodiment of an inverse CI-OFFT system of the invention.

FIG. **89**B illustrates an alternative functional embodiment of an inverse CI-OFFT system.

FIG. **89**C illustrates yet another functional embodiment of an inverse CI-OFFT system.

FIG. **90** illustrates a wavelet constructed from a plurality of CI carriers.

FIG. **91** illustrates a Morlet wavelet packet **9100** constructed from a superposition of CI carriers.

FIG. **92**A illustrates three overlapping CI pulses having different effective-carrier frequencies.

FIG. **92**B illustrates a superposition signal produced by combining the three CI pulses shown in FIG. **92**A. The superposition signal is characterized by a uniformly changing frequency.

FIG. **92**C illustrates a plurality of CI carriers that combine to generate the superposition signal shown in FIG. **92**B.

FIG. **93** illustrates a wavelet generated from a plurality of CI carriers. Signals may be expressed by wavelet parameters

(τ_n, s_n) and/or CI parameters (f_n, w_n). CI-based wavelets can be used to translate between wavelet parameters and CI parameters.

FIG. **94**A illustrates a CI-based wavelet (i.e., a CI superposition signal) characterized by a high time resolution (i.e., a narrow time-domain signal).

FIG. **94**B illustrates a plurality of narrowband CI carriers that are components of the superposition signal shown in FIG. **94**B.

FIG. **94**C is a frequency-domain illustration of the carriers shown in FIG. **94**B. Each frequency-domain component is characterized by high frequency resolution (i.e., a narrow frequency-domain signal).

FIG. **95**A illustrates a portion of a particular signal having multiple frequencies and transient signal characteristics. The signal may include an information signal. In some applications, the signal may be a received signal that may include noise and/or distortion. In other applications, the signal may include a transmit data sequence.

FIG. **95**B illustrates a plurality of narrowband CI signals that may be correlated (or similarly processed) with an information signal to provide a plurality of correlation values. The information signal may be processed, such as by filtering, to produce the correlation values. The correlation values are indicative of carrier weights. The carrier weights, when applied to hypothetical narrowband CI signals (such as shown in FIG. **95**B), provide a superposition signal with time and frequency-domain characteristics of the information signal.

FIG. **95**C illustrates a narrow time-domain signal resulting from a superposition of the CI signals. The narrow time-domain signal represents a narrow time-domain portion of the information signal that contributes to a sum of the correlation values represented by the CI signals shown in FIG. **95**B.

FIG. **96**A illustrates one aspect of the invention in which wavelet parameters (such as scale factors, translations, and/or wavelet type) are modulated or otherwise impressed onto CI signals for transmission.

FIG. **96**B illustrates a method of transmitting wavelet parameters over a communication channel wherein the wavelet parameters are converted to CI carrier weights.

FIG. **96**C illustrates a method of conveying wavelet parameters as a CI-based signal wherein the wavelet parameters are converted to CI waveforms.

FIG. **97**A illustrates a CI reception method of the invention.

FIG. **97**B illustrates an alternative CI reception method.

FIG. **97**C illustrates steps of a CI reception method.

FIG. **98** illustrates a CI transceiver of the invention. A receiver system couples a transmitted signal out of a communication channel. A transmitter system couples an information-bearing transmit signal into a communication channel.

FIG. **99** illustrates a control circuit that processes one or more system requirements and, optionally, one or more channel characteristics to adjust one or more CI parameters in a CI transceiver.

FIG. **100**A illustrates a plurality of subscriber units in a network having a plurality of access points. At least one of the subscriber units is adapted to generate a pilot or known reference signal that is processed by the access points in a channel-estimation step.

FIG. **100**B illustrates a plurality of access points adapted to transmit channel-compensated signals to at least one subscriber unit.

FIG. **101** illustrates a plurality of access points connected to a network. A central processing unit enables the access points to work together to enhance diversity and/or provide sub-space processing.

FIG. **102** illustrates a network architecture in which a plurality of subscriber units are adapted to function as routers and/or repeaters.

FIG. **103**A illustrates a CI transceiver adapted to perform routing.

FIG. **103**B illustrates a CI transceiver adapted to perform routing.

FIG. **103**C illustrates a further embodiment of a CI transceiver.

FIGS. **104**A, **104**B, and **104**C illustrate various network designs that may be used according to various embodiments of the invention.

FIGS. **105**A and **105**B illustrate further embodiments of networks that may be used according to various embodiments of the invention.

FIGS. **106**A-**106**E illustrate various embodiments of networks according to various embodiments of the invention.

FIGS. **107**A-**107**D illustrate various cellular networks according to various embodiments of the invention.

FIGS. **108**A-**108**D illustrate various network control-related aspects of various embodiments of the invention.

FIGS. **109**A and **109**B illustrate relay methods according to various embodiments of the invention.

FIGS. **110**A and **110**B illustrate transceiver processing and routing techniques according to various embodiments of the invention.

FIG. **111**A illustrates a method of receiving, processing, and re-transmitting signals.

FIG. **111**B illustrates a system adapted to receive, process, and re-transmit signals according to the method outlined in FIG. **111**A.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The description of the preferred embodiments assumes that the reader has a familiarity with CI described in the following publications, which are incorporated by reference:

B. Natarajan, C. R. Nassar, S. Shattil, M. Michelini, "Application of interferometry to MC-CDMA", accepted for publication in IEEE Transactions on Vehicular Technology.

C. R Nassar, B. Natarajan, and S. Shattil, "Introduction of carrier interference to spread spectrum multiple access," IEEE Emerging Technologies Symposium, Dallas, Tex., 12-13 Apr. 1999. B. Natarajan and C. R. Nassar, "Introducing novel FDD

FDM in MC-CDMA to enhance performance," IEEE Radio and Wireless Conference, Denver, Colo., Sep. 10-13, 2000, pp. 29-32.

Z. Wu, C. R. Nassar, A. Alagar, and S. Shattil, "Wireless communication system architecture and physical layer design for airport surface management," 2000 IEEE Vehicular Technology Conference, Boston, Mass., Sep. 24-28, 2000, pp. 1950-1955.

S. Shattil, A. Alagar, Z. Wu and C. R. Nassar, "Wireless communication system design for airport surface management—Part I: Airport ramp measurements at 5.8 GHz," 2000 IEEE International Conference on Communications, Jun. 18-22, 2000, New Orleans, pp. 1552-1556.

B. Natarajan, C. R. Nassar, and S. Shattil, "Carrier Interferometry TDMA for future generation wireless—Part I: Performance," accepted for publication in IEEE Communications Letters.

Z. Wu, C. R. Nassar, and S. Shattil, "Capacity enhanced DS-CDMA via carrier interferometry chip shaping," IEEE 3G Wireless Symposium, May 30-Jun. 2, 2001, San Francisco, Calif.

Z. Wu, C. R. Nassar, and S. Shattil, "Frequency diversity performance enhancement in DS-CDMA via carrier interference pulse shaping," The 13th Annual International Conference on Wireless Communications, Calgary, Alberta, Canada, July 7-10, 2001.

C. R. Nassar and Z. Wu, "High performance broadband DS-CDMA via carrier interferometry chip shaping," 2000 International Symposium on Advanced Radio Technologies, Boulder, Colo., Sep. 6-8, 2000, proceeding available online at http://ntai.its.bldrdoc.gov/meetings/art/index-.html.

Z. Wu and C. R. Nassar, "MMSE frequency combining for CI/DS-CDMA," IEEE Radio and Wireless Conference, Denver, Colo., Sep. 10-13, 2000, pp. 103-106.

D. Wiegand, C. R. Nassar, and S. Shattil, "High Performance OFDM for next generation wireless via the application of carrier interferometry," IEEE 3G Wireless Symposium, May 30-Jun. 2, 2001, San Francisco, Calif.

B. Natarajan, C. R. Nassar, and S. Shattil, "Exploiting frequency diversity in TDMA through carrier interferometry," Wireless 2000: The 12th Annual International Conference on Wireless Communications, Calgary, Alberta, Canada, Jul. 10-12, 2000, pp. 469-476.

B. Natarajan, C. R. Nassar, and S. Shattil, "Throughput enhancement in TDMA through carrier interferometry pulse shaping," 2000 IEEE Vehicular Technology Conference, Boston, Mass., Sep. 24-28, 2000, pp. 1799-1803.

S. A. Zekevat, C. R. Nassar, and S. Shattil, "Smart antenna spatial sweeping for combined directionality and transmit diversity," accepted for publication in Journal of Communication Networks: Special Issue on Adaptive Antennas for Wireless Communications.

S. A. Zekevat, C. R. Nassar, and S. Shattil, "Combined directionality and transmit diversity via smart antenna spatial sweeping," 38th Annual Allerton Conference on Communications, Control, and Computing, Champaign-Urbana, Ill., Oct. 4-6, 2000.

S. Shattil and C. R. Nassar, "Array Control Systems For Multicarrier Protocols Using a Frequency-Shifted Feedback Cavity" IEEE Radio and Wireless Conference, Denver, Colo., Aug. 1-4, 1999.

C. R. Nassar, et. al., *MultiCarrier Technologies for Next Generation Multiple Access*, Kluwer Academic Publishers: 2001.

Applications of CI, array processing, spatial interferometry, and related systems and methods are cited in the following patents and patent applications, which are hereby incorporated by reference:

U.S. Pat. No. 5,955,992
U.S. Pat. No. 6,008,760
U.S. Pat. No. 6,211,671
U.S. Pat. No. 6,331,837
PCT Appl. No. PCT/US99/02838
PCT Appl. No. PCT/US00/18113
U.S. patent application Ser. No. 09/347,182
U.S. patent application Ser. No. 09/472,300
U.S. patent application Ser. No. 09/433,196
U.S. patent application Ser. No. 09/393,431
U.S. patent application Ser. No. 09/718,851
U.S. patent application Ser. No. 09/703,202
U.S. patent application Ser. No. 10/034,386
U.S. patent application Ser. No. 10/078,774
U.S. Provisional Pat. Appl. No. 60/163,141
U.S. Provisional Pat. Appl. No. 60/219,482
U.S. provisional Pat. Appl. No. 60/259,433
U.S. provisional Pat. Appl. No. 60/286,850

Definitions

Various terms used in the descriptions of CI methods and systems are generally described in this section. The descriptions in this section are provided for illustrative purposes only, and is not limiting. The meaning of these terms will be apparent to persons skilled in the relevant art(s) based on the entirety of the teachings provided herein. These terms may be discussed throughout the specification and the cited references with additional detail.

The term carrier signal, or carrier, when used herein, refers to at least one electromagnetic wave having at least one characteristic that may be varied by modulation. Carriers may be referred to as subcarriers. Other wave phenomena, such as acoustic waves, may be used as carriers. Carrier signals may include any type of periodic signal. Carrier signals may include sinusoids, square waves, triangle waves, wavelets, and/or arbitrary waveforms. A carrier signal is capable of carrying information via modulation. A carrier signal may be modulated or unmodulated. Multicarrier signals may include multi-frequency signals, multi-spatial signals, multi-directional signals, multi-polarization signals, multiple-code signals, multiple sub-space signals, multi-phase-space signals, time-domain (discreet-time) signals, and/or any other set of electromagnetic signals having different orthogonal or quasi-orthogonal values of at least one diversity parameter. A code sequence can be regarded as a carrier signal.

Channel compensation describes signal processing performed on at least one received signal according to channel fluctuations. Channel compensation may include blind adaptive techniques. Alternatively, channel compensation may employ at least one pilot or training signal to probe the channel. Known signals can be used to compensate for various multipath effects (such as fading and/or inter-symbol interference), adapt to non-linear channel distortions (such as chromatic dispersion, four-wave mixing, mode dispersion, and other guided-wave distortions), and/or remove multi-user interference and/or jamming signals. Channel compensation may employ a combination of adaptive and reference-signal processing. Channel compensation may include adaptive channel equalization. Preferably, channel compensation in a CI and/or array implementation employs some type of combining.

Channel estimation describes any combination of blind adaptive techniques and reference-signal processing to determine signal distortion resulting from the effects of at least one communication channel. In one example, a pilot symbol is transmitted periodically from a remote transmitter. A local receiver exploits the known transmission time, frequency, polarization, and/or any other diversity-parameter value of at least one pilot symbol to process the transmitted pilot symbol and estimate the distortion caused by the channel environment. On the basis of an estimated value, distortion in the received data symbols is compensated.

A combiner, as used herein, describes any system, device, and/or algorithm adapted to combine a plurality of signals or symbol values. A combiner may combine multiple carriers

or signal values to generate a superposition signal. A combiner may provide weights to carriers or signal values to generate one or more superposition signals having predetermined characteristics, such as time domain, frequency domain, spatial domain, sub-space domain, and/or other physical characteristics. A combiner may compensate for noise, interference, and/or distortion.

Combining often involves generating weights based on channel estimates. The weights may be adapted relative to some performance measurement, such as probability of error, bit error rate (BER), signal-to-noise ratio (SNR), signal-to-noise-plus-interference ratio (SNIR), and/or any other appropriate signal-quality parameter. Performance measurements may include any combination of instantaneous and averaged performance measurements. Averaging may be performed over one or more diversity parameters. A combiner may perform combining in more than one diversity-parameter space. For example, MMSE combining may be performed in the frequency domain to generate a plurality of combined signals that may be processed via equal-gain combining in the time domain. Other types of combining, as well as combining in different dimensions may be performed.

A correlator or matched-filter receiver is any device, system, or algorithm, or combination thereof adapted to correlate at least one input signal with at least one reference signal. A correlator or matched-filter receiver generates at least one signal indicative of the degree of correlation between at least one input signal and at least one reference. In one set of embodiments, the degree of correlation is evaluated using some signal-processing technique (e.g., shift and sum, weight and sum, sample and sum) that depends on the reference. In another set of embodiments, the correlator multiplies (or performs some equivalent operation) reference and input signals and sums the products over a predetermined time interval. Various techniques are available for correlating a received signal with a reference sequence, including those using surface acoustic wave (SAW) correlators, tapped delay line (TDL) correlators, serial correlators, and others. A non-coherent digital matched filter may be employed, such as a matched filter having four real filter channels to perform four-phase quantization in the complex plane. A matched-filter receiver may separate the received signal into real and imaginary parts and correlate both real and imaginary parts for a plurality of chip sequences (e.g., in phase and quadrature phase chip sequences). A matched-filter receiver may combine the real and imaginary signals into a unified signal data stream. For each received symbol, the receiver may determine which of a plurality of phase sectors in which the phase angle lies.

A decoder, as used herein, describes any system, device, or algorithm capable of decoding an encoded information (e.g., data) signal. A decoder typically decodes an encoded signal with respect to one or more reference signals (e.g., codes, decode sequences, code keys, etc.). Decoding may take the form of a correlation process (as defined mathematically), matched filtering, or any kind of processing (e.g., complementary processing) that extracts at least one desired information signal from the coded signal. Correlation, as used herein without specifically conveying the mathematical process of correlation, is meant to convey any process of decoding a signal. In a preferred embodiment, decoding involves summing samples collected over a predetermined interval. In another embodiment, collected samples are phase shifted with respect to at least one code before being summed. In some multicarrier systems, it is impractical to perform matched filtering or the mathematical correlation process. Rather, data symbols are obtained from the output bins of a Fourier transform process. Similarly, other types of transforms or inverse transforms may be performed to decode signals.

A guard interval is a redundant signal period designed to reduce inter-symbol interference by cyclically repeating the signal waveform of the effective symbol period. The effective symbol length, the guard interval length and the number of carrier waves may be determined on the basis of either a fixed-reception mode or a mobile-reception mode. The optimal values of the guard interval length, the effective symbol length, and other transmission parameters may vary depending on the mode of reception.

An information signal, as used herein, describes one or more signals that convey some form of useful information via magnitude, phase, frequency, polarization, mode, direction, and/or some signal property derived therefrom. CI-based information signals may include any type of communication signal, such as, but not limited to voice, data, and text. Information signals may include any of various types of remote-sensing signals, such as radar signals, Lidar signals, spectroscopy signals of various types (e.g., absorption, scatter, luminescence, resonant, emission, harmonic, intermodulation, etc.), probing signals, and imaging signals (e.g., X-ray, gamma-ray, ultrasound, seismic survey, acoustic, sonar, optical, pulse radio, spread spectrum, etc.). Any information signal may be considered to be a CI-based signal if it is processed via CI signal-processing techniques. Thus, a received non-CI signal may be converted into a CI signal by decomposing the received signal into orthogonal sub-carrier components.

Interfering signals, as used herein, describes any plurality of signals (typically data symbols) impressed upon at least one similar diversity-parameter value. For example, two or more data symbols that are impressed on the same frequency and time interval of a signal received by a receiver are interfering signals. Although, the receiver may be a multi-element receiver that can spatially discriminate between (or separate) the received data symbols, the data symbols are considered to be interfering by virtue of the interferometry processing needed to separate them.

The term modulation, as used herein, refers to at least one method of impressing some signal (such as an information signal, a code signal, and/or a sub-carrier) onto an electromagnetic signal. Modulation describes the adjustment of one or more physical signal characteristics with respect to an information signal. Signals, such as analog and/or digital information signals, may be impressed onto one or more carrier signals via any combination of modulation techniques, including, but not limited to, amplitude modulation, phase modulation, frequency modulation, pulse modulation, and/or polarization modulation. Pulse modulation (such as CI-pulse modulation) may include pulse-amplitude modulation, pulse-code modulation, pulse-frequency modulation, pulse-position modulation, and/or pulse-width modulation. CI methods are commonly combined with modulation, such as Pulse Amplitude Modulation (PAM), Frequency Shift Keying (FSK), Phase Shift Keying (PSK), and Quadrature Amplitude Modulation (QAM). Coded modulation, such as trellis-code modulation, may be performed. Data symbols may be modulated onto a code sequence, such as a multiple-access code, a spreading code, an encryption code, a channel code, etc. A code sequence may include digital and/or analog signals. Examples of code sequences include direct-sequence codes, MC-CDMA codes, CI codes, CI/DS-CDMA codes, frequency-hopping codes, chirp codes, coherence-multiplexing codes, sub-channel codes, and code length

division multiplexing codes. Various types of modulation can include the formation of code-chip values, continuous-code values, and/or code-chip sequences based on data-symbol values. Data symbols may be input to a code-generation process.

A multi-element receiver describes any receiver adapted to produce multiple separate signals relative to different diversity-parameter values. Each element of a multi-element receiver preferably has a different responsiveness relative to at least one diversity parameter value. For example, spatially separated receiver elements typically have different amplitude and phase responses to received signals by virtue of their physical separation. This is particularly true when received signals are affected by a multipath environment. A multi-element receiver may include a single reflector with multiple feeds.

A multi-element receiver may have a single interface to a communication channel but provide different responsiveness to signals having different physical characteristics. A receiver having a filter bank or equivalent frequency-selective system can be regarded as a multi-element receiver. A receiver that processes a plurality of received coded signals is a multi-element receiver. A multi-element receiver may have selective responsiveness relative to different values of one or more diversity parameters, such as, but not limited to, phase, mode, polarization, polarization-rotation rate, phase-rotation rate, frequency rate-of-change, amplitude rate-of-change, angle of arrival, angle-of-arrival rate-of-change, spatial gain distribution, etc.

A multi-element transmitter, as recited herein, describes any transmitter adapted to couple multiple interfering signals into a communication channel. Interfering signals are signals having one or more similar or overlapping diversity-parameter values or that result in having one or more similar or overlapping diversity-parameter values due to propagation in a communication channel. A multi-element transmitter may include a single data source in which different data symbols or multiple-access channels are transmitted on overlapping diversity-parameter values.

A multi-element transmitter may include multiple data sources that are each transmitted by a separate transmitter unit. A multi-element transmitter may include a multi-frequency transmitter, a multi-code transmitter, a multi-polarization transmitter, a multi-directional transmitter, etc. Overlapping diversity parameters may include at least one of mode, frequency, phase, amplitude, polarization, polarization-rotation rate, phase-rotation rate, angle of arrival, spatial location, spatial gain distribution, beam-pattern sweep rate, code, etc.

Orthogonal overlapping carriers describe two or more carriers that are modulated such that their spectra overlap. If the frequency separation between any two adjacent frequencies is made equal to the reciprocal of the effective symbol period for multicarrier transmission, the nil point of the frequency spectrum of each modulated wave coincides with the center frequency of the adjacent modulated waves. CI signals can include orthogonal, overlapping signals. In some applications, CI carriers may be orthogonal, whereas superpositions of the CI carriers may include pseudo-orthogonal time-domain waveforms.

A receiver, as used herein, includes any system, device, or process that employs any combination of detection and estimation. Detection is the task of determining if a predetermined signal set is present in an observation. Estimation is the task of obtaining or determining values of one or more signal parameters. A receiver may perform various signal-processing operations, including, but not limited to, filtering, channel selection automatic gain control, timing recovery, carrier acquisition, carrier recovery, bandwidth adjustment, sample-rate adjustment, matched filtering, soft-decision quantization, amplification, decoding, DC signal removal, equalization, combining, spectral shaping, noise-bandwidth control, spectral translation, amplifier linearization, de-interleaving, in-phase/quadrature-phase gain and phase balancing, etc.

A sub-space processor, as described herein, includes any system, device, or algorithm, or combination thereof capable of separating interfering signals. Each separated interfering signal is said to occupy a signal sub-space. The type of signal sub-space corresponds to the type of processing and/or the diversity parameter(s) that define the interference. For example, a directional signal sub-space may correspond to phased array processing. A spatial signal sub-space may be defined as a subspace generated by spatial interferometry multiplexing. A phase sub-space (or phase space) can correspond to CI processing. Signal sub-spaces may be defined by one or more diversity parameters. Subspaces may even have their own subspaces.

Synchronization describes one or more time-domain-related techniques by which various timing aspects of signal processing are controlled. Successful CI reception requires that a receiver maintain the correct symbol synchronization and sampling frequency. Symbol synchronization means that the receiver knows at which point of time each symbol begins and times the symbol detection correspondingly. Sampling frequency refers to the frequency at which an A/D converter in the receiver takes samples from a received analog oscillation in order to convert the signal into digital form.

Introduction to Carrier Interferometry

Various aspects of the present invention are based on CI. Other aspects of the invention are particularly applicable to CI methods and systems. There are too many variations, permutations, and specific implementations of CI to describe in this introduction. Accordingly, the descriptions and examples of CI described herein are not intended to limit the scope of how CI is defined, but rather to illustrate a few of the many ways that the present invention may be implemented. Descriptions of CI are also intended to clarify some of the aspects and embodiments of the present invention.

Inter-symbol interference occurs when a reflected signal travels a distance sufficiently greater than the distance traversed by a line-of-sight signal so as to cause a delay greater than the duration of a data symbol. CI avoids inter-symbol interference by transmitting data symbols on narrowband carriers. Multipath fading occurs when a narrowband signal traverses two paths having a half-cycle phase difference. CI avoids the problem of multipath fading by transmitting each data symbol on multiple carriers that are adequately separated with respect to frequency (or some other diversity parameter). Redundant modulation typically reduces bandwidth efficiency. CI avoids the problem of reduced bandwidth efficiency by modulating up to 2N data symbols on each of N carriers. Increased interference on one or more carriers typically increases probability of error. CI avoids the problem of increased interference and probability of error by exploiting interferometry to orthogonalize data symbols modulated on the same carriers. Thus, CI achieves higher throughput with better signal quality than any other multiple-access protocol.

FIG. **1**A illustrates a basic form of CI in which a plurality of CI carrier sets **105**A, **105**B, and **105**C each have phase fronts aligned at a specific time t_1, t_2, and t_3, respectively. A plurality of superposition signals **110**A, **110**B, and **110**C

result from a summation of each carrier set **105**A, **105**B, and **105**C, respectively. The superposition signal **110**A illustrates a pulse envelope centered at time t_1. All of the carriers **105**A are in-phase at time t_1 and thus, combine constructively. The superposition signal **110**A has a maximum magnitude at time t_1. At other times (e.g., times t_2 and t_3), the carriers in carrier set **105**A combine destructively, resulting in low or undetectable signal levels.

In CI, the individual signal components **105**A, **105**B, and **105**C contributing to a CI pulse **110**A, **110**B, and **110**C, respectively, or information symbol s_n have an extended duration T_s relative to the pulse width T_{pulse}. The extended symbol duration T_s (i.e., the duration of component waveforms corresponding to a symbol s_n) reduces spectral sidelobes associated with the transmitted information symbol s_n. The extended waveform shape can be overlapped with extended waveforms associated with other symbols $s_{n'}$ ($n' \neq n$). Naturally, interference will occur between the waveforms associated with different data symbols. However, CI coding can be employed to provide orthogonality (or quasi-orthogonality) between the composite waveforms (i.e., the data symbols s_n).

Although multicarrier-based CI signals (such as signals **110**A, **110**B, and **110**C) can resemble sinc-shaped pulses, which are orthogonalized by time-domain pulse positioning, it is important to note that multicarrier-based CI signals are composed of multicarrier (e.g., multi-frequency) components and are processed (e.g., generated and/or decomposed) in the frequency domain.

The signal **110**A results from an addition of N carriers that have a uniform frequency separation f_s. FIG. **1**A illustrates a simple case of no tapered windowing of the carrier amplitudes. The CI carriers are uniformly spaced in frequency $f_n = f_o + nf_s$, where f_o is some zero or non-zero offset frequency, f_s is a non-zero shift frequency, and n is some integer or set of integers. A superposition CI signal, such as signal **110**A, is expressed by:

$$e(t) = \sum_{n=1}^{N} e^{j[(\omega_C + n\omega_s)t + n\Delta\phi]},$$

which has a magnitude of:

$$|e(t)| = \left| \frac{\sin(N(\omega_s t + \Delta\phi)/2)}{\sin((\omega_s t + \Delta\phi)/2)} \right|.$$

The CI signals are periodic with period $1/f_s$ for an odd number of carriers N and with period $2/f_s$ for an even number of carriers N. The main lobe has a duration $2/Nf_s$ and each of the N−2 side lobes has a duration $1/Nf_s$. The amplitude of the lth side lobe with respect to the main lobe amplitude is:

$$A(l) = \frac{1}{N \sin(\pi(l + 1/2)/N)}$$

Applying a phase shift of $n\Delta\phi_k$ to each nth carrier shifts the CI envelope in time by $\Delta t = \Delta\phi_k / 2\pi f_s$. Therefore, N signals can be positioned orthogonally in time. The phase shifts can provide necessary phase relationships to create the desired timing of the information signal received by at least one receiver (not shown).

The cross correlation between users is:

$$R_{cc}(\tau) = \frac{1}{2f_s} \frac{\sin(N2\pi f_s \tau/2)}{\sin(2\pi f_s \tau/2)} \cos((N-1)2\pi f_s \tau/2),$$

where τ is the time shift between envelopes. Zeros occur at: k/Nf_s, k=1, 2, . . . , N−1 and at $(2k-1)/2(N-1)f_s$, k=1, 2, . . . , N−1. CI can support N orthogonal users (or channels). If additional users or signals need to be accommodated, CI provides N−1 additional positions to place signals.

A CI signal centered at time τ is orthogonal to the CI signal centered at time t_1 whenever the difference between τ and t_1 is $\Delta t = k/Nf_s$, k=1, 2, . . . , N−1. This enables CI waveforms to represent information symbols located sequentially in time without creating inter-symbol interference. The superposition signal **110**D shown in FIG. **1**B represents a sum of the orthogonally positioned superposition signals **110**A, **110**B, and **110**C.

An offset in the time domain corresponds to linearly increasing phase offsets in the frequency domain. A CI signal with a time offset $\tau = k/Nf_s$ is equivalent to a CI carrier set with carriers 1 to N having phase offsets:

$$\{\phi_1, \phi_2, \ldots, \phi_N\} = \{0, 2\pi k/N, \ldots, (N-1)\cdot 2\pi/N\}.$$

Orthogonality between CI signals can be understood as an appropriate time separation $\tau \in \{k/f_s, k=1, 2, \ldots, N-1\}$ between superposition signals or as carriers of each carrier set coded with a different polyphase spreading sequence:

$$f(\phi) = \{e^{j\theta 1}, e^{j\theta 2}, \ldots e^{j\theta N}\} = \{e^{j0}, e^{j2\pi k/N}, \ldots, e^{j(N-1)\cdot 2\pi k/N}\}$$

with respect to values of k=0, 1, . . . , N−1.

A set of quasi-orthogonal signals can be determined from non-orthogonal time offsets that minimize the mean-squared value of the interference between the quasi-orthogonal signals. This criteria is satisfied by multiples of a time-offset value $\Delta t = 1/(2Nf_s)$. FIG. **1**C shows a first set of N orthogonal signals **110**D represented in time by:

$$\{t_1, t_2, \ldots, t_{N-1}\} = \{1/f_s, 2/f_s, \ldots, (N-1)/f_s\}.$$

A second set of N orthogonal signals **110**D' is represented in time by:

$$\{t'_1, t'_2, \ldots, t'_{N-1}\} = 1/(2Nf_s) + \{1/f_s, 2/f_s, \ldots, (N-1)/f_s\}.$$

The first set of signals **110**D is quasi-orthogonal to the second set **110**D' and results in a minimal amount of interference, as shown in FIG. **1**D.

This result can also be expressed in terms of carrier phase offsets using the equivalence between shifts in the time domain and phase offsets in the frequency domain. A first set of N orthogonal signals is represented in phase by N complex spreading codes:

$$f_1(\phi) = \{e^{j\phi 1}, e^{j\phi 2}, \ldots, e^{j\phi N}\} = \{e^{j0}, e^{j2\pi k/N}, \ldots, e^{j(N-1)\cdot 2\pi k/N}\}$$

A second set of N orthogonal signals is represented in phase by N complex spreading codes:

$$f_2(\phi) = \{e^{j\phi' 1}, e^{j\phi' 2}, \ldots, e^{j\phi' N}\} = \{e^{j(0+\Delta\phi)}, e^{j(2\pi k/N+\Delta\phi)}, \ldots, e^{j((N-1)\cdot 2+\Delta\phi)}\}$$

where $\Delta\phi = \pi/N$.

The superposition signal **110**D in FIG. **1**B can be thought of as a superposition of complex-weighted carriers in a carrier set **105**D or a sum of the superposition signals **110**A, **110**B, and **110**C. The carrier set **105**D represents a sum of

the carrier sets **105**A, **105**B, and **105**C. The complex amplitudes of carrier set **105**D can be characterized by a complex-weight vector $w=[w_1, w_2, \ldots, V\ w_]$. Each value w_n of the weight vector w corresponds to a particular carrier frequency f_n. The values w_n can be derived from a complex addition of carriers in the carrier sets **105**A, **105**B, and **105**C. The values w_n can be derived from summing complex numbers representing the magnitude and phase of each carrier in the carrier sets **105**A, **105**B, and **105**C.

CI signals demonstrate both excellent frequency resolution and excellent time resolution. A CI signal is composed of multiple narrowband carriers that allow it to be resolved into its frequency components. When observed in the time domain, a basic CI signal is very narrow, enabling it to be easily separated from other CI signals and to resolve the channel's multipath profiles.

Because the period and width of the pulse envelope depends on the amplitudes, relative phases, and frequency separation of the CI carriers, the frequency of each carrier may be changed without affecting the pulse envelope as long as the amplitudes, relative phases, and frequency separation are preserved. Thus, frequency hopping and frequency shifting of the carriers does not affect the temporal characteristics of the superposition signal, such as superposition signal **110**A. Tapering the amplitude distribution of the CI carriers broadens the main-lobe width and reduces the amplitude of the side lobes.

A CI signal has a number of carrier signals that may each have a bandwidth that is less than the coherence bandwidth of the communication channel. The coherence bandwidth is the bandwidth limit in which correlated fading occurs. The total bandwidth of the CI signal preferably exceeds the coherence bandwidth.

CI carriers corresponding to any particular user, channel, or data symbol may be spaced in frequency by large amounts to achieve a large system bandwidth relative to the coherence bandwidth. In this case, CI makes use of frequency to achieve uncorrelated fading. However, any diversity parameter or combination of diversity parameters may be used to achieve uncorrelated fading over the system bandwidth, or even between individual carriers.

The system bandwidth of a group of CI carriers may be selected relative to the coherence bandwidth of one or more subchannels, such as spatial subchannels. Carriers that are closely spaced in frequency may have uncorrelated fading if they are transmitted from different locations or have different degrees of directivity. CI carriers transmitted from different locations may have different fades over each spatial sub-channel and therefore, can benefit from diversity combining at a receiver (not shown).

Phase shifts applied to an nth carrier to separate a kth channel from adjacent channels are given by:

$$\phi_{kn}=\pi kn f_s(\Delta t)+\phi^o_{kn}=\pi kn/N+\phi^o_{kn}$$

where ϕ^o_{kn} is an initial phase-offset corresponding to the nth carrier and the kth channel. The values of Δt depend on whether the channel spacing is orthogonal or quasi-orthogonal.

Although FIG. **1**A and FIG. **1**B illustrate an in-phase superposition of carrier signals, this example can be extended to other superpositions of CI. For example, the time offset Δt (and the corresponding carrier phase shifts ϕ_{kn}) for adjacent channels may be applied to CI implementations that do not have in-phase superpositions. The time offsets Δt (and thus, the phase shifts ϕ_{kn}) derived in this case are also relevant to CI implementations that process the received carriers separately. When each carrier is processed separately, phase-offset coding (in addition to the phase offsets ϕ_{kn} used to separate channels) may be used to minimize the peak of the superposition signal.

The carrier sets **105**A, **105**B, and **105**C have phase offsets corresponding to a pulse-width duration. However, any type of orthogonal (e.g., non-overlapping) or quasi-orthogonal (e.g., overlapping) spacing may be provided. Carrier sets having quasi-orthogonal (or non-orthogonal) spacing may be processed with multi-user (or multi-channel) detection techniques or with any other type of interference suppression.

FIG. **1**A and FIG. **1**B illustrate several levels of signal decomposition that reduce a complex time-domain signal into simple components. The time-domain pulses may be scaled and positioned to produce a predetermined time-domain signal indicative of an information signal, coding, and at least one transmission protocol. Multiple frequency components may be weighted to produce an information signal having predetermined time-domain characteristics. Similarly, multiple frequency components that comprise the pulses may be selected and weighted to impart predetermined characteristics to the pulses. The scale of the components selected for signal processing can be selected to provide a desired granularity for the information architecture.

Modulation of the pulses, the carriers, or both may be performed over the duration of the signals shown in FIG. **1**A and FIG. **1**B. Carrier modulation may be performed over a pulse-repetition period, a pulse duration, or any multiple or fraction of either.

FIG. **2**A and FIG. **2**B illustrate how a constant weight applied to each of a plurality of carrier signals (e.g., carrier frequencies or time-offset pulses) generates a periodic binary code (such as a DS-CDMA code) sequence. In this case, each CI pulse is represented by a pulse envelope. A binary code chip $\beta_n(k)$ applied to a pulse envelope is represented by an upright pulse (corresponding to $\beta_n(k)=+1$) or an inverted pulse (corresponding to $\beta_n(k)=-1$). CI pulses may include an effective carrier signal bounded by a pulse envelope, as shown in FIGS. **1**A, **1**B, **1**C, and **1**D. Polyphase code chips may be represented by phase shifts of the effective carrier. Code chips may be impressed onto carrier signals (e.g., carrier frequencies or time-offset pulses) via any combination of modulation techniques, such as amplitude modulation, phase modulation, frequency modulation, pulse modulation, polarization modulation, etc. The code sequence may be modulated with information symbols over a code (pulse) period, or the information signal may be applied to code weights applied to the carriers during a code interval. Information symbols may include M-ary modulated symbols.

Information modulation applied to each group of carriers may include a relative time offset corresponding to a constant phase offset ϕ^o_{kn}. Modulation may include any modulation scheme including, but not limited to, pulse-amplitude modulation, amplitude modulation including continuous phase modulation (CPM) and phase shift key, phase modulation including continuous and shift key, frequency modulation including continuous and shift key, time-offset modulation, and/or any differential modulation techniques. Modulated signals may include guard bands, cyclic prefixes, codes, and the like, which are well known in the art.

Known CPM signals include several variations; these include minimum shift keying (MSK) and its variations, e.g., Gaussian pre-filtered MSK (GMSK), superposed quadrature amplitude modulation (SQAM), and staggered quadrature offset raised cosine modulation. Explanations of

various types of CPM techniques may be found in the following references: Frank Amoroso and James A. Kivett, "Simplified MSK Signaling Technique," IEEE Transactions on Communications, April 1977, pp. 433-441; Mark C. Austin and Ming U. Chang, "Quadrature Overlapped Raised-Cosine Modulation," IEEE Transactions on Communications, Vol. Com-29, No. 3, March 1981, pp. 237-249; Kazuaki Murota and Kenkichi Hirade, "GMSK Modulation for Digital Mobile Radio Telephony," IEEE Transactions on Communications, Vol. Com-29, No. 7, July 1981, pp. 1044-1050; and J. S. Seo and K. Feher, "SQAM: A New Superposed QAM Modem Technique," IEEE Transactions on Communications, Vol. Com-33, March 1985, pp. 296-300. The invention may utilize MSK signals. However, the use of other variants of MSK and other CPM signals are within the scope and spirit of the invention.

Various types of spread spectrum may be employed on each CI carrier. For example, direct-sequence coding, coherence multiplexing, code-length division multiple access, frequency-modulation sweep, and/or other spread-spectrum techniques may be provided to each carrier. Spread-spectrum coding may be provided to prior to or following modulation.

FIG. **3** shows a plurality N of carrier signals that are redundantly modulated with a stream of data symbols $s_k(t)$ associated with a kth channel. Each of the carriers may have a phase: $\phi_{kn}=\phi_{kn}(t)+\phi^o_{kn}$, where $\phi_{kn}(t)$ denotes a time-dependent phase and ϕ^o_{kn} denotes a constant-value initial phase. The time-dependent phase term $\phi_{kn}(t)$ can represent the relative phase variation between a plurality of carrier signals resulting from the carrier signals having different frequencies. The time-dependent phase term $\phi_{kn}(t)$ may include an impressed variation or coding to effect one or more benefits, such as reduced peak power of the superposition signal, enhanced security, improved diversity, and additional multiplexing/demultiplexing capabilities. The constant-valued terms may include zero and/or non-zero values. The terms ϕ^o_{kn} may be selected to provide operational benefits, such as reduced peak power of the superposition signal, coding, and enhanced channelization.

The terms ϕ_{kn} may be defined as parts of a code $\Phi_k=\Phi(\phi,t,k,n)$ that is a function of one or more elements of a set including phase ϕ, time t, channel (or user) k, and carrier n. Thus, a redundantly modulated data stream $s_k(t)$ can be represented as having been acted upon by the code $\Phi(\phi,t,k,n)$. A received signal may include a plurality of data streams, each acted upon by various codes $\Phi(\phi,t,k,n)$. A received signal can be defined as:

$$R(t)=\sum_{k=k'}^{k''}\Phi_k s_k(t).$$

One possible method for processing a coded data stream includes providing inverse coding to the received signal in order to decode at least one desired data stream:

$$\hat{s}_k(t)=\Phi_n^{-1}R(t).$$

Additional processing may be performed including, but not limited to, distortion compensation, multi-user detection, interference cancellation, filtering, sampling, and/or additional decoding.

FIG. **4**A illustrates different phases and time intervals applied to one set of carrier frequencies to distinguish a kth channel from at least one other channel. The set of carriers includes a plurality N of carrier frequencies that are redundantly modulated with a stream of data symbols $s_k(t)$ associated with the kth channel. However, each carrier is modulated in at least one of a plurality of time intervals, and at least some of the symbols $s_k(t)$ of the kth data stream are spread across multiple time intervals. This provides both frequency diversity and time diversity to the kth channel.

FIG. **4**B represents a plurality of data symbols $s_1(t)$, $s_2(t)$, and $s_3(t)$ that are each modulated onto the same carrier frequencies within the same time interval. Unlike conventional OFDM, which transmits one data bit per frequency channel per time slot, CI provides orthogonality to multiple data symbols sharing the same frequency channel and time slot. OFDM merely acts as a group of single-carrier channels, whereas in CI, the individual carriers work together to convey data symbols. Each of the CI carriers having an nth frequency f_n has a phase:

$$\phi_{kn}=\phi_{kn}(t)+\phi^o_{kn},$$

where $\phi_{kn}(t)$ denotes a time-dependent phase and ϕ^o_{kn} denotes a constant-value initial phase. In this case there are three channels, so k has values of 1, 2, and 3.

An nth carrier frequency of a kth channel may have a time offset t_{kn} where:

$$t_{kn}=t_{kn}(t)+t^o_{kn}.$$

The term $t_{kn}(t)$ denotes a time-varying time offset (or interval start time) and t^o_{kn} denotes a constant-value initial time offset. The time-varying term $t_{kn}(t)$ may represent a plurality of time intervals that are uniformly spaced (e.g., $t_{kn}(t)=m\Delta t_{kn}$, where m=0, 1, 2, . . . , and Δt_{kn} is some constant time interval) or non-uniformly spaced. A kth channel may be provided with a phase code Φ_k and/or a time code T_k wherein phase values ϕ_{kn} and/or time values t_{kn} are predetermined or adapted with respect to at least one performance objective, such as reducing peak power, improving a signal-to-interference plus noise ratio, enhancing diversity, providing security, reducing a BER, etc.

FIG. **5** illustrates a plurality of time-offset carrier signals having different initial time offsets t^o_{kn}. Data streams (or any other type of information signal) may be redundantly modulated onto the time-offset carrier signals, either directly or with respect to some spreading code corresponding to time-offsets, phase-offsets, carrier frequency, phase, or the like. The time intervals may have uniform or non-uniform duration. Each time interval typically has a duration of about a symbol interval. However, the time intervals may have durations that are longer or shorter. The time intervals may overlap, adjoin each other, or they may be separated.

One method for demultiplexing a kth channel from a received signal includes compensating for coded time offsets and/or phase offsets and then processing the signal components separately. Each carrier may be processed separately by a matched filter and decision system. Another method involves processing superpositions of the compensated components. The superpositions may be pre-processed with any well-known detection technique, such as matched filtering, down-conversion, envelope detection, Fourier transform, demodulation, decoding, etc. A preferred method for demultiplexing a kth channel from a received signal includes filtering the components of the coded signal and/or the superposition of the components.

FIG. **6**A illustrates a plurality of carriers corresponding to a plurality M of subchannels each having a plurality N of carriers. The carriers shown are uniformly spaced in frequency f_s. The total bandwidth of the channel is proportional to NMf_s. The bandwidth of a subchannel is related to Nf_s. However, the bandwidth of each subchannel may

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occupy frequency-band portions distributed over a wide bandwidth (e.g., a frequency band approximately equal to NMf_s) or over multiple non-contiguous bands.

FIG. **6**B illustrates a superposition of three subchannels that occupy the same time-domain space. However, the separability of the time-domain signals into their frequency components provides orthogonality to the signals (and the subchannels). FIG. **6**A and FIG. **6**B illustrate how a wide-band signal can be separated into smaller-bandwidth sub-channels that are easier to process in the time domain. The duration of each data symbol in a subchannel is M times the duration that a data symbol would have if its bandwidth occupied the total channel. However, each subchannel can be positioned such that the group of subchannels occupies almost the full bandwidth of the total channel. This enables a group of subchannels to derive substantially the same frequency-diversity benefits of the total channel.

FIG. **7** illustrates how time offsets may be used simultaneously with carrier-defined subchannels. Modulated carriers corresponding to each subchannel may be decoded relative to a time-spreading code and processed separately or combined to produce a superposition signal. The subchannels may employ other types of coding (such as phase coding) as well. Phase decoding, as well as time-offset decoding, and carrier-frequency selection may be performed to separate subchannels and facilitate processing of the data streams modulated on the subchannels.

Subchannels $s_1(t)$, $s_2(t)$, and $s_M(t)$ are shown having carrier components occurring in three different time intervals. An mth communication channel may be determined by an mth code sequence of carrier frequencies and time slots. For example, a symbol value for subchannel $s_1(t)$ is modulated onto the following carrier frequency-time interval pairs: $f_1:t_2$, $f_{M+1}:t_0$, and $f_{(N-1)M+1}:t_1$. More than one subchannel may use the same set of carrier frequencies and time intervals if different phases are provided. Although FIG. **7** shows uniformly spaced frequencies and time slots, non-uniform spacing may be employed.

A subchannel data stream encoded according to one or more of the techniques described in the specification may be processed at a receiver using one or more decoding techniques. A receiver may shift a plurality of its carriers with respect to a decoding sequence corresponding to one or more transmission channels. The decoded signals may be processed separately or combined to create a superposition signal. Alternatively, the receiver may generate a reference signal based on the code(s) of one or more channels and use the reference signal in a matched filter or equivalent receiver system to process the received signals.

A receiver, such as a CI receiver, may include one or more digital systems and/or algorithms, including, but not limited to, A/D converters, down converters, synthesizers, matched filters, filter banks, loop filters for carrier and/or symbol tracking, resampling filters (e.g., variable bandwidth and variable data rate resampling filters), AGC control loops, DC cancellers, demodulators, soft-decision quantizers, decoders, re-encoders, de-scramblers, de-interleavers, etc.

FIG. **8** shows a plurality N of carrier frequencies. A group of subcarriers is associated with each carrier frequency f_n (n=1, . . . , N). Each subcarrier is distinguished by one of a plurality M of phases fin. The subcarriers may be modulated and transmitted by a single transmitter. In this case, multipath effects (which cause frequency-dependent amplitude and phase variations in the carrier frequencies) do not affect the relative phases ϕ_{mn} and relative amplitudes of same-frequency subcarriers in each group of subcarriers transmitted by the single transmitter.

Groups of subcarriers transmitted by other transmitters may experience transmitter-specific multipath effects (such as due to corresponding propagation environments, transmitter-impressed multipath and/or coding, and/or different receiver responses to signals transmitted by different transmitters). Transmitter-specific multipath effects may be exploited by the invention to separate interfering groups of subcarriers. For example, spatial processing, beam forming, interferometry, or any other type of appropriate diversity-parameter processing may be performed to separate signals transmitted by a plurality of transmitters.

In a preferred embodiment of the invention, the carrier frequencies are orthogonal. Thus, the carrier frequencies are separable via various signal-separation techniques, such as filtering and correlation. In another preferred embodiment of the invention, the carrier frequencies are non-orthogonal or quasi-orthogonal. Thus, data symbols modulated onto different non-orthogonal carrier frequencies may be separable using multi-user or multi-channel detection between two or more carrier frequencies.

One embodiment of the invention separates a plurality of data symbols modulated onto interfering subcarriers each having a similar carrier frequency f_n. For example, filter banks or a plurality of matched filters may be used to provide differing proportions of interfering signals to a multi-channel detector (e.g., a weight-and-sum canceller, matrix diagonalizer, or the like). In this case, the different proportions correspond to different carrier phases ϕ_{mn}. Other diversity parameters (as well as diversity parameter combinations) may be employed to enable multiple access within a carrier-frequency channel.

A multi-channel detector separates the interfering signals and thus, enables a system capacity that approaches N·M. This corresponds to a bandwidth efficiency of M symbols/Hz. Spatial processing further enhances system capacity. If K spatial sub-channels are created, system capacity may be increased by a factor of K. If an L-ary differential-modulation scheme is employed, system capacity and bandwidth efficiency may be multiplied by the value L. Maximum system capacity C_s is expressed by:

$$C_s = N \cdot M \cdot K \cdot L$$

and maximum bandwidth efficiency e_{BW} is expressed by:

$$e_{BW} = M \cdot K \cdot L.$$

Diversity may be exploited to provide capacity and/or signal-quality benefits. In some cases, such as in interference-limited spread-spectrum systems, signal quality and system capacity can be improved simultaneously. Since multipath fading may cause certain frequencies and/or spatial locations to be unusable, the maximum system capacity G and bandwidth efficiency e_{BW} may not always be attainable. Redundancy may be employed in one or more diversity spaces to optimize the bit error rate. For example, multiple antennas may be used by the transmitter and/or the receiver to provide spatial redundancy. Similarly, different carrier frequencies may be modulated with the same data symbols.

Redundant modulation may be augmented with coding, such as multiple-access codes used as channel coding to encode data symbols. These codes may include standard binary codes, such as long codes, Gold codes, Hadamard-Walsh codes, etc. The codes may include CI codes or direct-sequence coding derived from any transform operation.

In one embodiment of the invention, the carrier signals shown in FIG. **8** may be redundantly modulated. The different-frequency carriers corresponding to phases ϕ_{11}, ϕ_{12},

and ϕ_{13} may be modulated with a first data symbol. Phases ϕ_{21}, ϕ_{22}, and ϕ_{23} may be modulated with a second data symbol. Phases ϕ_{31}, ϕ_{32}, and ϕ_{33} may be modulated with a third data symbol. This redundancy allows a receiver to select a preferred result from a set of three processes. Thus, fading or interference that substantially degrades one or two of the carrier frequencies does not substantially affect the BER of the received symbols. In one embodiment, the effects of interference and signal distortion at one or more carrier frequencies are distributed substantially evenly to all users such that no user experiences complete debilitation of their channel. In another embodiment, carrier frequencies may be changed to avoid deep fades and/or interference. Carrier-frequency selection and/or adjustment may be performed as a means of power control.

An alternative method for processing the received signals includes correlating the phase-frequency combinations for each data symbol and summing the correlation signals. A data symbol may be modulated (or otherwise impressed) onto a single carrier phase ϕ_{mn} corresponding to an mth phase in an nth frequency. A kth data symbol may be modulated onto a kth set of carrier phases $(\phi_{mn})_k$ corresponding to multiple m phases and multiple n frequencies. One or more of the correlation signals may be weighted with a complex weight, a vector of complex weights, or a complex-weight matrix prior to summing.

Each sub-carrier phase within a carrier frequency may experience interference from at least one other sub-carrier phase. In one case, a kth data symbol (or data channel) is redundantly modulated onto multiple carrier frequencies with respect to a kth group of phase shifts $(\phi_{mn})_k$. Subsequent data symbols are redundantly modulated onto the same set of frequencies. For example, a k'^{th} data symbol (or data channel) is redundantly modulated onto the same carrier frequencies with respect to a different (k'^{th} group) of phase shifts $(\phi_{mn})_{k'}$. The total interference $(I_{k'k})_T$ between the kth data symbol and the k'^{th} data symbol is expressed by:

$$(I_{k'k})_T = \sum_n (I_{k'k})_n$$

where interference between the data symbols is summed over the n carrier frequencies.

Since the interference $(I_{k'k})_n$ depends on the relative phase difference $\Delta\phi_{mn}=\phi_{m'n}-\phi_{mn}$ between the mth and m'^{th} phases for an nth carrier frequency, the phases ϕ_{mn} may be selected such that the sum of the interferences is zero or very small:

$$(I_{k'k})_T = \sum_n (I_{k'k})_n = 0$$

In another embodiment of the invention, the interference terms may be weighted with complex weight values w_{mn} such that the sum of the interferences is zero or very small:

$$(I_{k'k})_T = \sum_n w_{mn}(I_{k'k})_n = 0$$

Each complex weight value w_{mn} may include a single complex value, a vector of complex weights, or a matrix (or higher-order distribution) of complex weights.

In FIG. **8**, a superposition signal S_k corresponds to a kth group of phases $(\phi_{mn})_k$ for a special case in which m=k and the relative phases ϕ_{mn} within each n carrier are associated with incremental translations (in time) of the carrier. Thus, carrier phases ϕ_{k1}, ϕ_{k2}, ON are redundantly modulated with a kth symbol $s_k(t)$. In this case, there are three superposition signals S_1, S_2, and S_3 that are centered at times t_1, t_2, and t_3, respectively.

The phases ϕ_{1n} of the carrier frequencies f_n that correspond to the first symbol $s_1(t)$ produce a maximum (i.e., a superposition peak) at time t_1. Similarly, the second symbol's $s_2(t)$ phase relationships ϕ_{2n} provide for in-phase carriers at time t_2. The third phase relationships ϕ_{3n} provide in-phase constructive combining between carriers at time t_3. In this case, the superposition signals S_1, and S_3 do not overlap and, therefore, are substantially orthogonal in the time domain. Consequently, the phase relationships ϕ_{km} of the corresponding component carriers ensure orthogonality between the redundantly modulated symbols $s_k(t)$.

The relative phase of each carrier corresponding to a kth orthogonal superposition signal S_k is related to an integer multiple of the superposition-signal width:

$$\phi_{mn} = (1/f_sN)2\pi f_n m$$

where $(1/f_sN)$ expresses the width. The term f_s is the frequency separation and N is the number of carrier frequencies. An nth carrier frequency is expressed by f_n.

The time orthogonality of superposition signals (such as the superposition signals S_1 and S_3) demonstrates one class of orthogonality requirements for phase relationships ϕ_{mn}. However, the present invention may use orthogonal phase relationships that result in superposition signals that are not orthogonal in the time domain. For example, phase offsets may be provided to each carrier, such as to reduce the peak-to-average power of each superposition signal. Furthermore, various carrier-frequency and/or carrier-amplitude distributions may be used that support orthogonal or quasi-orthogonal phase spaces, but may not provide orthogonality in the time domain.

The use of pseudo-orthogonal coding is well known in spread spectrum and is equally applicable to CI. FIG. **8** also illustrates one form of pseudo-orthogonal phase coding that is illustrated by pseudo-orthogonal time-domain superpositions S_1, S_2, and S_3 of the carrier signals. The relative phase of each carrier corresponding to a kth superposition signal S_k is related to an integer multiple of half the superposition-signal width:

$$\phi_{mn} = (1/f_sN)2\pi f_n m$$

Pseudo-orthogonal phase relationships employed by the present invention do not necessarily have a quasi-orthogonal corollary in the time domain. For example, phase offsets may be provided to each carrier, such as to reduce the peak-to-average power of the superposition signals. Various carrier-frequency and/or carrier-amplitude distributions may be used that support orthogonal and/or pseudo-orthogonal phase spaces. These distributions may or may not be characterized by pseudo-orthogonality in the time domain.

Several embodiments of the present invention use space-frequency processing at either or both a transmitter and a receiver. This processing substantially eliminates inter-sym-

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bol interference caused by channel correlations across space (antenna correlation) and time (delay spread). This processing may include one form of CI processing, which decomposes a wide-bandwidth, high data rate communication signal into a plurality of small-bandwidth, low data rate channels without changing the time-domain characteristics of the wideband signal. For example, DS-CDMA may be decomposed into component signals at a transmitter and processed using advantageous parallel-processing and/or narrowband-processing techniques. A CI DS-CDMA signal may be received by a receiver and processed in any of several ways. A received CI DS-CDMA signal may be processed as a conventional DS-CDMA signal. A received signal may be processed with respect to its narrowband components in an array-processing operation or the like. A CI receiver may be used to process CI DS-CDMA components and exploit capacity and signal-quality benefits of CI.

FIG. **9**A shows an arrangement of N incrementally spaced-in-frequency carrier signals. This case illustrates one set of N carriers capable of having up to N orthogonal phase spaces wherein each of the phase spaces spans the entire set of carriers. The symbol duration T_s is equal to the inverse of the carrier-frequency spacing f_s. In a first embodiment of a CI architecture, a single user may use all of the available phase spaces. In a second embodiment, a plurality of users may use the same set of carriers but be assigned to different phase spaces.

FIG. **9**B shows an arrangement of N incrementally spaced-in-frequency carrier signals divided into M sets of carrier signals. In this case, each of the M carrier sets includes N/M carriers. There are N/M orthogonal phase spaces per set of carriers. The symbol duration T_s is equal to the inverse of the carrier-frequency spacing f_s. Carrier-frequency spacing in each carrier set may be selected to reduce correlated fading between adjacent carrier frequencies.

In a third embodiment of a CI architecture, each user is assigned to one of the M carrier sets. In one case of this embodiment, multiple users may be assigned to the same carrier set. Each user sharing a particular carrier set may be assigned to one time slot and/or phase space. Alternatively, each user sharing a carrier set may use more than on time slot and/or phase space. In another case of the third embodiment, only one user is assigned to each carrier set and that user can use one or more of the available phase spaces and/or time slots.

In a fourth embodiment of a CI architecture, each user is assigned to a plurality of the M carrier sets. In one case of the fourth embodiment, each user is assigned to the same constructive-interference time slot (or equivalent phase space) for each of the carrier sets to which the user is assigned. In another case of the fourth embodiment, each user is assigned to a different time slot and/or phase space relative to each carrier set. In another case, each user is assigned to a plurality of time slots and/or phase spaces for each carrier set. This plurality of time slots and/or phase spaces may include similar or different time slots and/or phase spaces relative to the different carrier sets.

In a fifth embodiment of a CI architecture, multiple users are assigned to the same time slot(s) and/or phase space(s) relative to each of one or more carrier sets. In this case, a code is applied to each phase space and/or superposition signal to differentiate users. For example, code chips applied to superposition pulses can provide a DS-CDMA signal in the time domain. In another example, the application of code chips to frequencies that comprise a phase space can enable information symbols modulated in that phase space to be separable from other symbols modulated in that phase space with a different code.

One advantage of the class of CI architectures illustrated in FIG. **9**B is that it allows a multicarrier protocol consisting of N carriers to be separated into smaller groups of carrier signals that are easier to process. The smaller groups also provide substantially the same frequency-diversity benefits as the full N-carrier architecture. The size of these groups and the carrier frequencies employed by each group may be adapted with respect to system and environment factors, such as fading, distortion, and interference.

FIG. **10**A shows a single carrier frequency f_n having a set of quasi-orthogonal phases $\phi_{(mn)k}$ used in a quasi-orthogonal phase-space division multiplexing technique. In this case, a kth user is provided with M phase channels. Alternatively, the phase channels may correspond to different users. The advantage of assigning all of the phase channels for a given frequency to a single transmitter is that each of the phase channels undergoes the same multipath effects and interference in a communication channel. Known correlations between the phase channels can be used to help separate interfering symbols transmitted on those channels. However, interference and multipath distortion do not substantially affect correlations between the phase channels.

FIG. **10**B shows a plurality of carrier frequencies f_n to $f_{n'}$ having sets of quasi-orthogonal phases $\phi_{(mn)}$ to $\phi_{(mn')}$. In this case, the number M of phase spaces is greater than the number N of carrier frequencies. Multiple carriers may be used to increase capacity or mitigate the effects of fading and interference via redundant modulation. In one case, the phases of each carrier may be selected with respect to incremental time offsets. In another case, the carrier phases may be incrementally spaced in phase. For example, binary phase-shift key modulation may be implemented with carrier phases spaced throughout an interval of 0 to π. Quadrature shift-key modulation may be implemented with carrier-phase channels throughout an interval of 0 to $\pi/2$. Differential amplitude modulation may also be performed in carrier-phases channels.

Coding may be provided to distribute a data symbol over a plurality of carrier frequencies, time intervals, and/or phases. Such coding techniques are commonly employed in OFDM. Similarly, guard bands, cyclic prefixes, and various signal-processing techniques used with OFDM and other multicarrier protocols may be provided to CI signals.

For M>N, multi-user detection is typically used to separate interfering data symbols. A multi-user detector may sample multiple phase offsets ϕ_{mn} for each carrier frequency. Sampling may be achieved via matched filtering. For redundantly modulated carriers (i.e., multiple frequency channels modulated with the same data symbol), either or both phase-domain sampling and time-domain sampling may be used. Time-domain sampling may involve combining the modulated carriers to generate superposition signals that can be separated via time-domain multi-user detection. Multi-user detection may include interference cancellation, interference suppression, constellation processing, and/or optimization.

FIG. **11** shows a CI-OFDM signal architecture for a plurality M of users. Each user is provided with a unique set of carriers. A user may be capable of using all available time slots/phase spaces associated with the set of carriers. Different users may or may not share the same carrier sets. Coding may be provided to distribute each data symbol over a plurality of carrier sets. Other signal-processing techniques associated with OFDM may be incorporated into CI pro-

cessing. A receiver may employ at least one matched filter to process individual carrier signals or carrier superpositions. A receiver may provide time-domain processing, such as sampling, to received signals. For example, superposition signals may be sampled with respect to predetermined time references and time intervals.

Another form of CI-OFDM assigns a plurality of frequency-diverse carriers to serve as each OFDM carrier. This form ensures that a single carrier is not significantly affected by deep fades and narrowband interference. A further adaptation of this CI-OFDM form allows multiple signals to share each OFDM carrier. Another form of CI-OFDM allows for each OFDM or CI-OFDM carrier to be spread or coded with a CI/DS-CDMA signal. In yet another form of CI-OFDM, each data symbol on each carrier is coded. The codes may include CI codes and/or any other form of coding. Coding may include at least one of a multiple-access code, a spread-spectrum code, a channel code, an encryption code.

FIG. **12** shows one of many possible CI MC-CDMA architectures. In this case, a kth user having a kth phase space ϕ_{kn} is provided with a spreading sequence c_{kn} in which a binary value is assigned to each of a plurality N of carriers. Multi-user detection may be employed to separate interference between the users.

FIG. **13**A is a time-domain representation of a plurality K of DS-CDMA codes generated from a CI architecture. Each chip of the CI DS-CDMA codes is generated from a CI superposition of carriers. Each chip is provided with a binary code value corresponding to a DS-CDMA spreading code. The chip shape can be adjusted by applying weights to the chip's carriers. In this case, the chips have a distinctive sinc-like shape that allows chip overlap (shown in FIG. **13**B). Chip overlap doubles the code length without increasing bandwidth. This can double capacity. Furthermore, CI provides enhanced frequency diversity, narrowband processing capabilities (e.g., spatial processing), and simplified signal processing at both the transmit and the receive sides.

FIG. **13**C shows one of many possible carrier architectures for a CI DS-CDMA system. A kth user is assigned a plurality M of phase spaces. Each phase space corresponds to a superposition of carriers that provide a chip for the kth user's DS-CDMA code, which has a code length of M Other users may share the same carriers and phase spaces. However, differences in users' codes provide for separation of the users.

In some applications, as described in Applicant's '992 patent, time-domain and/or frequency-domain shaping may be provided to the component waveforms. In one set of applications, time-domain shaping or windowing provides side-lobe reduction in the frequency domain. Time-domain shaping may also be employed to shape the main lobe. Similarly, frequency-domain shaping or windowing may be provided to shape either or both the time and frequency-domain characteristics of the composite waveforms and/or individual waveform components.

Windows used for either or both time-domain shaping and frequency-domain shaping may be constructed from products, sums, portions, or convolutions of simple windows and functions. Windows may include one or more window types, including, but not limited to, rectangle, triangle, $\cos^{a}(x)$, Hanning, Hamming, Riesz, Riemann, De La Valle-Poussin, Tukey, Bohman, Poisson, Cauchy, Gaussian, Dolph-Chebyshev, Kaiser-Bessel, Barcilon-Temes, Blackman, and/or Blackman-Harris windows.

In some applications, methods of exploiting known ratios of inter-symbol interference between overlapping waveforms (e.g., CI components and/or composite waveforms) may be exploited to separate the waveforms and/or determine symbols modulated on the waveforms. For example, any combination of cancellation filters and equalizers may be employed to mitigate the effects of inter-symbol interference. Inter-symbol interference may include any combination of frequency, time, polarization, code, or spatial overlap.

In one set of embodiments of the invention, individual CI components may be processed to compensate for inter-symbol and/or co-channel interference prior to combining. For example, an equalizer may be provided for each carrier to mitigate inter-symbol interference. An equalizer may follow a matched filter or Fourier transform.

An equalizer may follow a combiner. CI carriers or carrier symbol values, once compensated for inter-symbol interference, may be combined with respect to any CI combining technique. Similarly, equalization may optionally be employed to mitigate the effects of CI pulse or CI symbol overlap. In another set of embodiments, at least one optimal combiner may be employed to mitigate the effects of inter-symbol interference. Optimal combining may employ cancellation, including multi-user and/or multi-channel detection.

Co-channel interference may be removed via cancellation. Thus, cross-coupled canceling filters may be employed to remove co-channel interference and/or inter-symbol interference. Co-channel interference may be compensated with the aid of a multi-user detector.

CI symbol/carrier generation may be performed using any of various appropriate polyphase filters. Polyphase filters employed in the invention may incorporate additional functions, such as, but not limited to, up sampling and interpolation. Similarly, CI signals may be processed in a receiver by one or more polyphase filters, such as at least one polyphase filter adapted to perform matched filtering and down sampling.

Symbols and/or channels having predetermined or otherwise known interference ratios may be transmitted. Transmitted symbols may be intentionally overlapped with respect to time, frequency, space, and/or any other diversity parameters. Transmissions may be distorted by various channel effects (e.g., multipath effects, non-linear channel effects, etc.) to cause interference. In some cases, channel compensation at either or both the transmitter and the receiver can cause inter-symbol and/or co-channel interference. For example, carriers experiencing excessive noise and/or interference levels may be eliminated or discarded, resulting in overlap between adjacent CI symbols or signals. Interference ratios may be determined by any combination of training, pilot-signal processing, optimal combining, blind adaptive processing, as well as other adaptive techniques.

CI/DS-CDMA Transmitter Overview

Descriptions of CI/DS-CDMA transmission and reception are intended to illustrate the nature of CI processing. As these descriptions are intended to convey a basic understanding of CI and its applications to CDMA, they are not intended to suggest particular method or apparatus embodiments. Many embodiments fall within the scope of the invention. Descriptions of CI/DS-CDMA include particular signal-processing techniques to convey an understanding of CI principles rather than suggest any preferred signal-processing methods.

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In a CI/DS-CDMA system, a kth user's transmission signal is expressed by:

$$s^k(t) = b_k \sum_{i=0}^{N-1} \beta_i^k h(t - kT_c),$$

where b_k is a data bit for the kth user, $\beta_i^{(k)}$ is an ith value of a spreading sequence corresponding to the kth user, and h(t) represents a CI-based chip. T_c is the chip duration. The data bit b_k is typically a binary or M-ary PSK modulated symbol. The data bit b_k may be represented by other types of modulation.

The spreading sequence $\beta_i^{(k)}$ is typically a direct-sequence code. For example, values of $\beta_i^{(k)}$ may represent a long code, a Walsh code, a Gold code, a Kasami code, a Barker code, etc. Values of $\beta_i^{(k)}$ may represent a CI code, a wavelet code, or some other type of code or transform. Values of $\beta_i^{(k)}$ may be binary, polyphase, poly-amplitude, or some hybrid.

The CI-based chip h(t) is typically a CI pulse, as described herein. The CI-based chip h(t) may have a similar shape to a conventional DS-CDMA chip, such as a raised cosine, Gaussian, or sinc function. However, unlike conventional DS-CDMA chip shapes, which occupy a continuous bandwidth, CI-based chips h(t) are constructed from narrowband carriers. This enables CI/DS-CDMA to benefit from narrowband processing and exploit frequency-diversity reception. Whereas conventional DS-CDMA chips require a wide, continuous frequency band, CI/DS-CDMA can operate across non-contiguous frequency bands. CI-based chips h(t) may be constructed from closely spaced or sparsely spaced carriers. The carrier spacing may be incremental and/or non-incremental. Carriers may be positioned in multiple non-contiguous frequency bands.

The CI-based chips h(t) can belong to any type of code or transform, such as a wavelet transform. DS-CDMA codes may be constructed with respect to the orthogonal bases defined by a wavelet transform. DS-CDMA codes may be combined with other types of transforms, such as a wavelet transform. In any of these cases, CI may be used as the basis for the chip h(t). The chip duration T_c can depend on the chip spacing. Time-shifted pulses h(t) are orthogonal to each other if they are shifted by some integer multiple of the pulse width:

$$\int_0^{Ts} h(t - pTc)h(t - qTc)dt = 0 (p \neq q).$$

The chips $h(t-iT_c)$ can also be created by phase offsetting each nth carrier of the pulse h(t) by $2\pi n/N$.

Time-shifted pulses h(t) are substantially orthogonal (pseudo-orthogonal) to each other if they are shifted by some half-integer odd multiple of the pulse width. Similarly, corresponding phase shifts made to the CI carriers effect corresponding orthogonality conditions. Although the chip may actually extend over at least one symbol interval, the effective duration as seen in the time domain may be approximately a chip width (orthogonal case) or half of a chip width (pseudo-orthogonal case).

The basic CI chip shape h(t) can be expressed by:

$$h(t) = \sum_{n=0}^{N-1} A(n)\cos(2\pi(f_o + nf_s)t),$$

where A(n) expresses the chip shape in the frequency domain. For example, A(n) may be a frequency-domain window that shapes the time-domain characteristics of the chip h(t). In the most basic case, A(n) is constant and the chip shape h(t) is time-limited to one symbol duration T_s. In cases where a repetitive direct-sequence code is required, the chips h(t) in the code may have a much longer duration than the symbol duration T_s. In this case, the symbols b_k may time-limit the chip shape h(t). Raised cosines, sinc functions, Gaussian functions, and other chip shapes, including wavelets, may be constructed by choosing an appropriate chip-shaping function, such as A(n) and/or a time-domain window function. The basic chip shape may also be expressed by:

$$|h(t)| = \left| A \cdot \frac{\sin\left(\frac{1}{2}N2\pi\Delta ft\right)}{\sin\left(\frac{1}{2}2\pi\Delta ft\right)} \right|.$$

In the orthogonal case, the kth user's transmission signal can be expressed by:

$$s^k(t) = b_k \sum_{i=0}^{N-1} \beta_i^{(k)} \sum_{i=0}^{N-1} A(n)\cos(2\pi f_o t + 2\pi n f_s(t - iT_c))g(t)$$

where A(n) is an nth value of a window function that may provide a scalar or complex weight to each CI carrier. A time-domain window function g(t) may provide frequency-domain shaping to the chip shape h(t). The function g(t) may be a unit-amplitude rectangular waveform having a duration of T. The expression for $s_k(t)$ can be written as:

$$s_k(t) = b_k \sum_{i=0}^{N-1} \beta_i^{(k)} \sum_{n=0}^{N-1} A(n)\cos(2\pi f_o t + 2\pi n f_s t - ni2\pi/N)g(t)$$

where $T_c f_s = T_c/T_s = 1/N$. In the pseudo-orthogonal case, the expression for $s_k(t)$ is:

$$s_k(t) = b_k \sum_{i=0}^{2N-1} \beta_i^{(k)} \sum_{n=0}^{2N-1} A(n)\cos(2\pi f_o t + 2\pi n f_s t - ni\pi/N)g(t)$$

The total transmitted signal for K users is:

$$S(t) = \sum_{k=0}^{K-1} b_k \sum_{i=0}^{N-1} \beta_i^{(k)} \sum_{n=0}^{N-1} A(n)\cos(2\pi f_o t + 2\pi n f_s t - ni2\pi/N)g(t)$$

A CI/DS-CDMA transmitter may be defined as any system that generates CI/DS-CDMA signals as defined by either equation for the kth user's transmission signal or the equation representing the total transmitted signal for K users. Equivalently, a CI/DS-CDMA transmitter may be defined as any device adapted to generate one or more DS-CDMA signals made of N separable frequency components.

The CI/DS-CDMA transmission equations represent various mathematical relationships between various components of a transmitted CI/DS-CDMA signal. Accordingly, the transmission equations do not imply any particular order or process for generating CI/DS-CDMA signals. For example, one embodiment of the invention modulates a code sequence with a data stream whereas another embodiment impresses data symbols onto a code sequence during code generation. In one set of embodiments, CI/DS-CDMA carriers are generated by redundantly modulating a harmonic-signal source (such as a pulse generator) with data symbols (such as information-modulated code symbols). In another set of embodiments, individual carriers are modulated (e.g., in an IFFT) to generate CI/DS-CDMA signals.

A CI transmitter may be implemented via many different techniques. The present invention anticipates design variations of CI-based transmitters. A CI/DS-CDMA transmitter, as well as any other CI transmitter, is characterized by the signals generated. In particular, a CI/DS-CDMA transmitter is any device, system, or algorithm capable of impressing information onto a plurality of carriers and adjusting (e.g., weighting) the carriers to provide a superposition signal having predetermined time-domain characteristics. Such time-domain characteristics may include a signal resembling a direct-sequence code.

The superposition signal may be shaped to produce a low peak-to-average-power ratio (PAPR) or crest factor. For example, the individual carriers may be provided with predetermined or adaptive phase offsets to reduce PAPR. The phase offsets may be generated using any combination of deterministic, adaptive, and random processes. One set of embodiments employs Schroeder's method to generate carrier-phase offsets. Similarly, phase offsets may be provided to CI code chips.

The superposition signal may be shaped to produce other signal characteristics, such as predetermined frequency-domain characteristics. In other types of CI-based transmitters, transmitted signals may be shaped with respect to corresponding desired time-domain, frequency-domain, spatial, polarization, and/or any other type of diversity-parameter characteristics.

CI/DS-CDMA Receiver Overview

The receiver overview of CI/DS-CDMA signal processing describes particular signal-processing techniques to convey an understanding of CI principles, rather than suggest any preferred signal-processing methods. The mathematical analysis of CI/DS-CDMA signal processing illustrated herein does not necessarily imply any single preferred method or system for implementing the present invention.

In a Rayleigh frequency-selective slow fading channel, each multi-frequency carrier comprising the CI/DS-CDMA signal experiences a unique flat fade. In the simple case where all values of A(n) are unity, the received signal is represented by:

$$r(t)=\sum_{k=0}^{K-1}b_k\sum_{i=0}^{N-1}\beta_i^{(k)}\sum_{n=0}^{N-1}\alpha_n\cos(2\pi f_o t+2\pi f_s t-ni2\pi/N+\phi_n)g(t)+n(t)$$

where α_n is a gain, φ_n is a phase offset for an nth carrier of a CI pulse resulting from fading, and n(t) is additive white Gaussian noise. Assuming exact phase synchronization, a decision variable resulting from a received multi-frequency carrier component of each received chip is expressed by:

$$r_{m,n}=\sum_{k=0}^{K-1}b_k\sum_{i=0}^{N-1}\beta_i^{(k)}\alpha_n\cos(nm2\pi/N-ni2\pi/N)+n_{m,n}$$

The CI/DS-CDMA receiver for an ith user detects an mth chip at each carrier as shown in FIG. **18**A. The mth chip is separated into its N carrier components. Each chip and each carrier contribute a decision variable $r_{m,n}$ corresponding to

$$r_{m,n}=b_l\beta_m^{(l)}\alpha_n+b_l\alpha_n\sum_{\substack{i=0\\ i\neq m}}^{N-1}\beta_i^{(l)}\cos(nm2\pi/N-ni2\pi/N)+\sum_{\substack{k=0\\ k\neq l}}^{K-1}b_k\beta_m^{(k)}\alpha_n+\sum_{\substack{k=0\\ k\neq l}}^{K-1}b_k\alpha_n\sum_{\substack{i=0\\ i\neq m}}^{N-1}\beta_i^{(k)}\cos(nm2\pi/N-ni2\pi/N)+n_{m,n}$$

The first term represents the contribution from user **1**, carrier n, and chip m. The second term represents the other N−1 chips of the user **1**. The third term represents interference due to the mth chip of other users. The fourth term represents interference from user l's other N−1 chips. The fifth term is a zero-mean Gaussian random variable with variance $\sigma_n^2=N_0/2$. The terms, $n_{m,n}$, are correlated across chips, but not across carriers.

The covariance matrix of the vector noise ($n_{0,n}$, $n_{1,n}$, $n_{2,n}$, . . . $n_{N-1,n}$) corresponding to a fixed carrier number n and a variable chip number m is:

$$C_n=\frac{N_0}{2}\begin{pmatrix}1 & \cos(2\pi/N) & \cos(2*2\pi/N) & \cdots & \cos((N-1)*2\pi/N)\\ \cos(2\pi/N) & 1 & \cos(2\pi/N) & \cdots & \cos((N-2)*2\pi/N)\\ & & \vdots & & \\ \cos((N-1)*2\pi/N) & & & \cdots & 1\end{pmatrix}$$

Multi-frequency carrier combining is used to combine the $r_{m,n}$ terms across the carriers, as indicated by the functionality shown in FIG. **18**A. This results in frequency-diversity benefits when recreating each chip and removal of the second and fourth interference terms (which represent inter-chip interference).

Orthogonality Restoring Combining (ORC) may be used to remove the second and fourth interference terms. Each $r_{m,n}$ term is scaled by an and summed over n to provide a decision variable R_m for an mth chip:

$$R_m=\sum_{n=0}^{N-1}r_{m,n}\cdot 1/\alpha_n$$

However, ORC can result in substantial noise enhancement. Thus, ORC is most suitable for low-noise conditions (i.e., high SNR).

EGC is preferable for low signal to noise. EGC combines the N carrier terms for the mth chip according to:

$$R_m = \sum_{n=0}^{N-1} r_{m,n}$$

MMSEC minimizes the second term and the fourth term and optimizes frequency diversity while minimizing the noise. Using multicarrier MMSEC provides a decision variable R_m for an mth chip:

$$R_m = \sum_{n=0}^{N-1} r_{m,n} \bullet (\alpha_n / (K\alpha_n^2 + N_0))$$

A final decision variable Di for user **1** results from a typical DS-CDMA combining technique across chips, which eliminates multi-user interference. Each chip's decision variable R_m is multiplied by an mth spreading code f_1, and combined:

$$D_l = \sum_{m=0}^{N-1} R_m \beta_m^{(1)}$$

The orthogonal cross-correlation between spreading codes of different users minimizes the multi-user interference.

Although the receiver overview describes decision variables corresponding to each chip and each carrier, preferred embodiments of the invention may process either chips or carriers to derive decision variables. Chip sequences may be processed to provide a decision variable. In one set of embodiments, each carrier may be processed to compensate for channel effects and decode a particular data stream from interfering signals. In another set of embodiments, channel compensation is performed at the carrier level, the carriers are combined, and then the resulting superposition signal is processed in the time domain. The time-domain processing may be supplemented with RAKE reception.

Channel simulations show dramatically improved BER performance when a CI architecture is applied to a conventional DS-CDMA system. Because CI exploits frequency-diversity benefits that are inherent in multicarrier pulse shaping, CI does not require a RAKE receiver.

CI/DS-CDMA receivers may include multi-user detectors (MUDs) that operate in the time domain and/or the frequency domain. MUDs exploit cross correlations to substantially improve data detection. Thus, MUDs can increase channel throughput (e.g., system capacity) of interference-limited systems. MUDs are well known in the art and include various designs, such as optimal combiners (e.g., maximum-likelihood combiners), linear detectors (e.g., correlators, minimum mean squared error detectors), and non-linear interference cancellers (e.g., decision-feedback systems, successive-cancellation systems, Turbo MUDs, etc.).

CI/DS-CDMA MUDs may include space-time and/or space-frequency MUDs that exploit the spatial characteristics of the propagation environment with respect to time and/or frequency. Multi-user detection may be performed with respect to other diversity parameters. A Turbo MUD may be employed that exploits the multiple-access channel and the temporal structure induced by channel coding. A Turbo MUD may iterate between multi-user detection and channel decoding, exchanging soft decisions on symbol information at each iteration. Quantum MUDs may be employed to exploit quantum measurements and the multiple-access channel.

CI/DS-CDMA Transceiver System

FIG. **14**A shows components of one embodiment of a CI/DS-CDMA transmitter.

A symbol generator **1202** receives at least one input data stream from a data source **1200** and at least one code sequence from a code source **1201**. The symbol generator **1202** converts the data bits from the input stream into a plurality N of symbols s_n, n=1, 2, . . . , N. The symbols s_n are optionally stored in a register **1204**. The symbols s_n may optionally be weighted by a weighting system **1211**. The weighting system **1211** applies a plurality of complex weights w_n for channel compensation, channel coding, sub-channel coding, CI-based coding, PAPR reduction, encryption, multiple-access, or any combination thereof.

A frequency-to-time-domain converter **1206** converts a plurality of frequency-domain symbols into at least one time-domain signal. In the case where the converter **1206** is a digital system (such as an IFFT, an IOFFT, a digital filter bank, etc.), the output of the converter **1206** produces digital time-domain signals $x_{N'}$ that may be stored in a shift register **1208**. Optionally, the output signals $x_{N'}$ may be weighted by some complex-weighting system **1213**. Optional complex weights con' may be employed to provide pre-distortion for channel compensation and/or implement some additional coding, encryption, etc. Optionally, the output signals $x_{N'}$ may be interleaved prior to transmission.

A transmission system **1210** processes the signals $x_{N'}$ for transmission. The transmission system **1210** may provide A/D conversion, amplification, up-conversion, modulation, filtering, and/or any other signal processing typically performed by a transmitter. The transmission signals are then coupled into a communication channel (not shown). A communication channel, as described herein, typically comprises an RF channel. However, a communication channel may also comprise other transmission media, such as modulated laser, waveguide, ultrasound, or fluidic systems. A controller **1205** receives a clocking signal from a clock **1207**. The controller **1205** regulates timing and synchronization of operations performed by the components shown in FIG. **14**A.

The symbol generator **1202** may perform interleaving and/or channel coding. The code source **1201** may include one or more sets of CI codes that may be used for channel coding, multiple access, spread spectrum, encryption, etc. In one set of embodiments, the code source **1201** is adapted to provide a conventional direct-sequence code to the symbol generator **1202**. The symbol generator **1202** generates appropriate carrier weights to provide the CI superposition signal produced by the converter **1206** with appropriate time-domain characteristics of a direct-sequence signal. Similarly, other types of CI-based time-domain signals may be generated using the CI/DS-CDMA transmitter shown in FIG. **14**A.

In another set of embodiments, CI codes are generated by the code source **1201**. In yet another set of embodiments, one or more direct-sequence and/or CI codes are applied as weights in either or both weighting systems **1211** and **1213**. Applied codes may include one or more multiple-access, channel, spreading, and/or encryption codes.

The converter **1206** may perform any type of transform to generate a multicarrier signal. Although the converter **1206**

is illustrated as a frequency-to-time converter, other types of converters may be implemented with respect to the definition of a multicarrier signal. In one embodiment, the converter **1206** is a beam-forming system. In another embodiment, the converter includes a multi-port system that conveys each of a plurality of symbols to a different transmitter. The transmitters may be spatially separated. The transmitters may be characterized by different polarizations or otherwise have different transmission characteristics.

The converter **1206** may convey symbols to different types of subcarriers. For example, the symbols may modulate various orthogonal or quasi-orthogonal circular-polarized and/or elliptical-polarized carriers. Orthogonality between different polarized carriers may be characterized by different rotation rates, different directions of rotation, and/or orthogonal (e.g., perpendicular) polarization vectors in two or three dimensions.

The symbol generator **1202** may form data symbols and/or CI carrier weights via orthonormal-basis vectors. For example, if data symbols are generated from an 8-chip Hadamard-Walsh matrix, each of the eight row vectors (i.e., Walsh codes) of the matrix can be expressed by a linear combination of three orthonormal basis vectors:

[1 0 1 0 1 0 1 0]
[1 1 0 0 1 1 0 0]
[11 1 1 0 0 0 0]

Different combinations of the basis vectors (e.g., modulo-two additions, multiplications) can provide all eight Hadamard-Walsh codes. Furthermore, since the first four values of each orthonormal-basis vector are identical to the second four values (in the case of the third vector, the second four values are inverted relative to the first four values), only four values need to be stored for each vector. The all-ones vector does not need to be stored. Various matrices, including Hadamard-Walsh matrices, may be represented by a reduced set of vectors, such as orthonormal-basis vectors.

In one set of preferred embodiments, a CI-based signal is provided with symbols modulated onto various phase spaces. FIG. **15**A represents carrier phases of a plurality of CI carrier frequencies f_n corresponding to a plurality of orthogonal phase spaces Ps(n'). Orthogonal phase spaces are separated by a pulse width $T_{ps}=1/(f_s N)$ whereas quasi-orthogonal phase spaces are separated by a half pulse width $T_{ps}=1/(f_s 2N)$. Each CI carrier frequency f_n is expressed by: $f_n=f_o+nf_s$. At Ps(0), each carrier has an arbitrary phase ϕ_n.

FIG. **15**B shows a matrix that represents contributions of phase-shifted symbol values $s_{n'}$ to each carrier frequency f_n for each of a plurality of phase spaces Ps(n'). The columns correspond to phase spaces and the rows correspond to carrier frequencies Several simplifying assumptions are made with respect to FIG. **15**B. The arbitrary phases ϕ_n are zero and baseband signal processing is assumed (i.e., the frequency-offset f_o is zero).

Each of a plurality of CI pulses (represented by the orthogonal phase spaces Ps(n')) is modulated with a particular symbol value $s_{n''}$. Each phase space Ps(n') is characterized by a unique set of phase offsets applied to the carrier frequencies f_n. Since each phase space Ps(n') is defined by a plurality of phase offsets to the same set of carrier frequencies f_n, a symbol $s_{n'}$ applied to one phase space interferes with symbol values applied to at least some of the carrier frequencies f_n in the other phase spaces Ps(n'). In CI, the interfering symbol values cancel each other and the desired symbol values combine coherently when the carriers are combined in a particular phase space Ps(n'). Thus, a combination of symbols $s_{n'}$ and related phase offsets contribute to a complex value v_n associated with each frequency f_n. This complex value v_n is the sum of row elements shown in FIG. **15**B for a corresponding frequency f_n.

The matrix elements shown in FIG. **15**B illustrate basic mathematical relationships between carrier frequencies f_n and phase spaces Ps(n') that can simplify transforms between frequency-domain and time-domain signals. For example, given a set of symbol values s_n these mathematical relationships provide carrier-frequency weights that produce a superposition signal with time-domain characteristics corresponding to the symbol values $s_{n''}$.

For a particular frequency bin f_n, a corresponding phase-space vector is shown as follows:

$$f_{n'}:[1\, e^{i2\pi T_{ps} n f_s} e^{i2\pi 2 T_{ps} n f_s} \ldots e^{i2\pi(N-1)T_{ps} n f_s}]$$

This vector represents n full rotations in the complex plane. Each value in the vector corresponds to a particular phase space Ps(n'). Each phase-space value Ps(n') is multiplied by a corresponding data-symbol value $s_{n''}$. The sum of the data-modulated phase-space values provides an effective complex weight $w_{eff}(n)$ for frequency bin f_n. Thus, column vectors (i.e., phase spaces Ps(n') and their corresponding symbol values $s_{n'}$) are summed to generate the complex values $w_{eff}(n)$ associated with row vectors (i.e., frequency bins f_n).

A corresponding inverse transform may be provided. For example, a receiver may measure complex values $w'_{eff}(n)$ corresponding to each carrier frequency f_n. The complex values $w'_{eff}(n)$ represent the effective complex weight $w_{eff}(n)$ after it has been distorted by the channel and/or the receiver. Since the phase spaces Ps(n') are easily determined via column vectors of the matrix shown in FIG. **15**B, the measured complex values $w'_{eff}(n)$ can be weighted (e.g., shifted) and summed to estimate the symbols $s_{n'}$ transmitted in corresponding phase spaces Ps(n').

The column and row vectors of the matrix shown in FIG. **15**B are similar to each other in the absence of symbol values sw. Linear combinations of an orthonormal basis may be used to characterize the column and/or row vectors. For a set of vectors of length N, a linear combination of orthonormal-basis vectors may include modulo-N additions between two or more vectors, vector products, corresponding phase shifts, or equivalent operations. A set of orthonormal basis vectors for FIG. **15**B is shown as follows:

$$f_1:[1\, e^{i2\pi T_{ps} f_s} e^{i2\pi 2 T_{ps} f_s} \ldots e^{i2\pi(N-1)T_{ps} f_s}]$$

$$f_2:[1\, e^{i2\pi T_{ps} 2 f_s} e^{i2\pi 2 T_{ps} 2 f_s} \ldots e^{i2\pi(N-1)T_{ps} 2 f_s}]$$

$$f_4:[1\, e^{i2\pi T_{ps} 4 f_s} e^{i2\pi 2 T_{ps} 4 f_s} \ldots e^{i2\pi(N-1)T_{ps} 4 f_s}]$$

The vector corresponding to each nth frequency f_n represents n rotations in the complex plane. In one embodiment, orthonormal vectors representing $n=2^m$ rotations in the complex plane (where m=0, 1, 2, . . .) are stored in memory. The storage space required for each vector can be reduced by considering vector symmetry. In another embodiment, each orthonormal vector is generated. In one aspect of the invention, the vector representing one rotation in the complex plane serves as the basis to build other vectors, such as the orthonormal-basis vectors.

FIG. **14**B illustrates components of one embodiment of a CI/DS-CDMA receiver.

At the receiving end of a transmission link **113**, a receiver system **1216** couples transmitted signals from at least one communication channel (not shown). The received signals are typically filtered, amplified, down-converted, and digitized by the receiver system **1216**. Reception may include beam forming, any of various types of sub-space processing,

space-time processing, space-frequency processing, channel compensation, and/or demultiplexing. The digitized received time-domain signals may optionally be coupled into a register **1218**. An optional weighting system **1219** may apply weights to the time-domain signals prior to processing by a time-domain-to-frequency-domain converter **1220**.

Each set of N time-domain values in register **1218** is converted via the time-domain to frequency-domain converter **1220** to generate a set of frequency-domain symbols s'_n. This transformation is the inverse of the transformation generated by the frequency-to-time-domain transform **1206**. The communication link (not shown) will typically attenuate and/or phase shift the signals represented by x_n. The received signal values y_n and s'_n usually differ from the transmitted signal values s_n and x_n.

A filter bank or Fourier transform may be implemented as a bank of N single-pole filters (i.e., resonators) in which each n filter has a pole at a corresponding n^{th} frequency f_n. The invention may employ the Goertzel algorithm, which exploits the periodicity of the phase factors in a DFT, to perform a DFT computation as a linear filtering operation. The Goertzel algorithm is typically preferable when the DFT to be computed has a relatively small number M of values, where $M \leq \log_2 N$. Similarly, various aspects of the invention that employ periodic phase terms, such as CI coding, CI sampling, OFFT operations, phased-array processing, etc., may employ the Goertzel algorithm to provide filtering.

Each CI data symbol can be obtained by coherently processing corresponding CI components. Preprocessing is typically performed to remove the carrier frequency f_c, from the received signal. Each received signal can be processed to form an in-phase/quadrature-phase pair. The processed signals may be compensated for channel effects and/or receiver processing variations. The processed signals may then compressed by a DFT process, such as an FFT.

One or more sinc filters, such as digital sinc filters, may be used to generate CI sub-carrier frequencies. For example, data symbols may be modulated onto individual time-domain sincs or pulses. Filters characterized by periodic time-domain characteristics may be employed to generate multicarrier signals. Similarly, periodic filters may be used to process received CI signals. Various filter shapes, including Gaussian-shaped filters, may be employed.

The frequency-domain symbols s'_n may be stored in a register **1222**. An optional complex-weighting system **1224** or an equalizer (not shown) may be used to compensate for attenuations, phase shifts, and/or inter-symbol interference. The frequency-domain symbols s'_n are coupled to a symbol decoder **1228** that may optionally store the symbols s'_n in a buffer (not shown). The symbols s'_n are decoded to generate an estimate of the original data stream. Additional data processing and/or system control may be performed by an optional data sink **1230**. The data sink **1230** may include one or more feedback loops, optimal combiners, multi-user detectors, hard-decision systems, soft-decision systems, error-detection systems, and/or error-correction systems.

A system controller **1231** is provided with a clock signal from a clock **1233**. The controller **1231** regulates timing of signal-processing operations performed by a plurality of the receiver components. A transceiver may employ the same controller and/or clock for both transmission and reception.

The symbol decoder **1228** may perform inverse coding operations with respect to coding applied at a transmitter. The symbol decoder **1228** may perform adaptive decoding. The symbol decoder **1228** may perform partially blind adaptive coding with respect to transmitted data symbols, codes, and/or channel estimates. The symbol decoder **1228** may be adapted to perform de-interleaving, decoding, adaptive decoding, and/or channel compensation.

The symbol decoder **1228** may generate or otherwise be provided with at least one CI code, binary direct-sequence code, spreading code, channel code, encryption code, time and/or frequency-hopping code, pulse-position modulation code, etc. The symbol decoder **1228** may perform demultiplexing, de-spreading, and/or converting at least one signal from one phase space to another phase space. The symbol decoder **1228** may decode a CI-based signal, a CI-coded signal, a direct-sequence signal that employs CI codes, a direct-sequence signal implemented with CI chip-shaping, any CI-based signal with channel codes, a signal implemented with CI-based channel codes, a signal implemented with CI codes for any type of multicarrier CDMA, CIMA signals, CI signals coded with phase codes to achieve low PAPR, CI signals provided with signal masking, and/or CI-based and/or CI-coded signals provided with frequency-hopping.

Reference (e.g., despreading) codes are typically set equal to the codes (or complex conjugates of the codes) at the other ends of the link and only maximize the SNR of the decoded signals. In one set of embodiments of the invention, such operation is performed blindly. Transmitted codes may include weights applied at individual transmitter-array elements for spatial processing, channel compensation, etc. Received codes may include weights applied at receiver-array elements to provide spatial processing, channel compensation, etc. Codes may include weights applied to different signal components (e.g., frequencies, polarizations, codes, code chips, and/or any other diversity-parameter values of one or more signals) at either or both the transmitter and the receiver. Either or both coding and decoding operations may be performed using blind-adaptation techniques.

The transmit codes and channel distortions need not be known at the symbol decoder **1228**. This simplifies the processing used within the network by allowing use of unknown codes at the transceivers in the network. This also allows the use of adaptively determined codes that are continually optimized to mitigate noise, interference, and/or channel distortion encountered by the transceiver. Reference codes generated at the receiver may be adapted with respect to one or more characteristics of received signals. Transmitted codes generated at the transmitter may be adapted with respect to some reference, pilot, or feedback signal received from the receiver. Either or both the transmitter and the receiver may perform channel estimations that are used to adjust codes.

Preferred embodiments of the invention may use non-blind or calibrated techniques (e.g., least-squares techniques) that use knowledge of the baseband data sequence, channel distortion, and/or codes to develop ideal weights based on optimal signal estimation methods. Other preferred embodiments may use blind or non-calibrated techniques that use more general properties of the data signals to adapt code weights and/or decoding weights. Combinations of these techniques that use known and unknown components of the data signal, the code, and/or the transmission channel can also be used to construct an effective solution. Examples of blind techniques that are particularly useful include constant-modulus, multiple-modulus, and decision-direction techniques. These blind techniques use the message symbol constellation to adapt the decoding weights. A number of methods can be used to adapt multi-element, multi-frequency, and/or any other multi-diversity-parameter weights in or prior to the decoder **1228**. Dominant-mode prediction

(DMP) methods can exploit known packet arrival times, fading characteristics, or known coding parameters of a multicarrier signal. Code-gated self-coherence restoral (SCORE) methods exploit the known self-coherence (non-zero correlation between the spectrally separated signal components) in the multicarrier signal.

On the transmitter side of a multi-diversity parameter system (e.g., antenna array, multi-frequency, and/or any multi-valued diversity-parameter set having similar or identical sets of interfering signals), directive or retrodirective adaptation methods can be used to either direct returning signals of interest back to the transmit source with maximum power and/or minimum transmitted radio signals (directive mode), or to jointly direct the returning signals-of-interest back to the transmit source with minimum radiation in the direction of interfering sources (retrodirective mode). Processors can be used to accurately measure the received signal-of-interest steering vector (e.g., beam pattern, sub-space pattern, frequency-domain pattern, polarization-domain pattern, etc.) and direct a maximal beam back to the other end of the communication link without knowledge of the received signal-of-interest characteristics (e.g., direction-of-arrival, frequency profile, polarization profile, code, etc.) even though the interference sources completely cover the signal-of-interest passband and packet interval.

In some embodiments of the invention, it is preferable that each CI carrier be sufficiently narrow to allow the distortions in that sub-channel to be modeled by a single phase shift and attenuation. It is also preferable that CI carriers be sufficiently narrow to ensure that a sub channel that is turned off to prevent interference from narrow-band sources does not unduly waste bandwidth beyond that corrupted by the interference source. However, narrow channels increase system latency and the computational complexity of the frequency-domain-to-time-domain transformation and its inverse. Thus, it is preferable to achieve a balance between the benefits and drawbacks of various sub-channel widths. In one set of preferred embodiments, narrower subchannels are employed for frequencies having greater attenuations and/or phase shifts. Wider subchannels are used at frequencies with reduced attenuations and/or phase shifts.

FIG. **16**A illustrates basic components of a CI transmission system. A data source **1600** supplies a data stream to a symbol generator **1602** that generates symbols relative to the data stream and one or more CI codes, multiple-access codes, spread-spectrum codes, interleaving codes, error-detection codes, and/or channel codes. The symbol generator **1602** may generate symbols with respect to a CI/DS-CDMA code. A symbol generator, such as the symbol generator **1602**, may be adapted to modulate the symbols. The symbols are modulated with respect to any modulation technique, such as phase modulation, frequency modulation, amplitude modulation, polarization modulation, time-offset modulation, and/or any combinations thereof. The symbols are impressed onto carriers generated by a carrier generator **1606**.

In one embodiment, the carrier generator **1606** produces carrier frequencies that are processed with respect to the symbols. In another embodiment, the carrier generator **1606** produces periodic time-domain pulses that are modulated with symbols. The output of a periodic-pulse generator is a multi-frequency signal. However, the symbols used to modulate the pulses reflect the desired time-domain structure of the transmitted signal. Nevertheless, the frequency-domain profile of the transmitted time-domain signals are similar to a frequency-domain signal coded with corresponding polyphase signals. These frequency-domain characteristics differ from the conventional DS-CDMA frequency-domain structure, which is single carrier.

The modulated carriers are processed by a transmission system **1610** prior to being coupled into a communication channel (not shown). The transmission system **1610** may perform typical signal-processing operations corresponding to various parameters including channel characteristics, required transmission power, transmit frequency, receiver location, acceptable bandwidth, etc. In some embodiments, the carrier generator **1606** may perform one or more tasks of the transmission system **1610** (e.g., frequency up-conversion). For example, the carrier generator **1606** may include harmonic-generation capabilities coupled to a passband filter.

FIG. **16**B illustrates a more detailed embodiment of a CI transmitter. A code source **1601** is coupled to the symbol generator **1602**. In FIG. **16**A, the symbol generator **1602** was assumed to provide codes. The carrier generator **1606** is illustrated as an inverse Fourier Transform (IFT). This is one of many different carrier generators that may be implemented in a CI transmitter.

FIG. **16**C illustrates one particular embodiment of a CI transmitter. The data source **1600** and the carrier generator **1606** are coupled to a modulator **1609**. The carrier generator **1606** produces carriers having properties that reflect one or more input codes generated by the code source **1601**. For example, the code source **1601** may generate polyphase symbols with respect to a CI code. The code source **1601** may generate symbols with respect to other code types in addition to, or instead of, CI codes.

The modulator **1609** modulates data bits or symbols onto the carriers. Typically, the carrier generator **1606**, such as shown in FIGS. **16**A and **16**B, impresses data symbols onto the carriers. In some embodiments, the symbol generator **1602** may impress data bits or symbols onto code symbols via modulation or a code-generation process.

FIG. **16**D illustrates basic components of a particular set of embodiments of a CI transmitter. The carrier generator **1606** is illustrated as a sub-space carrier generator. The carrier generator **1606** may distribute codes corresponding to each data symbol across multiple transmitters. For example, each transmitter of an array may transmit a different code symbol corresponding to the same data symbol. Preferably, the code symbol is generated from a CI code or CI/DS-CDMA code. Each code symbol may be provided to each of a plurality of transmitters to generate a different beam pattern or sub-space channel corresponding to each code symbol. Other types of subspaces may be employed. Subspaces may be generated from any set of diversity-parameter values that overlap. For example, subspaces may be generated from signal polarizations (e.g., linear, circular, and/or elliptical polarizations), signal frequencies, signal phases, amplitude distributions, etc.

FIG. **16**E illustrates generalized components of a broad class of CI transmitters. The carrier generator **1606** is a system that generates carriers characterized by one or more diversity-parameter values and/or sub-space values.

Different CI codes may be characterized by polyphase projections onto two orthogonal diversity-parameter values. Specifically, in-phase and quadrature-phase magnitudes may be expressed by corresponding signal values impressed onto orthogonal diversity-parameter values or subspaces. For example, in-phase and quadrature-phase values may correspond to values imparted to vertical and horizontal linear polarized signals. Similarly, other orthogonal diversity-parameter values may be used.

CI carriers may be implemented with dynamically changing values imparted to in-phase and quadrature-phase components of any pair of orthogonal diversity-parameter or sub-space values. In one preferable set of embodiments, the in-phase and quadrature-phase components are characterized by an orthogonal set of sinusoids. The sinusoids represent sub-carrier modulations. For example, circular polarization results from in-phase and quadrature-phase sub-carrier modulation applied to vertical and horizontal linear-polarized signals. To maintain orthogonality, the frequency spacing f_s between the sinusoidal signals is inversely proportional to the symbol duration. These carriers are then processed to generate superposition signals having predetermined time-domain characteristics.

Generation of a CI-based signal may include providing the superposition of CI carriers with a circular or elliptical polarization. The polarization-rotation rate may be selected with respect to multipath delay profiles to reduce multipath fading. Predistortion of a circular-polarized CI signal may include providing elliptical polarization to the transmitted signal. In one set of embodiments, each CI carrier frequency is expressed as a polarization-rotation rate of a circular-polarized or elliptical-polarized signal. In another set of embodiments, each CI carrier has the same polarization-rotation rate, but may have different phase offsets. In yet another set of embodiments, each CI carrier frequency is provided with a unique polarization-rotation rate. CI codes CI/DS-CDMA, and/or other orthogonal cues may be applied to (linear, circular, elliptical, etc.) polarized signals. Phase coding may be applied in the form of a polarization-phase offset, a frequency-phase offset, or an offset to any other set of diversity parameter-values that indicates a phase offset.

In CI embodiments that employ orthogonal polarization-rotation rates, the polarized signals are processed in the same way as orthogonal carrier frequencies. For example, a receiver adapted to process received polarized CI signals may include a filter bank, a transform processor (e.g., any type of Fourier transform, including an orthogonal-frequency Fourier transform), a correlator, a complex-conjugate processor, and/or a sample-and-add system.

Multi-rate circular polarized signals may be implemented as wavelets. Polarized signals may be used in corresponding wavelet-transform operations. For example, wavelet families may be generated from polarized signals having durations that are inversely proportional to their polarization-rotation rates. Orthonormal wavelet bases may be generated via appropriate selections of scaling factors (i.e., scaling factors that are proportional to each other by powers of two). Wavelet filters may be implemented with circular and/or elliptical polarized signals. Orthonormal wavelet bases, such as polarization-based wavelets, may be used as code chips. Codes, including, but not limited to, multiple-access, spread-spectrum, and channel codes, may be generated from polarization-based wavelet chips. Wavelet chips may be provided with phase offsets to generate code chips, such as CI code chips.

Polarization-based wavelets may be shaped with respect to time-domain filters. Multiple signals having different polarization-rotation rates may be used to construct wavelets via superposition. Polarization-wavelet characteristics, such as shape, effective frequency, duration, etc., can be adjusted by providing weights to the wavelet sub-carriers. Polarization-based wavelet sub-carriers are analogous to CI carriers. Multiple signals having different polarization-rotation frequencies may be combined to construct code chips or other signals having predetermined time-domain characteristics. Weights provided to polarization-based sub-carrier signals may shape desired time-domain characteristics of the superposition signal.

FIG. **16**F illustrates basic components of a CI transmitter that impresses at least one data sequence, at least one channel code, and at least one multiple-access code onto a plurality of carriers. A carrier generator **1606** generates at least one carrier signal. The at least one carrier signal may be replicated by an optional carrier duplicator. A modulator receives inputs from a data source **1600**, a multiple access code source **1601**A, and a channel-code source **1601**B. Optionally, the multiple access code source **1601**A may include a spread spectrum code source.

In one set of embodiments, the multiple access code source **1601**A produces a code for a CI/DS-CDMA signal. In another set of embodiments, the multiple access code source **1601**A generates a CI code. In another set of embodiments, the channel-code source **1601**B generates a CI code.

The modulator **1609** performs any necessary combining of the input signals and impresses the signals onto the carriers. The carriers are optionally processed by a transmission system **1610** that couples the modulated carriers into a communication channel (not shown).

FIG. **17**A illustrates the multi-dimensional nature of coding provided to a CI/DS-CDMA signal produced by a CI transmitter. CI code chips $c_0, C_1, \ldots, C_{N-1}$ used to modulate individual carrier frequencies produces a carrier superposition a time-domain profile indicative of code chips $c'_0, c'_1, \ldots, c'_{M-1}$. The time-domain code may be a conventional direct-sequence code, a channel code, a CI code implemented as a multiple-access, spreading, and/or channel code, or any combination thereof. In one set of embodiments, the frequency-domain code may be a binary direct-sequence code and the time-domain code may be a CI code. In various embodiments of the invention, frequency-domain and/or time-domain chips may be interleaved in the time domain.

FIG. **17**B illustrates CI coding applied to a multi-dimensional signal. In one set of embodiments, a polyphase CI code $c_0, C_1, \ldots, C_{N-1}$ is applied to a set of carrier frequencies provided to an antenna array. Each data symbol is expressed by a code-chip value $c'_0, c'_1, \ldots c'_{M-1}$ corresponding to a different orthogonal diversity-parameter value, such as a different subspace. In another set of embodiments, the code-chip values $c'_0, c'_1, \ldots, c'_{M-1}$ are impressed upon carrier superpositions. The code chips $c'_0, c'_1, \ldots, c'_{M-1}$ are expressed as orthogonal values of at least one diversity parameter.

FIG. **17**C illustrates a three-dimensional diversity-parameter space. Each axis represents values of a different diversity parameter do. Orthogonal values are represented by a three-dimensional diversity parameters d_{xyz}. Diversity parameters in the diversity-parameter space may be modulated or otherwise impressed with at least one set of CI codes. One or more diversity parameters may represent a superposition of diversity-parameter values. For example, a time-domain axis or a phase-space axis can represent a superposition of multiple carrier frequencies.

In two dimensions, an instantaneous representation of a conventional stacked-carrier protocol transmitted and received by antenna arrays can be represented by an NXM matrix of subcarriers, where Nis the number of frequencies and M is the number of array elements at the receiver. The matrix elements can be modulated with at least one CI code. A CI code may be applied across frequencies (for example, to produce a CI superposition signal or a CI-based MC-CDMA signal), across subspaces, or across both. Time

introduces a third axis to produce an NXMXL space. CI code chips may be positioned across frequencies, subspaces, and/or time intervals. Multiple CI codes may be interleaved with respect to any diversity parameters.

A DS-CDMA code (a first dimension) may be modulated by another code (a second dimension). Thus, the first-dimension DS-CDMA code may be regarded as a carrier for the second code. In one embodiment of the invention, a binary-phase (0, π) DS-CDMA code is modulated with a second pseudo-noise code, such as a PSK code having a magnitude range within some small fraction of g. Either code may include a CI-based DS-CDMA code and/or a CI code. In another embodiment of the invention, the second code is a coherence-multiplexing code or some other code (e.g., a noise-like code) characterized by one or more code lengths. Similarly, DS-CDMA, CI, and/or CI/DS-CDMA codes may be impressed upon a coherence-multiplexing code, a code-length division multiple access code, or some other noise-like code.

Multi-dimensional codes may include codes derived from channel characteristics between at least one predetermined transmitter-receiver pair. For example, multipath and/or at least some other channel characteristics are typically unique for each transmitter-receiver link. Thus, link characteristics can be used to assign some form of coding to each transceiver. Link-characteristic coding may include CI codes and/or CI-based codes.

CI/DS-CDMA Array Processing

FIG. **18**B illustrates components of a CI receiver, such as a CI/DS-CDMA receiver. A receiver system **1816** couples transmitted CI signals from a communication channel. Receiver processing, such as filtering, down conversion, amplification, beam forming, etc., converts the coupled signals into electronic received signals. The received signals are processed in a time-to-frequency-domain converter **1820** that outputs data symbols modulated on the individual carriers. If the receiver system **1816** includes an antenna array and the converter **1820** provides time-to-frequency-domain conversion for each array element, the frequency-domain symbols may include multiple-access and/or multi-channel interference.

Various effects, such as multipath, receiver characteristics, and transmitter characteristics (e.g., array element spacing, beam directionality, spatial gain distributions, etc.), ensure that at least some of the interfering signals can be separated from each other. Diversity, such as spatial diversity, can be used to improve signal quality, increase bandwidth efficiency, or achieve some trade off between improved signal quality and increased throughput.

The interfering signals are coupled into a diversity combiner **1827** that combines the signals to generate desired signals having minimum noise and interference. The signals received by the separate antennas are independently demodulated before being applied to the combiner **1827**.

Demodulation, as used herein, may include synchronous demodulation, which may be performed with the aid of carrier and timing information derived from one or more received waveforms. A demodulator may provide one or more additional signal-processing operations, including, but not limited to, channel selection, bandwidth reduction, despreading, resampling, spectral equalization, matched filtering, timing/phase recovery.

The number of spatial sub-channels that can be processed by the combiner **1827** is typically equal to the number of receiver array elements. When CI is used with antenna arrays, array combining systems, and CI diversity combiners may be combined into a single diversity combiner, such as combiner **1827**.

A weight-generation system **1830** provides weights to the diversity combiner **1827**. An adaptive antenna array may include an MMSE diversity combiner or some other form of optimal combiner. The weight-generation system **1830** may select parameters accurately describing channel characteristics that minimize the mean squared error of the received signal, which decreases the signal error rate, suppresses interference, and maintains signal quality. These parameters may be estimated.

Parameters needed to optimize performance for diversity combining and/or sub-channel processing are typically determined from channel estimates and the instantaneous correlation of the received signals. Channel estimations may employ a multiple-pass system (not shown) to account for past, present, and future channel estimations. Because future references may be determined from a preceding pass, it is possible to refine channel estimations and accordingly achieve better weights. The weight-generation system **1830** may include a parameter estimator (not shown) adapted to process either or both the demodulated received signals prior to decoding and the combined received signal after demodulation and decoding by the receiver.

A symbol decoder **1828** decodes data symbols and provides blocks of undecoded symbols and/or decoded symbols to the weight-generation system **1830**. Symbol decoding may include channel decoding, demultiplexing, deinterleaving, error correction, etc. The symbol decoder **1828** may perform iterative decoding. In a CI/DS-CDMA system, the symbol decoder **1828** performs decoding with respect to the impressed DS-CDMA code.

Each received symbol may be evaluated with respect to a minimum mean square error or some other performance measurement. The minimum mean square error is a measure of error probability in a signal based on the mean value of the square of the error, $(y-\tilde{y})$, where $\tilde{y}$ is any estimate of y. In general, if y is a random variable having a mean value of $\bar{y}$, then choosing $\tilde{y}=\bar{y}$ minimizes the mean square error. Typically, it is necessary to estimate $\bar{y}$ based on supplied parameters. The accuracy and usefulness of the estimated mean square error is related to the quality of the parameters used in the estimation.

FIG. **18**C illustrates a CI receiver that represents a set of embodiments of the invention. An input coupler **1840** (such as an antenna) receives signals from a communication channel (not shown). The input coupler **1840** may be coupled to one or more receiver components, such as amplifiers and filters. In particular, a low-noise amplifier **1842** is provided to amplify a received signal. The amplified signal is coupled to an optional filter-and-down-convert component **1844**. The component **1844** may include a multi-stage frequency converter (not shown).

A variable-gain amplifier **1846** is shown coupled to an automatic gain control (AGC) and digital filter assembly **1850**. An A/D converter **1848** converts the analog gain-adjusted signal to a digital signal. The AGC and filter assembly **1850** separates the digital signal into a plurality of sub-carrier digital baseband signals that are combined in a combiner **1852**.

The A/D converter **1848** may optionally include a delta-sigma architecture. One set of delta-sigma architectures employs a feedback loop to provide a suitable over-sampling ratio. The A/D converter **1848** may optionally incorporate at least one band-pass filter in the feedback loop to allow the A/D converter **1848** to sample at an intermediate frequency.

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For example, the A/D converter **1848** may include a filter bank, such as a signal processor adapted to perform a Fourier transform, wavelet transform, or an equivalent operation.

Various system elements not shown may be incorporated into the receiver and/or the receiver components. For example, one or more synthesizers (not shown) may provide clock and/or local-oscillator signals. The receiver may include one or more phase-lock loops (PLLs) and/or tunable notch filters (not shown). In various embodiments of CI receivers, phase offsets (such as offsets resulting from timing mismatches, channel-induced phase offsets, clock drift, etc.) may be tracked and compensated with a PLL.

A weight generator (not shown) may be provided to calculate and/or apply weights to the subcarriers. Weights may be applied during A/D, filtering, and/or combining operations. Frequency offsets affecting the received signals may be compensated by one or more operations including carrier weighting, MUD, multi-channel detection, frequency translation at either or both the receiver and the transmitter, and adaptable combining. A symbol decoder (not shown) may follow the combiner **1852**. The symbol decoder (not shown) may provide soft-decision control to the weight generator (not shown) and may incorporate a feedback loop.

Various combinations of array processing and multicarrier protocols (such as described in U.S. Pat. Nos. 6,128,276, 5,671,168, 5,528,581, 5,973,642, 6,144,711, 6,211,671, and 6,008,760, which are hereby incorporated by reference) may be adapted for use with CI-based protocols to provide unusual improvements to system performance, signal quality, and throughput. CI may be implemented with various array-processing systems and techniques including, but not limited to, layered space time, space-frequency, spatial interferometry, vector-processing, matrix-processing, frequency diversity interferometry, marginal-isolation, beam-forming, interference-nulling, beam-steering, and blind adaptive array processing systems and methods. CI may be introduced to array processing systems and methods, such as described in U.S. Pat. Nos. 5,642,353, 5,592,490, 5,515,378, and 5,471,647, which are hereby incorporated by reference. CI may be implemented in array processing systems that provide any combination of diversity combining and sub-channel processing.

FIG. **19**A is a basic block diagram of a CI-based receiver implemented with a receiver array. A plurality of array elements **1916**.1 to **1916**.P are responsive to transmitted CI signals in order to generate a plurality of electronic receive signals. The transmitted signals may be transmitted from multiple, spatially separated, independent transmitters (e.g., mobile transceivers), multiple independent, co-located transceivers, a single transceiver adapted to transmit signals on a plurality of interfering channels, and/or a plurality of substantially co-located transceivers adapted to transmit data symbols on a plurality of interfering channels.

The receive signals are processed by a time-to-frequency converter (such as a plurality of FFTs **1920**.1 to **1920**.P) that separate the receive signals into a plurality of CI carrier-frequency components. The carrier-frequency components are coupled into a diversity combiner **1927** that includes a frequency combiner **1925** and a CI combiner **1929**. The frequency combiner **1925** combines signals received from the FFTs **1920**.1 to **1920**.P for each carrier frequency f_n to generate at least one signal corresponding to each carrier frequency f_n. The frequency combiner **1925** processes the receive signals to provide any combination of receiver performance and frequency reuse. The frequency combiner **1925** may generate a plurality of subchannels for each frequency wherein each frequency sub-channel corresponds to a particular signal frequency transmitted by a particular transmitter.

The CI combiner **1929** processes the multi-frequency signals produced by the frequency combiner **1925** to separate interfering data signals on each frequency sub-channel. The CI combiner **1929** may perform any necessary de-interleaving to compensate for data symbols spread over multiple diversity parameters.

The frequency combiner **1925** and the CI combiner **1929** may be provided with adaptive weights from a weight generator **1924**. The weights may be generated with respect to a known training sequence and/or estimates of the received data symbols. For example, a plurality of decoders **1928**.1 to **1928**.K decode the data signals received from the CI combiner **1929** to generate a plurality of data-symbol estimates. These estimates, as well as confidence measurements, may be used to generate hard or soft decisions from which weights are generated. The process of decoding may include adaptive weighting and/or iterative processing. Decoding may include error-detection coding, error-correction decoding, demultiplexing, despreading, compensation for channel distortions, decryption, etc. The decoders **1928**.1 to **1928**.K and/or the weight generator **1924** may include a parameter estimator (not shown).

The combiner **1929** may discard signals having one or more frequencies, signals in one or more subspaces, and/or signals from one or more antennas **1920**.1 to **1920**.P. For example, one or more received signals may be discarded to reduce the effects of noise and/or interference. The combiner **1929** and/or the decoders **1928**.1 to **1928**.K may include a decision processor (not shown) adapted to evaluate signal characteristics (e.g., power, SNR, SNIR, BER, interference level, channel distortion, etc.) in order to determine which signal(s) to discard. The decision processor (not shown) may update its determination of which signal(s) to discard relative to measured signal characteristics and/or one or more predetermined time intervals.

The decision processor (not shown) may provide a feedback signal to one or more remote transmitters from which signals are received. The feedback signal may include a performance indication of the received signals, channel estimates, and/or a known training sequence that allows the remote transmitter(s) to evaluate the channel. The feedback signal may be provided with control information to adjust or suggest adjustments to signal-transmission characteristics (e.g., signal power, CI carrier frequencies f_n, frequency offset f_o, frequency spacing f_s, number of CI carriers, pulse overlap, beam pattern, spatial gain distribution, signal polarizations, signal phases, interleaving, channel coding, etc.) to compensate for fading, inter-symbol interference, co-channel interference, jamming, etc. These types of transmission-signal adjustments may be made to perform power control, frequency-band adjustments (e.g., bandwidth exchange), link priority, multiplexing, multiple access, link security, throughput adjustments, adaptability to information type (e.g., voice or data), and ensure quality of service.

A diversity combiner (e.g., an MMSE diversity combiner) is used for diversity reception in various systems, such as an adaptive antenna array or a CI receiver. Diversity reception typically reduces or eliminates deep fades caused by multipath phase cancellations (i.e., multipath fading). Diversity combining also produces gain (relative to diversity switching or non-diverse reception) by effectively combining the power of multiple received signals. Diversity combining may be employed to optimize the quality of desired signals that are separated from interfering signals. The SNR (and/or

the signal-to-interference ratio) may be maximized in interferometry processes, such as CI and/or array processing. When CI is used with antenna arrays, array and CI diversity combiners may be combined into a single diversity combiner.

FIG. **19**B is a basic block diagram of a CI-based receiver having similar system components as those indicated by the same numbering in FIG. **19**A. However, the receiver shown in FIG. **19**B includes a combiner **1927** that does not have differentiated subsystems, such as the frequency combiner **1925** and the CI combiner **1929** shown in FIG. **19**A. Rather, the combiner **1927** is implemented as a combination of the frequency combiner **1925** and the CI combiner **1929**. Since array processing and CI combining processes can be similar, it is advantageous to combine these processes for some applications.

FIG. **19**C is a functional illustration of one possible embodiment of the combiner **1927** shown in FIG. **19**A. Each FFT **1920.1** to **1920**.P separates an input signal from an array element **1916.1** to **1916**.P into a plurality of frequency components f_1 to f_n. For example, the signals produced by FFT **1920.1** include $\{x_1(f_1)$ to $x_1(f_n)\}$. Signals produced by FFT **1920**.P include $\{x_p(f_1)$ to $x_p(f_n)\}$.

The frequency combiner **1925** includes a plurality of frequency-subspace combiners **1925.11** to **1925**.NK. Combiner **1925.11** generates a frequency-subspace signal $y(f_1,1)$ corresponding to frequency f_1 in spatial sub-channel 1. Combiner **1925**.N**1** generates a frequency-subspace signal $y(f_N,1)$ corresponding to frequency f_N in spatial sub-channel 1. In this particular embodiment of the invention, all of the frequency-subspace signals $\{y(f_1,1) \ldots y(f_N,1)\}$ corresponding to spatial sub-channel 1 are processed in a subsystem **1929.1** of the CI combiner **1929** to produce a CI signal y(k=1). Similarly, a CI signal y(k=K) is generated by a subsystem **1929**.K from a plurality of the Kth spatial sub-channel's signals $\{y(f_1,K) \ldots y(f_N,K)\}$ produced by frequency-subspace combiners **1925.1**K to **1925**.NK. In other embodiments, CI signal components may be distributed across multiple spatial sub-channels, time intervals, and/or other diversity-parameter values.

The frequency-subspace combiners **1925.11** to **1925**.NK are provided with complex weights $w(f_n,k)$ to help separate interfering signals into spatial sub-channels. Complex weights $\omega(f_n,k)$ are provided to the CI combiner **1929** to enhance the generation of CI signals y(k). The weights $w(f_n,k)$ and $\omega(f_n,k)$ may be generated with respect to one or more optimal-combining techniques. MMSE, ORC, maximum likelihood, equal gain, and/or other combining techniques may be employed. An iterative weighting process may be employed, such as a process that generates soft decisions and uses feedback. The weights may be generated via blind-adaptive processes.

FIG. **19**D illustrates one possible apparatus and method embodiment of the combiner **1927** shown in FIG. **19**B. A plurality of optimal-combining systems **1927.11** to **1927**.NK provide complex weights $\omega(f_n,k)w(f_n,k)$ to signals output by each FFT **1920.1** to **1920**.P. The complex weights $\omega(f_n,k)w(f_n,k)$ optimize sub-channel generation, as well as CI combining. In one possible variation of this embodiment, a weighted carrier or a weighted signal value $y(f_n,k)$ corresponding to a particular carrier frequency and subspace is provided at each optimal-combining system **1927.11** to **1927**.NK output. Values $y(f_n,k)$ corresponding to a particular CI signal are combined (e.g., summed). The resulting CI signal may be a CI-based coded signal, such as a CI/DS-CDMA coded signal or a CI-coded signal having a CI-based architecture. In this case, components of a kth CI signal correspond to a kth subspace. However, CI signal components may be distributed over multiple subspaces. Furthermore, CI signal components may be distributed over other diversity-parameter values, such as, but not limited to, time intervals, polarizations (linear and/or circular), and modes.

FIG. **20** illustrates a system adapted to transmit CI subspace coded data symbols into a multipath channel 99 and a receiver adapted to process and decode the CI subspace coded data symbols. One or more data streams are coupled into the transmitter via one or more data sources **1900.1** to **1900**.*n*. Each data stream is encoded with a code (e.g., a CI code or a CI/DS-CDMA code) by at least one coding system **1911.1** to **1911**.*n*. Each coding system **1911.1** to **1911**.*n* is coupled to a plurality N of transmitter elements **1910.1** to **1910**.N that couple the coded data into the communication channel 99.

A plurality P of receiver elements **1916.1** to **1916**.P are responsive to the transmitted coded data symbols to provide a plurality of received signals to a sub-space processor **1925**. The sub-space processor **1925** processes the received signals into separate sub-space signals. Sub-space processing may include blind-adaptive processing and/or may use known training sequences to generate and/or optimize subspace-processing weights. Various combining techniques, such as, but not limited to, MMSE, EGC, ORC, or maximum-likelihood combining, may be used.

Each subspace value generated by the sub-space processor **1925** may include one or more coded data symbols. The sub-space values are processed in a symbol decoder **1928** that may be integrated with the sub-space processor **1925**. The decoder **1928** decodes the coded data symbols. The decoder **1928** may generate a reference code for a matched filter. The decoder **1928** may adjust one or more signal parameters (e.g., phase, amplitude, etc.) of the coded data symbols with respect to a reference code. The decoder **1928** may combine the coded data symbols to separate at least one desired symbol from at least one interfering symbol. Thus, various combining techniques may be employed. The decoder **1928** may include a de-interleaver, a decision system, and/or a feedback loop to perform iterative decoding. Data-symbol estimates generated by the decoder **1928** may optionally be processed by a data processor **1930**.

The transmitted signal $x_n(t)$ due to an nth user can be expressed by:

$$x_n(t) = \sum_{i=1}^{B} b_n(i)s_n(t - iT)$$

where $b_n(i)$ is an ith coded data symbol, $s_n(t)$ is a corresponding signaling waveform. The channel impulse response of the nth user is expressed by:

$$h_n(t) = \sum_{l=1}^{L} a_{nl}g_{nl}\delta(t - i\tau_{nl})$$

where a_{n1} is the array response, g_{n1} is the path gain, and τ_{n1} is the path delay.

A signal received by one of the receiver elements **1916**.*p* is expressed by:

$$r_p(t) = \sum_{n'=1}^{n} x_{n'}(t) h_{n'}(t) + \sigma n(t)$$

where n(t) is a noise term. If the received signal $r_p(t)$ is processed by a space-time matched-filter receiver, the receiver output $y_n(i)$ is expressed by:

$$y_n(i) = \sum_{l=1}^{L} g_{nl}^{*} a_{nl}^{H} \int_{-\infty}^{\infty} r(t) s_n(t - iT - \tau_{nl}) \delta t$$

FIG. **21**A illustrates an embodiment of a space-time matched-filter receiver of the present invention. A plurality P of received signals $r_1(i)$ to $r_p(i)$ are coupled to a set of demodulators **2016**.**1** to **2016**.P that remove the signaling waveforms $s_n(t)$. A plurality P of matched filters **2020**.**1** to **2020**.P compensate for the space-time effects of the channel 99. Signals corresponding to at least one space-time subspace are combined to generate at least one received coded data symbol $y_n(t)$. For example, the coded data symbols $y_n(t)$ may include CI-coded symbols and/or CI-based coded data symbols. A symbol decoder **2028** processes the coded data symbol $y_n(t)$ to generate at least one data-symbol estimate.

FIG. **21**B illustrates an embodiment of a space-frequency matched-filter receiver of the present invention. A plurality P of matched filters **2020**.**1** to **2020**.P compensate for the space-frequency effects of the channel 99. Signals corresponding to at least one space-frequency subspace are combined to generate at least one received coded data symbol $y_n(t)$.

Since CI-based signals can be processed by time-domain and frequency-domain receivers, in some cases it can be advantageous to process received signals in both the time domain and the frequency domain. Thus, received CI signals may be processed by separate time-domain and frequency-domain receivers. Alternatively, received CI signals may be processed by a combined time-domain and frequency-domain receiver.

FIG. **21**C illustrates a space-time receiver of the present invention. A plurality of transmitted signals are received and processed by the receiver. The plurality of transmitted signals are coded to carry at least one data stream. Each symbol of a particular data stream is spread over the plurality of transmitted signals. For example, spreading may be performed via CI codes and/or CI/DS-CDMA codes.

The received signals $r_1(i)$ to $r_p(i)$, such as signals received from spatially separated transmitters, have different delay profiles. In a multipath environment, multiple replicas of the transmitted signals are received at different times. The received signals $r_1(i)$ to $r_p(i)$ are coupled to a set of demodulators **2016**.**1** to **2016**.P that remove the signaling waveforms $s_n(t)$.

A reference-code generator **2028** is coupled to a plurality P of matched filters **2020**.**1** to **2020**.P that compensate for the space-time effects of the channel 99. The combination of applying codes to the filters **2020**.**1** to **2020**.P and combining the filtered signals decodes the coded symbols. A jth user's code provides an ith matched filter with the following filter function:

$$h'^{-1}_i(t) = c^{*}_{jp}(t) h_i^{-1}(t)$$

where $c^{*}_{jp}(t)$ represents a pth complex-conjugate chip of a jth user's code. Preferably, the filter-function term, $h'^{-1}_i(t)$, is adapted to minimize the effects of noise and/or interference. Codes and/or the filter function, h_i^{-1} (t) may be adjusted to compensate for channel distortion. If the code is a CI code, the system may be designed without code-length constraints. For example, orthogonal CI code lengths may be adapted to a given number of transceiver elements or subset of transceiver elements, whereas Walsh codes are constrained to code lengths of powers of two.

FIG. **21**D illustrates a space-frequency receiver of the present invention. A plurality of transmitted signals r(t) are received and processed by the receiver. The plurality of transmitted signals are coded to carry at least one data stream. In one form of space-frequency coding, each symbol of a particular data stream is spread over a plurality of same-frequency transmissions. A particular information signal may be provided with (e.g., modulated by) a code bit associated with each antenna that transmits the signal. In another form of space-frequency coding, an information signal is transmitted on multiple carrier frequencies in addition to multiple antennas. Other forms and variants of space-frequency coding may be performed. In any of these cases, it is preferred that spreading be performed via CI codes and/or CI/DS-CDMA codes.

FIG. **21**E shows a generalized illustration of a multi-element receiver of the present invention. A plurality of interfering transmitted signals r(t) are received and processed by a spatial demultiplexer **2016**, which separates a plurality of desired signals $y'_1(t)$ to $y'_p(t)$ from one or more interfering signals. A symbol decoder **2028** processes the signals $y'_1(t)$ to $y'_p(t)$ with respect to code chips c_{jp} generated by a decode-weight generator **2026**. The desired signals $y'_1(t)$ to $y'_p(t)$ are weighted and combined with respect to some predetermined combining process, such as MMSE, EGC, ORC, and/or maximum-likelihood combining to generate a data-symbol stream y(t). Channel compensation may be integrated into demultiplexing and/or decoding.

FIG. **21**F shows an alternate embodiment of a multi-element receiver of the present invention. A spatial demultiplexer **2017** receives a plurality of interfering transmitted signals r(t) from a communication channel (not shown) and a plurality of code chips c_{jp} generated by a decode-weight generator **2026**. The received signals r(t) are weighted and combined to reduce interference from interfering spatial subchannels and/or perform decoding. It is preferable that decoding and coding operations be performed via CI codes and/or CI/DS-CDMA codes.

FIG. **21**G is a functional illustration of a multi-element receiver of the present invention. Symbols and indices used in the description of this embodiment do not necessarily correspond to the same symbols used elsewhere in the specification.

A plurality k of receiver elements **2016**.**1** to **2016**.*k* provide signals $d_1(t)$ to $d_k(t)$ (illustrated by a received signal set **2051**). A breakdown **2052** of the received signals $d_1(t)$ to $d_k(t)$ illustrates a linear combination of transmitted information signals $s_j(t)$ (j=1 to k) scaled by complex channel parameters a_jk indicative of channel distortion, such as multipath fading, inter-symbol interference, path loss, etc. Noise, although not shown, may be considered to be present in the breakdown **2052** of received signals. The number of transmitted signals $s_j(t)$ in each received signal $d_k(t)$ is preferably less than or equal to the number of received signals $d_k(t)$ (e.g., number of receiver elements) having algebraically unique combinations of the unknown transmitted signals $s_j(t)$.

A code generator **2027** and a subspace-weight generator **2029** provide a k'Xk matrix of weights applied to at least one set of received signals $d_1(t)$ to $d_k(t)$. The value k' represents the number of unknown transmitted signals $s_j(t)$, which may be less than or equal to the number k of received signals $d_1(t)$ to $d_k(t)$. The code generator **2027** provides at least one complex code, such as a jth code Σc_{jk}. The subspace-weight generator **2029** provides sub-space weights β that are used to reduce interference between received samples of the transmitted signals $s_j(t)$. The result of applying the sub-space weights β is that the interfering spatial channels are substantially separated. The separated spatial sub-channels are indicated by sub-channel terms $y_1(t)$ to $y_k(t)$ in a dot-product representation **2055** of the signals $d_1(t)$ to $d_k(t)$ with the k'Xk weight matrix. The terms $y_1(t)$ to $y_k(t)$ are represented by a decomposition **2056**.

The decomposition **2056** illustrates that a plurality of coded data symbols are present in each subchannel. In fact, after sub-channel processing, each sub-channel term $y_k(t)$ is represented by a linear combination of transmitted signals $s_j(t)$. Thus, the multiplication of each term $y_1(t)$ to $y_k(t)$ by a jth code, c_{j1} to c_{ik}, and a subsequent summation process **2057** provides an estimate $r_j(t)$ of the jth transmitted signal $s_j(t)$. Various optimization techniques, including iterative soft-decision techniques, may be employed to reduce the effects of noise and/or interference.

FIG. **22** illustrates a receiver array processor that provides an additional dimension to coding. A plurality P of receiver elements **2016**.1 to **2016**.P receive coded transmissions to generate received signals $r_1(t)$ to $r_p(t)$. The received signals $r_1(t)$ to $r_p(t)$ are processed in a plurality of filter banks **2040**.11 to **2040**.PK. The filter banks **2040**.11 to **2040**.PK and/or the receiver elements **2016**.1 to **2016**.P may provide conversion to baseband and/or intermediate frequencies. For example, received signal $r_1(t)$ is processed by K sets of filters **2040**.11 to **2040**.1K, where K is the number of data channels to be separated. Each filter (such as filter **2040**.11) may be a time domain matched filter expressed by a plurality L of delay taps. Digital filters, such as polyphase filters, adapted to perform down sampling may be adapted to perform up sampling.

Filtered signals from different receiver elements **2016**.1 to **2016**.P for each of the K data symbols are optionally weighted with complex weights **205**.111 to **205**.PKL. Applied weight values a_{pkl} correspond to at least one of receiver element p, data symbol k, and path l. The weighted signals are combined with summing circuits **2042**.1 to **2042**.K. The combined signals may optionally be weighted **206**.111 to **206**.P1L and combined **2045** to produce a vector estimate $y_1(t)$ to $y_x(t)$ of the transmitted data vector. Coding may be integrated into weights g_{11} to g_{PL} and/or weights a_{111} to a_{PKL}.

The vector estimate $y_1(t)$ to $y_x(t)$ is optionally processed by a decoder **2028**. The decoder **2028** may decode data symbols that are encoded via one or more codes, such as, but not limited to, multiple-access, channel, spreading, encryption, and error-correction codes. Preferably, the codes are CI and/or CI-based codes. Either or both code chips and weights may be adjusted with respect to channel estimation. Code and/or weight adjustments may be made with respect to some optimization process. For example, codes and/or weights may be adjusted to optimize some measurement, such as signal power, SNR, SNIR, etc.

FIG. **23**A illustrates one of many possible CI/DS-CDMA signal structures. A repetitive CI pulse structure (such as a CI pulse structure characterized by uniformly spaced carriers) is provided with coding that generates a direct-sequence-like time-domain structure. Polyphase codes may be applied to individual carriers to produce a direct-sequence structure. Alternatively, direct-sequence codes may be applied to the time-domain pulses to produce a direct-sequence structure.

A repetitive direct-sequence code $C_1=\{c_1, c_2, \ldots, C_N\}$ is provided with data symbols $d_1, d_2, \ldots, d_m$. In this case, overlapping pseudo-orthogonal pulses are provided with DS-CDMA codes. The number of carriers is N/2 and the repetition rate is related to the inverse of the carrier spacing f_s. The pulses, as well as the direct-sequence periods may overlap.

One or more transmitter elements may transmit the signal illustrated by FIG. **23**A. Each of a plurality of transmitter elements may transmit a separate signal component, such as a pulse or a carrier frequency. Phase sweeping may be applied to one or more transmitter elements to achieve spatial-diversity benefits in addition to directionality.

FIG. **23**B illustrates signal structures of one set of embodiments of a multi-dimensional CI/DS-CDMA method and apparatus of the invention. A plurality k of coded data streams are used to convey one or more streams of data symbols d_{mfk}. For example, an mth data bit d_{mf1} of a first (k=1) coded data stream is provided with an mth N-chip code $C_{mf1}=\{c_{1mf1}, c_{2mf1}, \ldots, c_{N\,mf1}\}$, where f is some diversity-parameter space.

Codes C_{mfk} may differ for different values of m, f and/or k. Similar codes may be used for different data symbols d_{mfk} if it is possible to differentiate between codes due to one or more diversity-parameter values. Multiple diversity-parameter values may be impressed with one or more coded data streams. Multiple diversity-parameter values may be modulated with multiple coded data streams. The interfering data symbols may be separated via any combination of sub-space processing and decoding.

FIG. **24** illustrates a signal structure derived from an alternate set of apparatus and method embodiments of the invention. A first-layer direct-sequence code $C_1=\{c_1, c_2, \ldots, c_N\}$ (which may be a CI/DS-CDMA and/or CI code) is provided as a carrier for coded data sequences. For example, an mth data bit d_m is impressed onto a second-layer code $CC_1=\{cc_1, cc_2, \ldots, cc_{N'}\}$ having a duration of a plurality of first-layer code C_1 periods. In this case, each code bit $cc_{mN'}$ spans one period of the first-layer direct-sequence code C_1. Data symbols and data streams can be separated via differences in either the first-layer-layer code C_1 or the second-layer code CC_1.

Although transceiver arrays are typically regarded as spatially diverse antenna arrays, any diversity parameter may be used to characterize a transceiver array. The importance of transceiver arrays with respect to many aspects of this invention is particularly directed to the sub-space processing. CI signals may include any sub-space bases as carriers. CI signals may be encoded via sub-space processing and/or spread across multiple sub-space bases.

Sub-space bases, as used herein, refers to any overlapping set of diversity parameters that are processed, such as via interferometry, to produce independent, substantially orthogonal sub-channels are generated. Some sub-space bases include spatial sub-spaces, directional sub-spaces, polarization sub-spaces, temporal sub-spaces, phase sub-spaces, quasi-orthogonal code sub-spaces, quasi-orthogonal wavelet sub-spaces, frequency-band subspaces, CI phase-space subspaces, and any combination of the above-mentioned subspaces.

In-phase and quadrature-phase subspaces may be established, such as via a pair of orthogonal diversity parameters (e.g., perpendicular polarizations, a phase offset of 90

degrees between two signals, orthogonal frequencies, orthogonal codes, orthogonal time intervals, etc.). In-phase and quadrature-phase subspaces may be designated as a pair of orthogonal subspaces. One subspace is used to convey a signal magnitude related to magnitude of an in-phase component and a second subspace is used to convey a signal magnitude representing a quadrature-phase signal magnitude.

FIG. **25**A illustrates a basic subspace processing method of the present invention. A data-sequence vector u having length N is provided to a transmit filter **2501** before being coupled into a communication channel 99. The channel acts on a transmitted data vector x via an N×N non-singular matrix H and an additive noise vector n having a variance of $N_o/2$. A signal vector y received from the channel 99 is expressed by:

$$y=Hx+n$$

The received signal vector y is processed by a matched filter **2502** to generate an output signal vector z, which is expressed by:

$$z=R_f x+n'$$

where R_f =H*H and n'=H*n. An estimate of x given z is expressed by:

$$x=R_b z+e$$

where $R_b^{-1}=R_f(N_o/2)R_{xx}^{-1}$, R_{xx} is the covariance of x, and e is the MMSE error.

Additional processing, such as any of various adaptive feedback techniques, may be incorporated at the receiver end.

Although sub-space processing is commonly associated with array processing, the methods of the present invention may incorporate decoding into sub-space processing techniques. In one set of embodiments, sub-space processing and CI combining methods are combined. Sub-space processing may include frequency-diversity interferometry and/or interferometry between one or more sets of diversity-parameter values including, but not limited to, polarizations, codes, modes, phases, and delays.

FIG. **25**B illustrates a subspace processing method of the present invention that employs decision feedback. In this case, Cholesky factorization provides:

$$R_f=G^* S_o G$$

where S_o is a diagonal matrix and G is a monic, upper-diagonal matrix. A decision feedback equalizer includes a feed-forward filter **2503**, a decision system **2504**, and a feedback filter **2505**. A decision feedback equalization algorithm that may be used in conjunction with the invention is represented by:

$$\tilde{z}:=S_o^{-1}G^{-*}H^* y$$

for $k=0,N-1$

$$\hat{x}_{N-k} := \text{decision}\left(\tilde{z}_{N-k} - \sum_{i=1}^{k} g_{N-k,N-k+i}\hat{x}_{N-k+i}\right)$$

end

where g_{ij} are elements of G and $\hat{x}_i$ and $\hat{z}_i$ are elements of $\hat{x}$ and $\hat{z}$, respectively.

A decision feedback equalizer may reorder the received substreams by rearranging the rows and columns of H. For example, a layered processing approach may be employed. Symbols are detected sequentially and interference from previously detected symbols is subtracted. Received vector elements are weighted to null (or reduce) interference from undetected symbols.

CI/DS-CDMA Frequency Agility

CI-based signals can mimic the bandwidth characteristics of conventional protocols, such as TDMA (e.g., GSM) and DS-CDMA protocols. Adjacent overlapping CI carriers appear as a continuous spectrum over the bandwidth of the conventional protocol. However, frequency-diversity benefits diminish as the coherence bandwidth of the channel increases.

FIG. **26**A is a frequency-domain plot of an alternative CI-based protocol and FIG. **26**B is a frequency-domain plot of an associated conventional protocol. For example, the CI-based protocol may be CI/DS-CDMA and the conventional protocol may be DS-CDMA. The CI/DS-CDMA signal has the same total bandwidth as the conventional signal. However, the CI carriers that characterize the CI-based protocol are distributed non-continuously throughout a given frequency band.

The CI carriers may be predetermined or dynamically chosen to enhance frequency-diversity benefits, compensate for channel distortions, avoid interference, ensure quality of service, adapt to different link priorities, provide for changing data rates, accommodate coding, and/or provide multiple access. The CI carriers may be grouped with respect to available, but not necessarily continuous, frequency bands. The CI carriers may be selected dynamically with respect to changing frequency allocations, different applications, changes in throughput, changing system requirements, different numbers of users, etc.

CI carriers may be selected or adjusted to affect various control procedures, such as, but not limited to, power control, carrier sense procedures, authentication, identification, validation, switching, routing, encryption key transmission, and/or conveying control signals. One or more CI carriers may be adjusted with respect to amplitude, frequency, and/or phase. Other diversity parameters, such as polarization, directionality, etc. may be adjusted.

FIG. **27** illustrates carrier placements for multiple CI channels that simultaneously benefit from frequency diversity of nearly the entire frequency band. Frequency profiles of the CI carriers are arranged such that adjacent carriers correspond to different channels. However, frequency components associated with each channel are preferably positioned throughout a relatively wide frequency band. In one set of embodiments, the aggregate bandwidth of the CI frequency components equals the bandwidth of a corresponding conventional single-carrier signal. Although the aggregate signal bandwidth of the CI-based signal is identical to the bandwidth of the conventional signal, the CI-based signal enables wideband-like frequency diversity benefits.

Variations to carrier spacing and distributions of each user's signals may be made without departing from the scope of the present invention. For example, the carriers of one or more users may overlap. The number of users may be less than or greater than the number of carriers. The relative frequency-domain positioning of users' signals may be changed with respect to time. Carrier frequencies may be positioned uniformly or non-uniformly. Users may simultaneously share one or more carrier frequencies. Carrier frequencies may be selected and/or adjusted with respect to channel conditions, such as interference, distortion, and jamming. Predistortion may be applied to the carriers. Carriers having particular frequencies may be amplified,

attenuated, and/or avoided with respect to channel conditions that affect carrier reception or that cause the carriers to impact the performance of some other system.

FIG. **28**A illustrates a set of methods for generating CI-based signals. Since CI is a multicarrier-based signal architecture, a step of providing for carrier generation **2801** may precede or follow at least one time-domain shaping step **2802**. Alternatively, carrier generation **2801** and time-domain shaping **2802** may be combined. A multicarrier signal having a predetermined time-domain profile may be coupled **2803** into a communication channel.

Carrier generation **2801** may include providing for a CI-based multicarrier architecture. For example, carrier generation **2801** may include any method of transforming frequency-domain data symbols into one or more time-domain signals characterized by a multicarrier architecture. Various transformation techniques may be used, including, but not limited to Fourier transforms, wavelet transforms, and Walsh transforms. Various permutations and methods of performing these transforms may be incorporated into the carrier generation step **2801**.

Carrier generation **2801** may include the generation of harmonic or non-harmonic carriers. For example, a pulse generator or some other harmonic source may be employed to generate signals having a substantially uniform frequency spacing. A plurality of local oscillators or other signal-generation systems may be coupled together to provide carrier generation. Non-linear devices may be used to generate harmonically rich signals. Various methods involving cross coupling, interferometry, feedback, and/or mode locking may be used to generate multicarrier signals. Alternatively, a wave look-up table may provide an integral part of a carrier-generation step **2801**.

Time-domain shaping **2802** may include any combination of pre-processing and post-processing relative to carrier generation **2801** that helps shape the time-domain characteristics of a superposition of carriers. Shaping **2802** may be performed via selection of frequency-bin values in a Fourier transform operation. Consequently, time-domain shaping **2802** may include calculating frequency-bin values. Typically, time-domain shaping includes impressing data symbols onto the carriers. However, data modulation may be performed in the carrier-generation step **2801**.

Alternatively, CI codes may be generated without physically generating carriers. Since CI codes are based on relations between carriers, the carrier-generation step **2801** may simply provide one or more basic CI codes. Carrier generation **2801** may include calculating or retrieving complex variations of simple CI codes. Time-domain shaping **2802** may provide data modulation or any other form of signal shaping prior to coupling **2803**.

The coupling step **2803** may perform any necessary signal processing to facilitate conveyance by a communication channel. For example, the coupling step **2803** may include filtering, amplification, up-conversion, modulation, etc.

FIG. **28**B illustrates a set of methods for receiving one or more CI-based signals. CI signals are coupled **2804** out of a communication channel and processed in a frequency-domain combining step **2805**. Signals produced by frequency combining are optionally passed to a data-processing step **2806**.

The coupling step **2804** may include any of various signal-processing steps (not shown) required to convey a received signal into at least one intermediate-frequency or baseband signal. The combining step **2805** may separate received signals into carrier-signal components and provide complex weights to the signal components prior to combining. Various combining techniques may be used, including, but not limited to MMSE, maximum likelihood combining, EGC, zero forcing, etc. The combining step **2805** may employ iterative feedback techniques and/or equalization techniques.

Data processing **2806** may be performed on signals output from the combining step **2805**. Various data processing techniques that may be employed include, but are not limited to, demodulation, decoding, symbol estimation, correlation, etc.

Alternatively, the combining step **2804**, when performed on a CI-coded signal, may include decoding. For example, combining **2804** may include matched filtering, coherence multiplexing, and/or some complementary signal processing (e.g., phase shifting) provided to the received signal relative to some received or locally generated reference signal.

Performance Overview of CI-Based Protocols

CI provides substantial improvements in throughput, power efficiency, and signal quality while maintaining the time-domain characteristics of various multiple-access protocols. Published performance improvements of CI with various conventional multiple-access protocols are summarized as follows:

In MC-CDMA, CI coding enables a seamless transition between orthogonal and quasi-orthogonal coding. CI codes are capable of supporting twice as many users, doubling network capacity without performance degradation.

In TDMA, CI coding provides over 10 dB performance gain at probability of errors of 10^{-3}. CI-TDMA with 2N symbols per burst still outperforms tradition TDMA (with the usual N symbols per burst and using a DFE equalizer) by up to 7 dB at a probability of error of 10^{-3}.

In DS-CDMA, CI provides a 14 dB performance improvement at probability of errors of 10^{-2}. Furthermore, CI applied to DS-CDMA can double the capacity of DS-CDMA while maintaining performance improvements.

CI-OFDM provides a 10 dB performance benefit over OFDM at a probability of error of 10^{-3}. CI-OFDM can trade off some of its performance benefit for significant gains in the throughput of OFDM systems. Coded CI-OFDM offers the same throughput as ideal OFDM with the performance of conventional coded OFDM. Furthermore, CI-OFDM eliminates problems of high PAPR.

CI Codes

Basic CI Codes

CI codes, as used herein, may include basic CI codes or advanced CI codes. CI codes are based on mathematical relationships between CI carriers and phase spaces. CI codes can be used as direct-sequence codes, multicarrier codes (e.g., MC-CDMA), etc. Applications of CI codes can be extended to any application of conventional binary direct sequences, including but not limited to, spread spectrum, multiple access, channel coding, encryption, anti jamming, etc. CI codes may be applied across any set of orthogonal or quasi-orthogonal diversity-parameter values or subspaces. Although CI codes can be represented with respect to phase relationships generated by vector precession in the complex plane, the implementation of CI coding can be extended to circular, elliptical, and linear polarizations.

In one set of embodiments of the invention, basic CI polarization codes may be based on vector precession in a two- or three-dimensional polarization plane. Advanced CI codes may be based on basic CI polarization codes. Similarly, vector rotation in a plane or higher-dimension field of other orthogonal bases may be used to generate basic and/or advanced CI codes. The basic family of CI codes (also

referred to as basic CI codes) can be generated from an M×M matrix of elements having phases ϕ_{mn} described by:

$$\phi_{mn}=2\pi mn/M+2\pi f_o m/f_s M,$$

where m and n are row and column indices, respectively. M may have any positive integer value. The second term in ϕ_{mn} is an optional phase shift applied to all terms in a row. The phase-shift value corresponds to a carrier frequency offset f_o and a sub-carrier separation f_s. A basic CI code on can be a row or column vector consisting of terms:

$$c_m = e^{im\phi'}\sum_{n=0}^{N-1} e^{imn\phi}$$

where $\phi=2\pi/M$ and $\pi'=2\pi f_o/f_s M$.

Some of the CI codes are complex-conjugate pairs. For example, correlations between CI codes are expressed by the following relationship:

$$\mathrm{corr}_{m,m'} = \left(\frac{1}{M}\right)e^{i(m+m')\phi'}\sum_{n=o}^{M-1} e^{in(m+m')\phi}$$

The correlations are non-zero for (m+m')=M.

CI codes may have polyphase and/or multi-magnitude values. A CI code set may include one or more binary code vectors corresponding to at least one conventional binary-phase code. In the case where CI codes include complex-valued chips, the real and imaginary values may be impressed upon different orthogonal parameters. For example, a magnitude corresponding to a real value may be modulated onto an in-phase carrier component whereas a corresponding imaginary value may be modulated onto a quadrature-phase carrier component. Orthogonal components may include, but are not limited to, perpendicular linear polarizations, left-hand and right-hand circular or elliptical polarizations, orthogonal polarization spins, subspaces (e.g., spatial, directional, temporal, phase, polarization, etc.), orthogonal frequencies, orthogonal time intervals, direct-sequence codes, etc. Modulation may include one or more of any modulation type, such as phase modulation, amplitude modulation, frequency modulation, polarization modulation, etc.

Phase shifts corresponding to CI code chips may be impressed upon a single carrier or onto multiple carriers. In one embodiment, phase shifts are impressed relative to a transmitted or locally generated reference phase. In another embodiment, differential phase modulation (DPM) is employed. In one embodiment, DPM may be employed on a single carrier. In another embodiment, DPM is applied to a multicarrier transmission protocol. In one embodiment, each phase shift is conveyed as a phase differential between at least two carriers.

CI codes may be applied to ordinary direct-sequence (e.g., DSSS or DS-CDMA), MC-CDMA, OFDM, coded OFDM, Discreet Multitone, Wavelength Division Multiplexing (WDM), ultra-dense WDM, Multi-tone CDMA, Discreet Wavelet Multitone, Multi-code spread spectrum (such as described in U.S. Pat. No. 6,192,068), or any of the Carrier Interferometry protocols (such as described in Applicant's papers, patents, and patent applications that are incorporated by reference). In the case where CI codes are utilized in a multicarrier transmission protocol, phase-shift coding may be accomplished in any of several ways. Each carrier may be phase shifted with respect to each chip of a CI code chip sequence. Each carrier may be modulated with respect to any single-carrier modulation scheme. Each carrier may be modulated with one or more subcarriers that are encoded with CI code chips. Each carrier may be provided with at least two diversity parameters that are modulated to convey real and imaginary parts of the CI code chips.

Multicarrier signals may be defined by any set of substantially orthogonal diversity-parameter values. These diversity parameters may include, without limitation, frequency, phase space, polarization (including linear, circular, elliptical) in two or three dimensions, mode, code (e.g., DS and/or CI), time, any type of subspace, and any combination of diversity parameters.

The basic CI codes can be combined (with each other or with other direct-sequence codes) to form other families of polyphase and/or poly-magnitude CI codes. In any set of CI codes, the chip sequences may be truncated, appended, rearranged, concatenated, etc., to generate orthogonal or quasi-orthogonal chip sequences. Codes of similar or different lengths may be concatenated. Different chip sequences may be combined in such a way that at least one chip sequence is interleaved with chips from at least one other code.

CI code vectors may be multiplied by other code vectors, including, but not limited to, direct-sequence codes, complementary codes, and/or other CI codes. Groups of CI code chips may be modulated (scaled and/or shifted) with respect to other code chips. For example, a CI code may be overlayed with a long code, a Hadamard-Walsh code, a Barker code, a Gold code, a Kasami code, another CI code, or some other code.

CI coding may include multiple levels of coding wherein at least one set of code chips modulates at least one other set of code chips.

The basic CI codes of a particular length form an orthonormal basis. New orthonormal bases can be generated by linearly combining CI codes of a particular length. More advanced permutations of CI codes may also be combined to form orthonormal bases. The orthonormal bases may be multiplied by code chips of other sequences, such as Hadamard-Walsh, Gold, CI, etc.

Data symbols may be mapped to CI codes to effect channel coding. For the purpose of mapping, a set of CI codes may be doubled by including a code set multiplied by the value −1 (e.g., bi-orthogonal codes). CI codes may be used to generate trans-orthogonal (e.g., simplex) codes. Quasi-orthogonal mapping may be performed by phase shifting or scaling the CI codes. A second set of orthogonal CI codes may be generated by rotating the phase of a first code set by $\pi/2$, thus providing in phase and quadrature phase CI codes.

CI codes may be decoded in the same manner in which conventional direct-sequence or multicarrier codes are decoded. A received signal may be correlated with a complex-conjugate code. The received signal may be processed with an FIR filter having coefficients set appropriately to decode a desired signal. The received signal may be sampled and summed. Optionally, samples of the received signal may be weighted prior to being summed to compensate for any of various factors, such as channel effects, transmitter-side encoding (e.g., to reduce PAPR), jamming, etc. Weighting may be performed with respect to one or more optimization processes in which weights are adjusted with respect to some measurement, such as SNR, BER, received signal power, etc.

The received signal may be phase shifted with respect to chip phases of a decoding signal. If a received signal includes multiple samples per chip interval, the chip samples may be time shifted with respect to the chip phases of the decoding signal. In another embodiment, the samples corresponding to each chip are cyclically shifted with respect to a decode chip sequence. Subsequent processing, such as sampling, adding, comparison, quantizing, and/or decision making (hard and/or soft) may be performed to evaluate data symbols measured after the decoding process.

Advanced CI Codes

Advanced CI codes can involve one or more types of processing applied to basic CI codes. Some examples of advanced CI codes illustrated herein include matrices resulting from processing basic CI codes with code vectors from a Hadamard-Walsh matrix, matrices resulting from vectors derived from Hadamard-Walsh/CI matrices, and expanded CI matrices based on Hadamard-Walsh matrix expansion. The term, advanced CI code, may describe many other forms, variations, and implementations of CI coding.

FIG. **29**A shows a conventional 4×4 Hadamard-Walsh matrix $HW_{4\times4}$. An nth row of the matrix is an orthogonal Hadamard-Walsh code vector $HW_{4\times4}(n)$. Each code vector $HW_{4\times4}(n)$ has zero cross correlation with the other code vectors $HW_{4\times4}(n'\neq n)$ and a non-zero correlation with itself.

FIG. **29**B shows a basic 4×4 CI matrix, $CI_{4\times4}$. An nth row of the CI matrix $CI_{4\times4}$ denotes a CI code vector, $CI_{4\times4}(n)$. CI matrix (row x column) sizes are not constrained to powers of two. Basic N×N CI matrices may be generated with any value of N.

FIG. **30**A shows the 4×4 CI matrix $CI_{4\times4}$ multiplied by values of the first-row Hadamard-Walsh vector, $HW_{4\times4}(1)$. Each column value of vector $HW_{4\times4}(1)$ multiplies a corresponding column of the CI matrix $CI_{4\times4}$. In this case, the vector $HW_{4\times4}(1)$ consists of all ones. Thus, the CI matrix $CI_{4\times4}$ multiplied by $HW_{4\times4}(1)$ produces the original CI matrix, $CI_{4\times4}$.

FIG. **30**B shows the 4×4 CI matrix $CI_{4\times4}$ multiplied by values of the second-row Hadamard-Walsh vector, $HW_{4\times4}(2)$. The row vectors in FIG. **30**B are the same as the row vectors in FIG. **30**A, except that their order in the matrix has been cyclically shifted by two positions.

FIG. **30**C shows the 4×4 CI matrix $CI_{4\times4}$ multiplied by values of the third Hadamard-Walsh row vector, $HW_{4\times4}(3)$. The first and third rows of the matrix shown in FIG. **30**C correspond to the third and fourth rows of the 4×4 Hadamard-Walsh matrix shown in FIG. **29**A. The second and fourth rows of the matrix shown in FIG. **30**C are quaternary-phase vectors that do not correspond to either of the two quaternary-phase vectors in the 4×4 CI matrix $CI_{4\times4}$ shown in FIG. **29**B. The quaternary-phase code vectors shown in FIG. **29**B and FIG. **30**C form an orthogonal code set.

FIG. **30**D shows the 4×4 CI matrix $CI_{4\times4}$ multiplied by values of the fourth Hadamard-Walsh row vector, $HW_{4\times4}(4)$. The row vectors in FIG. **30**D are the same as the row vectors shown in FIG. **30**C, except that their order in the matrix has been cyclically shifted by two positions.

FIG. **31**A illustrates a selection of the quaternary-phase vectors from the matrices shown in FIG. **30**A and FIG. **30**C. These vectors form a 4×4 poly-phase code matrix $PC_{4\times4}$ shown in FIG. **31**C. The vectors PC4×4(n) shown in FIG. **31**C have zero autocorrelation and zero cross-correlation for code vectors that are not complex conjugates of each other. None of the CI code vectors in PC4×4 include an all-ones vector.

FIG. **31**B illustrates a selection of binary-phase vectors from the matrices shown in FIG. **30**A and FIG. **30**C. These vectors are the components of the basic Hadamard-Walsh matrix $HW_{4\times4}$ shown in FIG. **29**A.

FIG. **32**A shows an 8×8 Hadamard-Walsh matrix $HW_{8\times8}$ generated from the 4×4 Hadamard-Walsh matrix $HW_{4\times4}$ using the Hadamard-Walsh matrix-expansion technique. This technique uses a $2^{n-1}\times2^{n-1}$ matrix $A_{2^{n-1}\times2^{n-1}}$ to generate a $2^n\times2^n$ matrix $A_{2^n\times2^n}$:

$$A_{2^n x 2^n} = \begin{bmatrix} A_{2^{n-1} x 2^{n-1}} & A_{2^{n-1} x 2^{n-1}} \\ A_{2^{n-1} x 2^{n-1}} & -A_{2^{n-1} x 2^{n-1}} \end{bmatrix}$$

where A is a matrix typically characterized by orthogonal code vectors.

FIG. **32**B shows an 8×8 CI matrix $PC4_{8\times8}$ generated from the 4×4 polyphase CI matrix shown in FIG. **31**C via the Hadamard-Walsh matrix-expansion technique. Each of the 8 code vectors is a quaternary 8-chip code. The first and third vectors $PC4_{8\times8}(1)$ and $PC4_{8\times8}(3)$ are complex conjugates of each other. Other complex-conjugate pairs include vectors $PC4_{8\times8}(2)$ and $PC4_{8\times8}(4)$, $PC4_{8\times8}(5)$ and $PC4_{8\times8}(7)$, and $PC4_{8\times8}(6)$ and $PC4_{8\times8}(8)$.

FIG. **32**C shows an 8×8 CI matrix $CI_{8\times8}$ generated from a 4×4 CI matrix $CI_{4\times4}$ via the Hadamard-Walsh matrix-expansion technique. Although the Hadamard-Walsh matrix expansion is designed to generate Hadamard-Walsh codes of length 2^n, this matrix-expansion technique may be used to generate CI codes from any N×N CI-code matrix. The code length Nis not constrained to be 2^n.

The 8×8 CI matrix $CI_{8\times8}$ shown in FIG. **32**C includes two binary-phase 8-chip codes (which correspond to the first and second rows of the 8×8 Hadamard-Walsh matrix $HW_{8\times8}$ shown in FIG. **32**A), two quaternary-phase code vectors (which correspond to the first and third rows shown in FIG. **32**B), and four octonary-phase code vectors including two complex-conjugate pairs $CI_{8\times8}(2)$ and $CI_{8\times8}(8)$, and $CI_{8\times8}(4)$ and $CI_{8\times8}(6)$.

FIG. **33**A shows an 8×8 CI matrix $HW_{8\times8}(1)\times CI_{8\times8}$ resulting from multiplication of the 8×8 CI matrix $CI_{8\times8}$ shown in FIG. **32**C by the first row vector $HW_{8\times8}(1)$ of the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$, shown in FIG. **32**A. Each value of vector $HW_{8\times8}(1)$ multiplies the corresponding column of the CI matrix $CI_{8\times8}$. In this case, the vector $HW_{8\times8}(1)$ consists of all ones. Thus, the CI matrix $HW_{8\times8}(1)\times CI_{8\times8}$ is identical to the CI matrix $CI_{8\times8}$. The CI matrix $HW_{8\times8}(1)\times CI_{8\times8}$ includes two binary-phase 8-chip codes, $HW_{8\times8}(1)$ and $HW_{8\times8}(2)$, two quaternary-phase code vectors, $PC4_{8\times8}(1)$ and $PC4_{8\times8}(3)$, and two complementary octonary-phase code pairs, $CI_{8\times8}(1)$ and $CI_{8\times8}(1)^*$, and $CI_{8\times8}(2)$ and $CI_{8\times8}(2)^*$.

FIG. **33**B shows an 8×8 CI matrix $HW_{8\times8}(2)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the second row vector $HW_{8\times8}(2)$ in the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$. The code vectors in matrix $HW_{8\times8}(2)\times CI_{8\times8}$ are identical to the code vectors in matrix $HW_{8\times8}(1)\times CI_{8\times8}$, except the order of the vectors is shifted by four chip positions.

FIG. **33**C shows an 8×8 CI matrix $HW_{8\times8}(3)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the third row $HW_{8\times8}(3)$ of the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$. The CI matrix $HW_{8\times8}(3)\times CI_{8\times8}$ includes two binary-phase 8-chip codes, $HW_{8\times8}(3)$ and $HW_{8\times8}(4)$, two quaternary-phase code vectors, $PC4_{8\times8}(2)$ and $PC4_{8\times8}(4)$, and two complementary octonary-phase code pairs, $CI_{8\times8}(5)$ and $CI_{8\times8}(5)^*$, and $CI_{8\times8}(6)$ and $CI_{8\times8}(6)^*$.

FIG. **33**D shows an 8×8 CI matrix $HW_{8\times8}(4)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the fourth row $HW_{8\times8}(4)$ of the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$. The code vectors in matrix $HW_{8\times8}(4)\times CI_{8\times8}$ are identical to the code vectors in matrix $HW_{8\times8}(3)\times CI_{8\times8}$, except the order of the vectors is shifted by four chip positions.

FIG. **33**E shows an 8×8 CI matrix $HW_{8\times8}(5)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the fifth row vector $HW_{8\times8}(5)$ of the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$. The CI matrix $HW_{8\times8}(5)\times CI_{8\times8}$ includes two binary-phase 8-chip codes, $HW_{8\times8}(5)$ and $HW_{8\times8}(6)$, two quaternary-phase code vectors, $PC4_{8\times8}(5)$ and $PC4_{8\times8}(7)$, and two complementary octonary-phase code pairs, $CI_{8\times8}(3)$ and $CI_{8\times8}(3)^*$, and $CI_{8\times8}(4)$ and $CI_{8\times8}(4)^*$.

FIG. **33**F shows an 8×8 CI matrix $HW_{8\times8}(6)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the sixth row $HW_{8\times8}(6)$ in the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$. The code vectors in matrix $HW_{8\times8}(6)\times CI_{8\times8}$ are identical to the code vectors in matrix $HW_{8\times8}(5)\times CI_{8\times8}$, except for a cyclic shift of four chip positions.

FIG. **33**G shows an 8×8 CI matrix $HW_{8\times8}(7)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the seventh row vector $HW_{8\times8}(7)$ of the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$. The CI matrix $HW_{8\times8}(7)\times CI_{8\times8}$ includes two binary-phase 8-chip codes, $HW_{8\times8}(7)$ and $HW_{8\times8}(8)$, two quaternary-phase code vectors, $PC4_{8\times8}(6)$ and $PC4_{8\times8}(8)$, and two complementary octonary-phase code pairs, $CI_{8\times8}(7)$ and $CI_{8\times8}(7)^*$, and $CI_{8\times8}(8)$ and $CI_{8\times8}(8)^*$.

FIG. **33**H shows an 8×8 CI matrix $HW_{8\times8}(8)\times CI_{8\times8}$ resulting from a multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the eighth row $HW_{8\times8}(8)$ in the 8×8 Hadamard-Walsh matrix, $HW_{8\times8}$. The code vectors in matrix $HW_{8\times8}(8)\times CI_{8\times8}$ are identical to the code vectors in matrix $HW_{8\times8}(7)\times CI_{8\times8}$, except for a cyclic shift of four chip positions.

FIG. **34**A shows a set 16 octonary codes C(n) that result from the multiplication of the 8×8 CI matrix $CI_{8\times8}$ by the rows $HW_{8\times8}(n)$ of the 8×8 Hadamard-Walsh matrix $HW_{8\times8}$. The codes C(n) include at least some of the same code vectors $CI_{8\times8}(n)$ shown in FIG. **33**A through FIG. **33**H.

FIG. **34**B shows auto correlations and cross correlations of the 16 octonary codes C(n) shown in FIG. **34**A. The correlation relationships are preferably used to choose orthogonal or quasi-orthogonal code sets from the codes C(n). For example, the codes C(1), C(1)*, C(2), C(2)*, C(4), C(4)*, C(7), and C(7)* form an orthogonal eight-code set. Note that the code pair [C(1), C(1)*] has zero cross correlation with C(2), C(2)*, C(4), C(4)*, C(7), and C(7)* and thus, can be used with these codes to provide orthogonal code sets. Note that code C(1) has a non-zero cross correlation with codes C(1)*, C(5), and C(6)*. Thus, an orthogonal set may include codes C(1) and C(5), for example, and exclude codes C(1)* and C(6)*.

The codes C(3), C(3)*, C(5), C(5)*, C(6), C(6)*, C(7), and C(7)* form another orthogonal eight-code set. Codes C(7), C(3), C(8), C(4), C(1), C(5), C(2), and C(6) form yet another orthogonal eight-code set. Many other code sets are possible.

FIG. **35** illustrates generalized method and apparatus embodiments of the invention in which data transmitted on two codes, such as codes C(5)* and C(6), is processed with a single despreading code, such as code C(1)*. The cross correlations C(5)*C(1)* and C(6)C(1)* are orthogonal to each other in the complex plane. Thus, throughput of a channel may be increased by increasing the number of codes on the transmit side without having to increase the number of reference codes on the receive side.

A plurality of data streams $s_1(t)$ and $s_2(t)$ are processed by an encoder **3502** to provide at least two coded data streams to an apparatus **3504** that combines (e.g., sums) the coded data streams and conveys the resulting signal to a transmitter **3506**. The transmitter **3506** may perform signal processing to facilitate coupling the coded data streams into a communication channel. For example, the transmitter **3506** may perform D/A conversion, up conversion, mixing, filtering, amplification, beam forming, etc.

A receiver **3508** couples transmitted signals from the communication channel. The receiver **3508** may process received signals prior to coupling the signals to a decoder **3510**. For example, the receiver **3508** may perform down conversion, mixing, filtering, amplification, A/D conversion, beam forming, multi-user detection, sub-space processing, etc. The decoder **3510** is adapted to perform CI decoding. For example, at least one code (such as code C(1)*) is provided to the decoder **3510**. The decoder **3510** may perform correlation, shifting, or other matched-filter operations to produce a plurality of decoded signals. If the decoded data signals overlap each other in time (e.g., they exhibit orthogonality or quasi-orthogonality in the complex plane), the decoded data signals are passed to a complex-plane processor **3512** that performs an orthogonalizing process (e.g. multi-user detection) to separate the overlapping data symbols.

A quasi-orthogonal transmission mode provides for transmitting data on at least two codes. Quasi-orthogonal coding may include a plurality of codes (such as codes C(5)*, C(6), and C(1)) having non-zero cross correlations with at least one despreading code, such as code C(1)*. The cross correlation C(1)C(1)* maps into cross-correlation spaces C(5)*C(1)* and C(6)C(1)*, thus providing interference. The interference can be removed using any well-known technique, including decision processing, interference cancellation, multi-user detection, optimal combining, etc.

Orthogonal and quasi-orthogonal code sets may be implemented separately or simultaneously. Code sets may include combinations of different M-ary polyphase codes. An M-ary code set may include codes with a code length (i.e., number of code chips) that is less than or greater than M. Code sets may include numbers of codes that are less than or greater than the code lengths. Code sets may include same-length and/or different-length codes.

Although basic CI codes and one family of advanced CI codes are described herein, many other implementations of coding based on CI are clearly anticipated. CI code sets may be selected or manipulated to provide cross-correlation values that are shifted by $\pi/2$. Cross-correlation values may include CI chip values that may be processed accordingly. CI codes may be used to generate bi-orthogonal and/or trans-orthogonal CI code sets. CI codes can be generated from linear combinations of other CI codes. CI code generation can include Hadamard-Walsh matrix expansion, code concatenation, code interleaving, code superposition, and/or weighted code superposition wherein weights are applied to one or more code chips.

CI codes may be generated by multiplying CI codes with other code vectors, such as Hadamard Walsh codes, long codes, Golay codes, Barker codes, Gold codes, Kasami codes, CI codes, etc. A CI code may include at least one set of CI matrix elements, such as a row, a column, a diagonal, and/or matrix elements selected with respect to some predetermined pattern or algorithm.

CI code chips may be cyclically shifted, swapped, or otherwise re-ordered. CI codes may be implemented as multi-level codes with one or more codes that are not necessarily CI codes. Multiple codes including at least one CI code may be interleaved. CI codes may be interleaved with same length or different length codes.

CI codes may be implemented in block coding, convolutional coding, turbo coding, Trellis coding, any other form of channel coding, encryption, multiple-access coding, spread-spectrum coding, peak-power mitigation, etc. CI codes may be implemented with orthogonal coding, quasi-orthogonal coding, bi-orthogonal coding, trans-orthogonal coding, or any combination thereof.

CI codes may be generated by convolving at least one set of CI codes with at least one other set of codes, including one or more of the following: a CI code, a binary direct-sequence code, a channel code, a spreading code, a multiple-access code, etc. CI codes may be provided with one or more parity-check symbols formed by linear combinations of data symbols and/or code chips.

Comparison of CI to Direct Sequence Spread Spectrum

FIG. **36**A shows a frequency-domain plot of a data symbol **3601** that is converted to a wideband spread-spectrum signal **3602** via direct-sequence processing. FIG. **36**B shows a frequency-domain plot of the data symbol **3601** that is converted to a CI signal having a plurality N of narrowband components **3603**.1 to **3603**.N. Although the narrowband CI components are spread across a wide frequency band, the sum of the component bandwidths is approximately equal to the data-symbol **3601** bandwidth. The time-domain characteristics of a superposition of the data symbols **3603**.1 to **3603**.N can be made substantially identical to the time-domain characteristics of the data symbol **3601** via an appropriate selection of frequencies and complex amplitudes of the data symbols **3603**.1 to **3603**.N. Multiple frequency/complex-amplitude combinations may be provided that substantially reproduce the data symbol's **3601** time-domain characteristics.

FIG. **37** shows a time-domain plot of a plurality N of narrowband CI components **3702**.1 to **3702**.N and a data symbol **3701** indicative of a superposition of the CI components **3702**.1 to **3702**.N. The apparent duration of the data symbol **3701** is relatively small compared to the duration of each CI component **3702**.1 to **3702**.N.

The definition of spread spectrum (B. Sklar, *Digital Communications, Fundamentals and Applications*, Prentice-Hall, Inc., New Jersey, 1988) includes all of the following requirements:

The transmitted signal bandwidth is greater than the bandwidth necessary to transmit the data.

Spreading is accomplished by a spreading signal.

A receiver uses a replica of the spreading signal to despread a received signal.

The basic implementation of CI is not classified as spread spectrum because it does not satisfy all of the requirements of the definition.

The version of CI processing illustrated by FIG. **36**B increases the frequency band over which signal components are distributed, but does not increase the total bandwidth of the transmitted signal. The version of CI processing illustrated by FIGS. **36**B and **37** employs more than one "spreading" signal. The data symbols **3601** and **3701** are redundantly modulated onto multiple carriers and thus, are not spread in the conventional sense. A CI receiver may process received CI signals in many different ways. One of these techniques involves correlating the received signal with a despreading signal. The despreading signal may be a complex conjugate of the spreading signal, rather than a replica. Other techniques include, but are not limited to, providing complementary phase shifts to a received CI signal, sampling the received CI signal and summing the samples, summing weighted samples of a received CI signal, and performing an orthogonal transform (such as an orthogonal-frequency Fourier transform).

In at least a few cases, CI/DS-CDMA can be regarded as spread spectrum. A time-domain analysis of a CI/DS-CDMA signal reveals a direct-sequence-like signal even though CI/DS-CDMA is a multicarrier signal. This gives the appearance of a CI signal having been spread with a direct-sequence code. In some implementations of CI/DS-CDMA, CI pulses may actually be spread with a direct-sequence code. Even though time-domain characteristics of a CI signal may be made to appear as a direct-sequence signal, many reception techniques other than generating a code replica may be used to process a received CI/DS-CDMA signal. For example, each CI carrier may be processed with a complex-conjugate code in the frequency domain.

Polyphase CI codes comply with the first two definitions of a spread-spectrum signal. However, a complex-conjugate code, rather than a code replica, is usually required to decode received signals.

Direct sequence describes a spectrum-spreading technique that modulates a data symbol with a pseudo-random noise sequence. A pseudo-random noise sequence is defined by the following attributes:

There is an approximate balance between the number of zeros and the number of ones.

Various run-length constraints need to be satisfied with respect to sequences of ones and zeros.

The correlation of a code with its cyclic shift has approximately the same number of agreements and disagreements.

In the case of CI signals, each data symbol is mapped into a phase space, which corresponds to a set of complex weights. In the simplest case, the complex weights are phase shifts. Basic CI signals make use of orthogonality between different phase spaces in the frequency domain rather than orthogonality between different digital sequences in the time domain. Thus, CI signals are not related to direct-sequence signals.

CI/DS-CDMA (or CI/DSSS) signals are CI signals and thus, are not direct-sequence signals. FIG. **38** illustrates frequency-domain characteristics of a typical direct-sequence signal **3801** in comparison to frequency-domain characteristics of a plurality of different CI/DS-CDMA signaling types. A CI/DS-CDMA signal may have non-overlapping spectral components **3802** or overlapping spectral components **3803**. Spectral components **3804** of a CI/DS-CDMA signal may be uniformly spaced.

Alternatively, CI/DS-CDMA spectral components **3805** may be non-uniformly spaced.

CI/DS-CDMA signals differ from digital sequences in that different CI/DS-CDMA signals can occupy the same set of discreet frequency components, whereas orthogonal digital sequences are characterized by occupying a common continuous frequency spectrum. Even though time-domain characteristics of a CI/DS-CDMA signal may be similar to a direct-sequence signal, the spectral characteristics of any of the CI/DS-CDMA embodiments are notably different than a direct-sequence spectrum. This frequency-domain difference indicates an important and fundamental difference between CI/DS-CDMA and DS-CDMA.

Direct-sequence signals are processed in the time domain for both transmission and reception. For example, a Rake receiver is typically used in a direct-sequence system to

achieve path-diversity benefits. CI/DSSS signals are advantageously processed in the frequency domain (although they can be processed in the time domain instead of, or in addition to, the frequency domain). Preferably, CI/DSSS signals are frequency-domain processed at the receiver to achieve frequency-diversity benefits.

Polyphase CI codes can be implemented in the same way as direct-sequence codes. However, polyphase CI codes do not conform to the definition of spread spectrum. CI codes are not necessarily pseudo-random codes. Basic CI codes exhibit some randomness. For example, the phases of CI code chips tend to be uniformly distributed over 27t radians. However, polyphase CI codes typically do not follow the same balance and run-length constraints of a binary direct-sequence code. Furthermore, cyclic shifts of a CI codes can rotate the phase of the correlation between the CI code and its complex conjugate.

In addition to twice the number of orthogonal users, CI codes may be adapted to bi-orthogonal signaling. A set of CI signals may be further partitioned into in-phase and quadrature-phase signals. Various quasi-orthogonal multi-level phase-shift and/or amplitude-shift codes may be used.

Overview of CI Multiple-Access Coding

FIG. **39**A illustrates a CI code consisting of an nth vector of CI code chips $[c_{n1}, c_{n2}, \ldots, c_{nN}]$ wherein each code chip is mapped into an orthogonal diversity parameter value $[\Lambda_1, \Lambda_2, \ldots, \Lambda_N]$. CI codes may be used in place of direct-sequence coding when the CI code chips are mapped into the time domain, as shown in FIG. **39**B. CI codes can resemble MC-CDMA codes when the code chips are mapped onto orthogonal frequencies, as shown in FIG. **39**C. The order of the code chips with respect to the frequencies may be changed.

CI code chips may be impressed onto different transmit beam patterns or spatial directions, as shown in FIG. **39**D. An nth data stream $s_n(t)$ is provided to at least one coder **3902** that encodes each data symbol $s_n(t)$ with respect to a plurality of code chips cn**1** to c_{nN}. Preferably, the code chips cn**1** to c_{nN} are derived from CI or CI-based codes. The coded symbols are coupled to a beam-forming system **3904** that processes the symbols into signals that are suitable for transmission via a plurality N of transmitter elements **3906**.**1** to **3906**.N. In this case, the transmitted symbols are associated with transmit beam patterns. Each transmitted symbol may be associated with one or more complex spatial gain distributions (indicated by complex vectors an) that are transmitted into a communication channel 99.

Many different design variations may be provided to the transmission system shown in FIG. **39**D. For example, more than one data stream may be coded and transmitted. A plurality of coded signals corresponding to different data symbols may be provided to the same spatial gain distribution. One or more coded data symbols may be provided redundantly to multiple beam patterns. The coder **3902** and/or the beam-forming system **3904** may interleave the coded data symbols in one or more diversity-parameter spaces. The coder **3902** may provide channel coding to the data symbols.

Although the transmit beam patterns may be orthogonal, a multipath environment typically converts each transmit direction into multiple directions of arrival at a receiver, resulting in flat fading, frequency-selective fading, or inter-symbol interference. Sub-space processing may be performed to separate the interfering terms, and thereby orthogonalize the received beam patterns. Similarly, appropriate channel compensation techniques may be performed at the transmitter to help orthogonalize transmissions received by the receiver. The quality of the sub-space channels may vary greatly. However, since coding spreads each multiple-access channel over multiple sub-space channels, sub-space diversity is achieved.

Received spatial-gain patterns are characterized by a plurality of complex vectors β_{n1}. The vectors may indicate complex amplitudes of multiple (1) paths, directional gain distributions with respect to angles of arrival, complex-values associated with signals collected at each receiver element **3908**.**1** to **3908**.N' over some predetermined time interval, etc. Received signals are processed in a beam-forming system **3910** that may be adapted to perform sub-space processing, diversity combining, multi-user detection, etc.

The received signals may be down converted to baseband or IF prior to, during, or following beam forming. Sub-space values are provided to a decoder **3912** that may be adapted to perform decoding prior to or after optimal combining, multi-user detection, and/or spatial processing. The decoder **3912** may provide additional baseband processing, including, but not limited to, iterative feedback processing, control-signal generation, demodulation, demultiplexing, decision processing, constellation mapping, and/or generating confidence measurements.

CI coding may be provided to a transmitter array **3906**.**1** to **3906**.N, as shown in FIG. **39**E, such that each code chip c_{n1} to c_{nN} corresponding to at least one multiple-access channel is applied to an individual spatially separated transmitter element **3906**.**1** to **3906**.N. Sub-space processing at a remote receiver array **3908**.**1** to **3908**.N' separates each code chip of each coded data symbol into spatial sub-spaces. Because the channel quality can vary greatly between sub-spaces, multiple-access coding is used to spread each user's signal over multiple sub-space channels. Thus, impairment of a small number of sub-space channels does not substantially impair any user's link. Rather, the sub-space channel quality is averaged and provided uniformly to each multiple-access channel.

FIG. **39**F illustrates how multiple-access CI coding can be applied to non-orthogonal diversity parameter values, such as linear polarizations. A receiver (not shown) may orthogonalize interfering linear polarizations to separate CI code chips impressed on each polarization. CI code chips ci to civ may be impressed upon other non-orthogonal diversity-parameter values, provided that some sort of multi-channel (e.g., multi-user) detection or subspace processing is performed at the receiver.

FIG. **39**G illustrates how CI code chips ci to civ can be impressed onto orthogonal circular (or elliptical) polarizations. In this case, each polarization has an integer number of rotations in a given time interval and thus, are orthogonal over that time interval. Other orthogonal polarizations may include opposite-direction rotations and/or $\pi/2$ phase offsets. Polarization rotations resemble sub-carrier processing. Consequently, circular or elliptical polarizations can be processed in the same way as CI carriers. Orthogonal polarizations may be redundantly modulated. CI phase spaces may be extended to polarization and/or other diversity parameters. Multiple data symbols may be modulated onto each polarization signal and provided with polarization and/or signal phase relationships to orthogonalize the interfering data symbols.

A two-dimensional circular-polarized signal has linear vertical and horizontal components that can be described by in-phase and quadrature-phase sinusoidal functions:

$$A_{vert}=A_o \sin(2\pi f_n t+\phi)$$

$$A_{horiz}=A_o \cos(2\pi f_n t+\phi)$$

In the case where the rotational frequencies $\omega_n=2\pi f_n$ are orthogonal, the frequencies f_n can be expressed by:

$$f_n=f_o+nf_s$$

where f_o is an offset frequency, n is an integer, and f_s is a shift frequency. A symbol modulated onto one or more of the frequencies is provided with a symbol period T_s, expressed by:

$$T_S=l/f_s$$

where l is some integer.

In order to illustrate reception of orthogonal circular polarized signals, the value oft is set to one. A circular-polarized receiver provides in-phase and quadrature-phase multiplicative terms to the vertical and horizontal components of the received signal. A received symbol r(t) is evaluated by integrating or summing the receiver output over the symbol period T_s.

$$r(t)=\int_0^{T_s}\left(\sum_{n,n'}(A_nA'_n,\sin(2\pi f_n t)\sin(2\pi f_{n'}t)+A_nA'_{n'}\cos(2\pi f_n t)\cos(2\pi f_{n'}t))\right)\partial t$$

where f_n is the frequency of the receiver's circular polarization and $f_{n'}$ is the circular-polarization frequency of the received signal. Amplitudes A, and $A'_{n'}$ correspond to receiver gain and received signal amplitude, respectively.

The expression for r(t) can be separated into two sets of equations corresponding to n=n' and n≠n':

$$r_{nn}(t)=A_nA'_n\int_0^{T_s}(\cos^2(2\pi f_n t)+\sin^2(2\pi f_n t))\partial t$$

$$r_{nn'}(t)=\int_0^{T_s}\left(\sum_{n\neq n'}(A_nA'_{n'}(\sin(2\pi f_n t)\sin(2\pi f_{n'}t)+\cos(2\pi f_n t)\cos(2\pi f_{n'}t))\right)\partial t.$$

The equation for $r_{nn}(t)$ simplifies to the value $A_nA_{n'}T_s$.

Phase modulation or phase misalignment can cause a phase offset ϕ_b between the receiver's polarization angle and the angle of the received polarized signal. Any such phase offset ϕ_b causes a modulation of the received symbol $r_{nn}(t)$ by a factor of $\cos(\phi_b)$.

The equation for $r_{nn'}(t)$ can be simplified to the expression:

$$r_{nn'}(t)=\int_0^{T_s}\sum_{(n-n')}A_nA'_{n'}\cos(2\pi(n-n')f_s t)\delta t=$$

$$\frac{1}{2\pi(n-n')f_s}\left(\sum_{(n-n')}A_nA'_{n'}\sin(2\pi(n-n')f_s t)\right|_0^{T_s}\Bigg)=0$$

Thus, $r_{nn'}(t)=0$ for all non-zero integer values of (n−n'). This illustrates how the multicarrier orthogonality condition can be applied to signals having circular polarization. Similarly, orthogonal sets of elliptically polarized signals may be developed.

CI Multiple-Access Transceiver

FIG. **40**A illustrates a CI transceiver of the invention. An information signal, such as a stream of data bits or data symbols may be processed with an optional coder/interleaver **4001**. The coder/interleaver **4001** may perform channel coding, error-correction coding, interleaving, puncturing, and/or any other type of data processing that is typically performed prior to multiple-access or spread-spectrum coding.

Data symbols are coupled to a CI encoder **4002**, such as a modulator, that impresses the data symbols onto at least one CI code generated by a CI-code generator **4003**. A CI-code generator, such as the CI-code generator **4003**, is any algorithm, device, or system adapted to generate CI codes as described and/or defined herein. A CI encoder, such as the CI encoder **4002**, includes any algorithm, device, or system adapted to combine, merge, or otherwise impress at least one data symbol onto a plurality of CI code chips. The CI encoder **4002** may impress each CI code chip onto one or more diversity-parameter values prior to or after impressing data symbols onto the CI code. A CI code may be impressed onto at least one IF carrier. The CI encoder **4002** may perform multiplexing. For example, the CI encoder **4002** may encode data streams onto different CI codes. The CI encoder **4002** may employ other diversity parameters on which to multiplex multiple data streams.

The encoded data is coupled to a transmit coupler **4004** that optionally performs carrier-frequency (e.g., RF or optical) processing on the encoded data prior to coupling the encoded data into a communication channel 99. The transmit coupler **4004** may up convert baseband or IF data symbols to RF or optical signals. The transmit coupler **4004** may modulate one or more carriers with the encoded data symbols prior to transmission. The transmit coupler **4004** may impress CI code chips onto one or more sets of diversity-parameter values. For example, the transmit coupler **4004** may include a beam former (not shown).

A receive coupler **4006** couples received signals from the communication channel 99 and converts the signals to some form (e.g., baseband) that facilitates processing by the rest of the receiver portion of the transceiver. The receive coupler **4006** typically performs carrier-frequency processing on the received signals. The receive coupler **4006** may down-convert the received signals to baseband or IF signals. The receive coupler **4006** may perform diversity combining, multi-user detection, sub-carrier processing, interference cancellation, sub-space processing, beam forming, channel characterization, channel compensation, and/or various types of adaptive processing.

The receive coupler **4006** provides CI-encoded data symbols to a CI decoder **4007**, such as a demodulator, that also receives an input from the CI-code generator **4003**. The CI decoder **4007** extracts or estimates the data symbols encoded with at least one CI code. Received Data symbols are typically distorted by the communication channel 99. Thus, the CI decoder **4007** may include an optimal receiver, a channel estimator, and/or a channel compensator.

Decoded data symbols may be optionally processed in a decode-signal processor **4008**. The decode-signal processor **4008** may be integrated with the CI decoder **4007**. The decode-signal processor **4008** may include a decision processor (not shown) that generates hard and/or soft decisions.

The decode-signal processor **4008** may include a feedback loop (not shown) to the CI decoder **4007** and/or the receive coupler **4006** to adjust processing with respect to one or more signal-quality measurements. The decode-signal processor **4008** may convert decoded data symbols into an information bit stream.

A CI decoder, such as the CI decoder **4007**, is any algorithm, device, or system adapted to decode at least one CI-encoded signal. A CI-encoded signal typically is a CI-encoded information-bearing signal. A CI decoder may convolve and/or correlate at least one decode signal with the at least one CI-encoded signal to extract the at least one information signal or at least one estimate of the information signal. A CI decoder may perform hard and/or soft estimates of the information signal. A CI decoder may include multiple decoders and perform an iterative process of conveying soft decisions between the multiple decoders. A CI decoder may perform one or more of the following: de-interleaving, channel decoding, multiple-access decoding, demultiplexing, demodulating, decrypting, channel analysis, channel compensation, despreading, error detection, and error correction. A CI decoder may provide corrective phase offsets to compensate for non-zero phase signals, channel distortion, phase jitter, and/or phase offsets applied to transmitted signals to achieve some predetermined objective, such as minimizing PAPR, enhancing security, etc.

A decode-signal processor, such as the decode-signal processor **4008**, is any algorithm, device, or system that is adapted to process at least one decoded signal. The decode-signal processor may provide hard and/or soft decisions when evaluating the decoded signal. A decode signal processor may include one or more quantizers, comparators, iterative decoders, feedback loops, interference cancellers, optimal detectors, and/or any other devices that contribute to a decision and/or detection process. A decode-signal processor may provide other types of decoding in addition to CI decoding. For example, a decode-signal processor may decode block-encoded signals, convolutional-encoded signals, encrypted signals, turbo-coded signals, compressed signals, etc. The decode-signal processor may perform demultiplexing and/or de-interleaving, if necessary. The decode-signal processor may perform multi-user detection, optimal combining, diversity reception, and/or any other technique designed to enhance signal quality by mitigating the effects of interference, distortion, and/or noise.

FIG. **40**B illustrates one embodiment of the CI-code generator **4003**. A CI-symbol generator **4109** generates a plurality of CI symbols that are coupled to a symbol combiner **4110**. The symbol combiner **4110** groups the CI symbols to generate one or more CI codes.

A CI-symbol generator, such as the CI-symbol generator **4109**, includes any algorithm, system, or device adapted to generate a plurality of CI symbols. CI symbols include CI base symbols, which are symbols generated from any integer-number of rotations of a vector through the complex plain. CI symbols may include at least one set of polyphase symbols. CI symbols may be discreet-valued or continuous-valued numbers or functions. CI symbols may be values derived from at least one invertible transform function, such as a Fourier transform, a Laplace transform, a Walsh transform, a wavelet transform, etc. CI symbols may include linear combinations of other CI symbols, linear combinations of CI symbols with other code symbols, CI symbols modulated with code sequences from a predetermined code set including one or more of the following: spread-spectrum codes, multiple-access codes, channel codes, encryption codes, multi-level codes, compression codes, hybrid codes, and CI codes.

A symbol combiner, such as the symbol combiner **4110**, includes any algorithm, system, or device adapted to group CI symbols to generate at least one CI-chip sequence. A symbol combiner may append, concatenate, interleave, shift, puncture, or re-order one or more CI symbols sets. A symbol combiner may combine CI symbols with other types of symbols. A symbol combiner may provide a CI chips sequence with at least one parity-check symbol.

FIG. **41**A illustrates general steps of a transmitting method of the present invention. An information signal s(t) is optionally encoded and/or interleaved **4101**. Encoding may include code puncturing. Preferably, coding includes CI or CI-based coding. The coding/interleaving step **4101** may include generating or otherwise acquiring symbol values to be impressed onto multiple carriers. The information signal may be provided with predetermined training symbols in a training symbol injection step **4102**. Training symbols may be used for channel estimation, signal-quality estimations, synchronization, etc. An IFFT **4103** or equivalent process impresses the coded data symbols onto a plurality of carriers. Optionally, a cyclic prefix may be added to the coded data symbols. An FIR filtering and interpolation step **4104** is performed prior to preparing the resulting signal for transmission into a communication channel (not shown).

Various steps and systems adapted to perform the steps shown in FIG. **41**A may be included in transmission systems and methods pertaining to other aspects and embodiments of the invention. Furthermore, various signal-processing steps that are typically performed in transmission systems may be included herein. For example, pre-equalization steps and/or systems may be included in the transmitter embodiments shown in FIG. **41**A. An array processing step (not shown) may be performed, such as after FIR filtering and interpolation **4104**. Alternatively, array processing may be integrated into the coding **4101**, IFFT **4103**, and/or FIR filtering **4104** steps.

FIG. **41**B illustrates general steps of a reception process of the present invention. One or more transmitted signals are coupled out of a communication channel (not shown) and provided to an FIR filtering and decimation step **4105**. Filtered signals may be processed in a synchronization step **4111** to control the timing of various reception processes, such as, but not limited to a cyclic prefix removal and FFT step **4106**. Complex-amplitude values associated with individual carrier frequencies, such as estimates obtained via known training symbols and/or unknown data symbols, may be used in a channel-estimation step **4113**. The channel estimation step **4133** can facilitate the generation of weights (e.g., array-processing and/or CI combining weights).

Array processing **4107** is performed to achieve some preferred combination of system capacity (i.e., sub-channel generation) and signal quality (i.e., diversity combining). For example, array processing may include spatial interferometry multiplexing and/or any other form of array processing. Array processing **4107** may be assisted by an interference-estimation step **4116**. A CI combining step **4118** may be performed in conjunction with the array-processing step **4107** and/or a decoding and de-interleaving step **4108**. Alternatively, either or both the array-processing step **4107** and the decoding and de-interleaving step **4108** may perform CI combining **4118**. The decoding and de-interleaving step **4108** performs any necessary deinterleaving of data symbols received from the array-processing step **4107** prior to, or

following decoding. Decoding may include channel, multiple access, spread spectrum, encryption, and/or other decoding processes.

CI Channel Coding

FIG. **42** shows a system diagram of a CI transceiver. An information source **4201** provides data symbols to a CI coder/interleaver **4211**. A modulator **4221** is adapted to modulate the coded symbols onto one or more carriers that are transmitted by a transmitter **4222** into a communication channel 99. The channel 99 may be characterized by AWGN and/or multipath. Similarly, other types of channel distortion may be considered. A receiver **4224** couples the transmitted signals from the channel 99. A demodulator **4225** retrieves symbols from the received signal. A CI decoder/de-interleaver **4235** decodes (and deinterleaves, if necessary) the received symbols into information symbols that are optionally processed in an information processor or sink **4236**.

Channel coding provides signal transformations that are designed to improve communication performance by enabling transmitted signals to better withstand the effects of various channel impairments (e.g., noise, fading, interference). CI channel coding may include waveform coding and/or structured sequences. CI waveform coding (such as CI, Trellis code modulation, convolutional CI coding, CI turbo coding, M-ary signaling, orthogonal coding, bi-orthogonal coding, trans-orthogonal coding, etc.) transforms waveforms to make them less subject to error. CI-structured sequences transform a data sequence into one or more sequences having structured redundancy. Redundant data symbols or bits are used for detecting and/or correcting errors.

CI coding may include replacing a data set with an orthogonal codeword set. In one embodiment, the decoder may multiplex multiple coded data symbols together by providing an orthogonal codeword set. An orthogonal CI codeword set may be selected such that each codeword vector has zero projection onto all other CI codeword vectors except for its complex conjugate. The receiver's decoder **4235** may include multiple matched filters (or equivalent systems or algorithms) that output zero unless a corresponding encoded data symbol is received.

The bandwidth requirements for bi-orthogonal CI codes are half of the requirements for comparable orthogonal codes. Bi-orthogonal codes have slightly better performance over orthogonal codes because antipodal signal vectors have better distance properties than orthogonal signals. Trans-orthogonal (e.g., simplex) codes, when compared to orthogonal and bi-orthogonal codes, require the minimum SNR for a particular symbol error rate. Channel codes may be overlaid onto multiple-access codes. Depending on the processing gain of the multiple-access codes, channel coding may not require additional bandwidth.

In one embodiment, the coder **4211** maps data symbols to CI code words using a look-up table. In another embodiment, the CI code words are generated with respect to each data symbol. Code-word generation may be performed with a CI code generation matrix G. All CI codes of a given set of CI code words can be constructed from a combination of linearly independent code vectors that form the CI code generation matrix G.

Although code generation is described with respect to basic CI codes, orthonormal basis vectors and a corresponding CI code generation matrix may be constructed for advanced CI codes. Each code in a basic CI code set can be defined by a different number of full rotations in the complex plain. For example, an orthonormal basis for a set of 64 basic CI codes can be defined by the CI code generation matrix:

$$G=\begin{bmatrix} C(\text{rotations}=1) \\ C(\text{rotations}=2) \\ C(\text{rotations}=4) \\ C(\text{rotations}=8) \\ C(\text{rotations}=16) \\ C(\text{rotations}=32) \end{bmatrix}$$

where C(rotations=m) is a code vector corresponding to:

$$C(m)=e^{im\phi}(1,e^{im\phi},e^{i2m\phi},\ldots,e^{i(N-1)im\phi})$$

Since this basic CI code set is totally defined by G, the coder **4211** needs to store only k rows of G instead of the 2^k vectors of the CI code. Furthermore, since the first half of the each row vector C(m) of G is the same as the second half (except C(1)'s first and second halves differ by a factor of −1), the coder **4211** and decoder **4235** need only store one half of each row vector C(m).

A CI receiver may perform error detection using any of several techniques. Symmetry relationships between the first and second halves of a received code can be exploited to determine whether an error occurred. Other relationships between code symbols may be used to provide error detection and/or correction. For example, adjacent CI code symbols (except for the all-ones code) are typically not identical. Depending on the code, the values of adjacent code symbols change in a predetermined way. For example, adjacent code chips of the basic code C(m) differ by $e^{im\Phi}$.

A parity-check matrix H (defined by the equation, $GH^T=0$) can be used to test whether a received vector is a member of a codeword set. The decoder **4235**, upon detecting an error, may perform forward error correction and/or request a retransmission. Preferably, the decoder **4235** estimates the transmitted code vector using some sort of optimizing strategy, such as the maximum-likelihood algorithm. The receiver may erase ambiguous signals. The decoder **4235** may implement error correction that corrects erasures or corrects erasures and errors simultaneously.

It is preferable that the coder **4211** select codes that maximize the Hamming distance between codes. An advantage of using CI polyphase codes is that they provide a superior Hamming distance compared to binary codes. For example, an (n,k)=(8,3) binary code has an n-tuple space of $2^n=2^8=256$ binary words, of which $2k=2^3=8$ are code words. An octonary-phase (m=8) (8,3) code has an n-tuple space of $2^{mn}=2^{64}$ octonary words. The fraction of words that are code words decreases dramatically with increasing values of m. When a small fraction of the n-tuple space is used for code words, a large Hamming distance can be created.

CI codes may be processed as cyclic codes, which are described in many prior-art references, such as B. Sklar, *Digital Communications, Fundamentals and Applications*, Prentice-Hall, Inc., New Jersey, 1988. For example, components of a CI code vector $C=(C_0, C_1, \ldots, C_{N-1})$ can be treated as coefficients of a polynomial U(X), as follows:

$$U(X)=u_0+u_1X+u_2X^2+\ldots+U_{N-1}X^{N-1}$$

where $X=e^{i2\pi nk/N}$, and where k is the order of the code: k=0, 1, . . . , N−1. Well-known cyclic code processing may then be performed.

FIG. **43**A shows a (2,1) polyphase (M-ary) convolutional coder with constraint length K=3. There are n=2 modulo-M adders. The code rate k/n is ½. The coder **4211**, when implemented with a convolutional coder, may include phase shifters or a tapped delay line to effect phase shifts. The function of the polyphase convolutional encoder can be

expressed with an M-ary trellis diagram shown in FIG. **43**B. A decoding process involves choosing a path through the trellis with respect to optimizing some performance metric, such as a likelihood or log-likelihood metric. There are many possible paths that are not shown in FIG. **43**B. The decoder **4235**, when implemented as a convolutional decoder, may include phase shifters or a tapped delay line to effect phase shifts. The decoder **4235** may convert received signals to polyphase or modulo-M symbols prior to decoding in a microprocessor (not shown).

The decoder **4235** may be configured to discard paths that are not good candidates for the maximum likelihood sequence. Thus, the decoded path is chosen from a reduced set of possible paths. This reduces the decoding complexity. Any of several algorithms may be used to provide approximate solutions to the maximum likelihood decoding problem, including sequential and threshold algorithms. A convolutional decoder may include a Viterbi, sequential, and/or a feedback decoder.

The coder **4221** may include an interleaver and the decoder **4235** may include a de-interleaver. Interleaving a coded message before transmission and de-interleaving after reception causes bursts of channel errors to be spread out in one or more sets of diversity-parameter values. This allows the decoder **4235** to handle bursts of errors as random errors.

Interleavers typically make use of time diversity. However, other diversity parameters may be exploited instead of, or in addition to time. For example, interleaving may be performed across one or more diversity-parameter values of each transceiver, such as frequency, polarization, phase space, beam direction, code, mode, etc. Interleaving may be exploited across multiple receivers. For example, subspaces (spatial and/or non-spatial) may be exploited for interleaving.

The demodulator **4225** may make a hard decision as to the value of a received symbol and pass that value to the decoder **4235**. The demodulator **4225** may provide the decoder **4235** with an unquantized or over-quantized (quantization level >M) value to the decoder **4235**. Sending an over-quantized value to the decoder **4235** is equivalent to sending a measure of confidence along with a code-symbol value. The decoder **4235** may include multiple decoders (not shown) that provide soft-decision variables to each other in an iterative fashion to optimize decoding performance.

FIG. **43**C illustrates polyphase channel coding that may be provided by a CI channel coder coupled to a modulator adapted to perform high-level (e.g. M-ary) modulation. The codes illustrated in FIG. **43**C provide for channel coding without increasing the bandwidth of the transmission signal. In this case, a plurality of code values of a code vector **4303** (which represents a CI-encoded superposition of data symbols d_1 to d_N **4301**) may be expressed as symbols w_n characterized by a higher-order constellation of symbol values w_n (n=1, . . . , N) compared to the data symbol values d_1 to d_N.

The code vector **4303** may be generated from a product of a data-symbol vector **4301** with a CI code matrix. In this example, contributions of data symbol −1 to the code vector **4303** are determined by CI code values in a corresponding column **4312** of a CI code matrix. The code value w_n=−2i is an expression (e.g., a sum) of a linear combination of weighted data symbols expressed by a scalar product of the data-symbol vector **4301** with a row **4311** of the CI code matrix. Although binary data symbols **4301** are shown, the data symbols d_1 to d_N may be expressed by higher-order modulations.

In the case of basic CI coding (i.e., CI code values $c_{nn'}$=1 for n=1 or n'=1), symbol w_1 may be used as a simple parity check of the data symbol values d_1 to d_N. Other parity checks may be represented by the other symbol values w_n. The parity checks may be used in error detection and/or symbol estimation. Parity checks may be part of an iterative optimization process that employs a multi-step methodology (e.g., turbo decoding) to reduce the effects of noise and/or interference. Data-symbol redundancy may be provided in CI channel coding via any additional form of channel coding (e.g., Trellis coding, convolutional coding, block coding, etc.). Quasi-orthogonal spaces (i.e., orthogonal positions or codes provided by pulse overlapping in CI pulse-shaping) may be used to convey coded and/or otherwise redundant data symbols.

In one set of embodiments, the symbol values w_n may be characterized by a set of phases. In another set of embodiments, the symbol values w_n may be characterized by a set of multi-level amplitudes and phases. In some embodiments, the symbol values w_n may be characterized, at least in part, by modulo-N combining of a plurality of coded data symbols. Symbols w_n may be provided by any combination of generating (e.g., combining sets of coded symbols) and acquiring (e.g., selecting values from a look-up table) symbol values.

CI channel decoding may employ Trellis decoding, such as illustrated by FIG. **43**D. Any of various Trellis decoding algorithms, such as the Viterbi algorithm, may be employed. Alternatively, one or more types of correlation or matched-filtering algorithms may be performed to provide data-symbol estimates. In some applications, the symbols w_n may be combined to provide estimates of the data symbols. For example, each data-symbol estimate may be generated by providing at least one set of phase shifts (i.e., a phase-space vector) to the symbols w_n and combining the phase-shifted symbols w_n. Noise estimates may be generated using any combination of expected data-symbol values di to d_N, code values w_n, and parity-check values (e.g., w_n). Noise estimates may be generated with respect to measurement parameters associated with redundant sets of CI-encoded data symbols. Noise estimates and/or data-symbol estimates may be generated iteratively. For example, noise and/or data-symbol estimates may be adjusted or selected and evaluated with respect to probability of error using any combination of signal-quality measurements.

FIG. **44**A shows a possible embodiment of the coder **4211**. A block coder **4401** encodes input data symbols with at least one block code. The block encoded symbols are then encoded in a convolutional coder **4402** to generate convolutional-encoded, block-encoded data symbols.

FIG. **44**B shows a convolutional coder **4402** and a block coder **4401** switched in order with respect to the coder shown in FIG. **44**A. The output signal is a block-encoded, convolutional-encoded data sequence. One or more interleavers (not shown) may be provided in FIGS. **44**A and/or **44**B. The interleavers may be provided before or after either or both the block coder **4401** and the convolutional coder **4402**.

FIG. **45**A and FIG. **45**B illustrate possible embodiments for the decoders corresponding to the coders shown in FIG. **44**A and FIG. **44**B, respectively. Similarly, one or more de-interleavers (not shown) may be provided to the decoders with respect to any interleaver provided to the coders.

FIG. **46** illustrates basic components of a turbo coder/decoder system that may be used to process CI codes. A data sequence is encoded with at least two error-correction codes applied by at least two coders **4601** and **4602**. The data

sequence is interleaved by an interleaver **4604** prior to encoding by the second coder **4602**. The coded data symbols are multiplexed together into a single symbol stream that may be processed by a transmit processor **4608** before being coupled into a communication channel 99.

Received signals from the communication channel 99 are optionally processed by a receiver processor **4610**. Basic received signal processing tasks, such as amplification and filtering, may be performed by the receiver processor. A baseband processor **4612** may include a matched filter and sampler or some other systems or software adapted to convert the received signals into a symbol stream. A demultiplexer **4614** demultiplexes the resulting symbol stream into two symbol streams. Each symbol stream is processed in one of a plurality of decoders, such as decoders **4621** and **4622**.

Turbo coding combats random and burst errors by combining error-correction coding and interleaving. A first code encodes a data stream. A second code encodes an interleaved version of the data stream. Each decoder **4621** and **4622** provides de-interleaving (if necessary) and decoding. The output of one decoder **4621** aids the other decoder **4622** in an iterative fashion. Soft outputs from each decoder **4621** and **4622** are provided to the other decoder **4622** and **4621**. Soft outputs indicate reliability of a symbol estimate produced by a decoder. A soft-decision value produced for each bit in a symbol includes an estimate of the symbol and the relative probability of a particular bit having a particular value. Preferably, the first soft decision is produced by the decoder **4621** or **4622** provided with the highest signal strength. The resulting soft-decision variable typically has higher reliability and, thus, reduces the number of iterations.

The codes applied by the coders **4601** and **4602** may be CI codes. The multiplexer **4606** and demultiplexer(s) **4614** may perform CI processing and/or sub-space processing. Different coded symbols may be multiplexed onto different CI carriers, different CI phase spaces, different subspaces, etc. The coded symbols may be coded with respect to some multiple-access code as part of the multiplexing procedure. Preferably, the multiple-access code spreads the symbols to provide the decoders with diversity benefits. Multiple-access-encoded symbols may be spread across different diversity-parameter values. For example, CI and/or binary-phase codes can spread a signal across a broad frequency band, multiple time intervals, multiple subspaces, etc. This spreading can provide the coded symbols with diversity benefits, thus reducing the number of decoding iterations.

The demultiplexers **4614** may include an optimal combiner (not shown). The demultiplexer **4614** may include other types of receivers and receiver components including, but not limited to, a multi-user detector, an interference canceller, a spatial interferometry demultiplexer, and/or any diversity-parameter beam former, including a spatial beam former. The demultiplexers **4614** may be provided with soft-decision values from either or both of the decoders to facilitate optimal reception. Variations to the function of the demultiplexers **4614** may be provided with respect to SNR, BER, and/or probability of error, as determined by the soft-decision values.

CI codes may be implemented in various types of channel coding. In one set of embodiments of the invention, one or more data symbols $s_n(t)$ are mapped into a plurality of CI symbols represented by CI carrier weights $w_n(t)$.

FIG. **47**A illustrates a set of data symbols **4701** that are impressed onto a plurality of CI pulses **4702**. FIG. **47**B illustrates a modulated pulse stream **4703** resulting from impressing the data symbols **4701** onto the pulse stream **4702**. FIG. **47**C illustrates a plurality of CI symbols represented by a plurality of CI carrier weights $w_n(t)$. A superposition of the carriers **4705** produces the modulated pulse stream **4703**.

The data symbols **4701** may be binary symbols (as shown) or symbols derived from a more complex alphabet. The CI pulse stream **4702** may include overlapping and/or non-overlapping pulses. The pulses of the pulse stream **4702** may be uniformly and/or non-uniformly positioned in time. Data symbols **4701** may be impressed onto the pulses via any type of modulation, including amplitude modulation, frequency modulation, phase modulation, time-offset modulation (e.g., pulse-position modulation), polarization modulation, or any combination thereof.

The CI carriers **4705** may be characterized by overlapping and/or non-overlapping carriers. The carriers **4705** may be uniformly and/or non-uniformly spaced-in-frequency carriers. The weights $w_n(t)$ corresponding to the carriers **4705** depend on the carrier frequencies. The weight values $w_n(t)$ also depend on any carrier frequency amplitude profiles, such as may be provided to shape the time-domain pulses and/or provide for frequency-domain shaping. Similarly, weight values $w_n(t)$ depend on any phase coding provided to the carriers, such as to reduce the PAPR of the pulses.

In one set of embodiments of the invention, data symbols $s_n(t)$ are literally impressed onto CI pulses. The CI carriers are processed to provide carrier weights $w_n(t)$. In another set of embodiments, data symbols $s_n(t)$ are impressed onto non-CI signals that are decomposed into CI carrier components to provide carrier weights $w_n(t)$. In yet another set of embodiments of the invention, the descriptions of CI carrier processing are merely a representation of a mathematical process that derives CI symbols $w_n(t)$ corresponding to a given set of data symbols.

The CI symbols can optionally be interleaved prior to being impressed onto a plurality of diversity-parameter values. In one embodiment of the invention, the CI symbols are transmitted as a serial symbol stream. In another set of embodiments, CI symbols are transmitted in parallel. For example, CI symbols may be transmitted on multiple frequencies, multiple subspaces, etc. Various combinations of diversity parameters and serial and/or parallel processing may be implemented.

Each CI symbol $w_n(t)$ corresponding to a particular data set $s_n(t)$ $\{n=1, \ldots, N\}$ may convey the same plurality of data symbols $s_n(t)$. Interferometry between the CI symbols $w_n(t)$ enables the data symbols $s_n(t)$ to be extracted. If some of the CI symbols $w_n(t)$ are corrupted or lost, the encoded data symbols $s_n(t)$ can still be recovered with minimal degradation. This type of CI coding enables error correction without increasing bandwidth requirements or reducing throughput. Furthermore, CI coding combined with quasi-orthogonal pulse shaping enables simultaneous benefits of error-correction enhancement and increased throughput.

FIG. **48** shows one of many possible embodiments of a CI-code transmitter and a CI-code receiver. A set of data symbols **4701** is processed by a CI symbol generator **4820**. The CI symbol generator **4820** may incorporate any system design that processes received data symbols to generate at least one set of CI symbols. In this case, a pulse waveform generator **4801** processes input data symbols $s_n(t)$ to produce a plurality of modulated CI waveforms **4703** that are processed with a Fourier transform **4802** into a plurality of CI symbols $w_n(t)$. An optional parallel-to-serial converter **4803** provides a serial symbol stream output from the CI symbol generator **4820**.

Optionally, the CI symbols $w_n(t)$ may be interleaved by an interleaver **4804** prior to being provided to a transmission

system **4805**. The transmission system **4805** may perform modulation, multiple-access processing, multiplexing, coding, D/A processing, spreading, frequency conversion, filtering, amplification, and/or beam forming prior to coupling transmission signals into a communication channel **4899**.

A receiver couples transmitted signals from the communication channel **4899** into a receiver system **4806**. The receiver system **4806** may perform beam forming, amplification, filtering, down conversion, despreading, decoding, demultiplexing, multiple-access processing, demodulation, A/D processing, data storage, and/or other typical receiver processing techniques. Received signals may optionally be processed by a channel-compensation system **4807**. If necessary, received signals may be deinterleaved in a deinterleaver **4808** prior to processing by a CI signal processor **4830**.

The CI signal processor **4830** receives a set of samples that may include distortion and/or interference resulting from propagation through the channel **4899**. The CI signal processor **4830** processes the samples, which may directly or indirectly be in the form of CI symbols. In this case, a serial-to-parallel converter **4809** prepares a serial input for inverse-Fourier processing **4810** followed by waveform processing **4811**. The waveform processor **4811** may sample a time-domain waveform resulting from a combination (e.g., a superposition) of CI symbols or waveforms represented (e.g., weighted) by CI symbols.

FIG. **49** illustrates the relationship between CI symbol values w_n and data symbols s_n. CI code chip values are arranged in columns with respect to phase spaces, such as phase space (column) **4901**. As shown previously, a phase space is analogous to a pulse position. The phase spaces (i.e., pulse positions) may be orthogonal or quasi-orthogonal. Thus, the number of CI symbols w_n may differ from the number of data symbols s_n. Each data symbol value s_n is impressed upon a phase space such that each set of CI code chip values expresses the value of the corresponding data symbol s_n. Each code-chip value is analogous to a complex weight applied to a particular CI carrier such that a superposition of the carriers produces a CI waveform bearing the data symbol value s_n at a particular pulse position.

A CI superposition waveform bearing multiple data-symbol/pulse-position characteristics can be created by applying weights to CI carriers that correspond to sums of carrier weights for each data-symbol/pulse-position. Similarly, each CI symbol, such as symbol w_2, may be represented as a sum of a row of data-bearing CI code chips, such as row **4902**.

Decoding may include any appropriate inverse of the coding operation represented by FIG. **49**. For example, to extract an nth data symbol value s_n from a vector of received CI symbol values w, the complex conjugate of a vector of the nth phase space (or CI code) values, w^*_n may be correlated with the received CI symbol vector w. Alternative equivalent decoding processes may be performed. The decoding process may be performed with respect to one or more combining techniques, such as, but not limited to, MMSE, EGC, maximum likelihood combining, or any combination thereof. Decoding may include turbo decoding, Trellis decoding (e.g., Viterbi decoding), block decoding, etc.

FIG. **50** illustrates basic components of a CI coding system and a CI decoding system. A data symbol stream **4701** is processed by a CI symbol generator **5020** that outputs a plurality of CI symbol values w_n representing a coded version of the data symbols s_n. The symbols w_n may optionally be interleaved by an interleaver **5004** prior to being prepared for transmission into a communication channel **5099** by a transmission system **5005**. The symbols w_n are typically multiplexed onto one or more diversity-parameter spaces prior to being transmitted.

A receiver system **5006** couples transmitted signals from the channel **5099**, performs any necessary processing, such as filtering, amplification, demultiplexing, de-spreading, decoding, and/or beam forming, prior to outputting an IF or baseband digital signal. Optionally, channel compensation **5007** may be performed to mitigate effects of channel distortion and/or interference. Any necessary de-interleaving processes **5008** may be performed prior to processing by a CI signal processor **5030**.

The CI signal processor **5030** processes received CI symbols w'n to produce data-symbol estimates **4701'**. The data-symbol estimates **4701'** may be output to additional signal-processing systems (not shown).

The CI symbol generator **5020** converts a predetermined number of input data symbols s_n into a plurality of CI code symbols w_n. This conversion may involve summing information-modulated CI code chips. A first step in a CI symbol generation process involves generating code chips and/or acquiring code chips stored in memory or received from an input data stream. In some applications, code chips may be generated from a reduced set (e.g., an orthonormal basis) of code chips or vectors. Various methods for generating CI code chips are described throughout the specification. In some applications, code chips or orthonormal bases codes may be received over a communication link.

A second step in a CI symbol generation process involves impressing at least one data symbol s_n onto at least one set of code chips. The code chips may be multiplied, phase shifted, modulated, or otherwise impressed with data symbol values s_n. The code chips represent a phase space, such as a pulse position. Optionally, the code chips may be provided with phase offsets with respect to some PAPR-minimizing code or encryption code.

A third step in a CI symbol generation process involves combining the code chips to produce CI code symbols w_n. FIG. **49** illustrates how rows of CI code chips are combined to produce CI code symbols w_n. Predistortion may be performed by providing channel-compensation weights to the CI code symbols w_n.

The CI signal processor **5030** processes received CI symbols w'_n to produce data-symbol estimates **4701'**. A first step in a CI signal processing method includes generating code chips and/or acquiring code chips stored in memory or received from an input data stream. Code chips may be generated from a set of orthonormal codes or a subset of chips comprising one or more orthonormal codes.

A second step in a CI signal processing method includes correlating at least one vector of the code chips with a vector of the received data symbols w'_n. The correlation process may include a scalar multiplication between the code-chip vector and the received data-symbol vector followed by integrating (e.g., summing) the products. Another embodiment of correlation includes adding together selected samples over a predetermined sample interval. Additional processing may be performed to produce estimates of the transmitted data symbols.

The CI signal processor **5030** may perform various types of combining, such as weighted combining as part of an MMSE, EGC, maximum likelihood, or any other measurement-based optimization process. The CI signal processor **5030** may perform channel compensation. The CI signal processor **5030** may perform various receiver-processing functions, as described throughout the specification.

Overview of CI Channel Coding in a Multiple-Access System

In channel coding, a sequence of symbols from a first alphabet is represented by one or more symbols from a second alphabet. In general, an alphabet of order $M=2^N$ is required to represent the M=2N possible unique binary symbol sequences of N symbols each. A signaling system that represents an N-element binary symbol sequence using a symbol alphabet of order $M=2^N$ is typically referred to as M-ary signaling. In M-ary signaling, the equivalent binary data rate R is the symbol rate S multiplied by the number of bits per symbol N (i.e., R=S*N). The number of bits per symbol N is $\log_2 M$.

For each data symbol presented to a transmitter, the transmitter generates a corresponding symbol waveform selected from a set of discrete symbol waveforms. The symbol waveform is then transmitted over a communications channel to be received by at least one receiver. Each transmitted symbol waveform is subject to distortion and noise that can make the received symbol waveform differ from the original transmitted symbol waveform. Consequently, it is necessary to decide which symbol of the discrete set of known symbols was most likely transmitted. This decision is performed in the receiver. The receiver output is a symbol sequence selected from the known set of symbols that represents the best estimation of the transmitted symbol sequence.

The receiver synchronizes each received symbol waveform with a coherent integration interval. In the absence of correct synchronization, the symbol content of the received waveform can be misinterpreted. Synchronization can be lost due to multipath effects, such as fading and inter-symbol interference.

One approach that mitigates the effects of inter-symbol interference is to use M-ary orthogonal signaling with code waveforms that are a factor of log 2M times longer than each data symbol. Just as M-ary signaling with an orthogonal modulation format (such as MFSK) improves the probability-of-bit-error performance, waveform coding with an orthogonally constructed signal set, in combination with correlation detection, provides the same improvement. Since the waveforms are orthogonal, each data symbol's waveform has no projection onto the waveform of any other data symbol. If the symbol duration of the code waveforms is much longer than the multipath delay spread, the effect of the multipath is reduced. Consequently, each data symbol is more easily distinguished from other data symbols.

In one form of CI signaling, each data symbol is constructed from a superposition of narrowband component waveforms. The superposition of the CI waveforms ensures orthogonality in the time domain with respect to other CI component-waveform sets that are phase shifted with respect to an integer-multiple shift of a full or half pulse duration. If the duration of the component waveforms is much longer than the multipath delay spread, the effect of the multipath is reduced. CI waveforms can be supplemented with an antipodal signal set to form a bi-orthogonal signal set. Trans-orthogonal CI waveforms may be generated. CI waveforms may be adjusted to provide the superposition signal with in-phase and quadrature-phase values, thus, enabling additional orthogonal waveform codes.

Multiple-access coding uses one or more code orthogonality properties to separate users. Certain types of channel coding can use one or more code orthogonality properties to separate data symbols. Thus, coding used for multiple access (e.g., CIMA, CI/DS-CDMA, CI multiple-access codes, etc.) can also be used to encode data symbols and/or increase processing gain of a spread-spectrum system by increasing the effective duration of each data symbol. Furthermore, forms of CI coding may be combined with direct-sequence coding and/or any type of channel coding. Such combinations may be made to produce various benefits, including multi-level coding, increased processing gain, improved channel coding, enhanced multiple access, and/or variable-rate communications.

CI codes used in higher-order signaling alphabets are more flexible than conventional binary codes, such as Walsh codes, which are constrained to lengths of 2n. CI-coded data symbols may be co-modulated with a DSSS waveform, CI-based waveform, or any other type of multicarrier, frequency-hopped, or chirped waveform. One objective of this type of co-modulation is to effectively increase processing gain for a given data rate without increasing the spread spectrum transmission bandwidth. Similarly, conventional coding techniques (such as DSSS, conventional channel coding, non-orthogonal signaling, Hadamard-Walsh coding, etc.) may be combined with CI-based waveforms (CI-TDMA, CI/DS-CDMA, CI/MC-CDMA, CI-OFDM, etc.) to increase the processing gain of a CI-based communication system. Processing gain in a CI system is usually related to the number of carriers on which a data symbol is modulated, whereas frequency diversity is related to the frequency band(s) in which CI carriers are distributed. Processing gain may be provided with respect to time-domain (e.g., direct-sequence) encoding of the data symbol.

One preferred embodiment of the invention employs mutually orthogonal polyphase CI waveforms that can be synchronously modulated upon a spread-spectrum code. All transitions of both the polyphase CI waveforms and the spread-spectrum waveforms occur simultaneously with a transition of a common clock signal. The clock-signal frequency may be selected to support the finest possible pulse structure in each polyphase and spread-spectrum waveform. The finest pulse structure that can occur in a waveform determines the bandwidth of the waveform. Therefore, the clock rate establishes the bandwidth of the waveform. As long as a waveform signal transition occurs at a clock edge, a multiplicative composite of a polyphase CI and spread-spectrum waveform will not require additional bandwidth beyond the bandwidth of its two constituent waveforms. Consequently, polyphase waveforms having a bandwidth less than or equal to the bandwidth of the DSSS waveform can be used without any increase in bandwidth of the polyphase/DSSS composite waveform.

In another preferred embodiment, the orthogonal signal set is supplemented with an antipodal signal set to form a bi-orthogonal signal set, further increasing the data rate achievable at a given DSSS or CI processing gain. Other embodiments include differential phase-shift key (DPSK) polyphase codes, CI-Walsh coding, differential CI-Walsh coding, coherent and/or non-coherent M-ary phase-shift keying combined with orthogonal polyphase and/or CI signaling within a single symbol; and differentially encoded coherent phase shift keying across two symbols, with orthogonal signaling within a symbol.

Although CI is commonly provided for multiple access, CI may also be used to encode data symbols. In another preferred embodiment, each of a plurality of data symbols is mapped into a weighted sequence of carrier waveforms. Preferably, the weighted sequences are orthogonal or quasi-orthogonal to each other. The weighted sequence of subcarriers may be MC-CDMA signals. Preferably, the weighted sequence includes a sequence of CI signals. The weighted sequences may be further characterized by a superposition

of waveforms having a time-domain structure similar to direct-sequence or polyphase signals. The superposition of waveforms may be provided with a low PAPR.

FIG. **23**A illustrates a time-domain relationship between each of a plurality of data symbols d_1, d_2, . . . , d_m and multiple-access or spread-spectrum code chips c_1, c_2, . . . , c_N. The code chips are illustrated as shaped, overlapping chips. However the chips may be non-overlapping. Any form of chip shaping may be employed, such as raised cosine, sine, and/or CI chip shaping. A kth user modulates each data symbol onto at least one period of its corresponding code. The code may be a binary code (e.g., a direct-sequence code) or a polyphase code (e.g., a CI code). In addition to a multiple-access and/or spreading code, each data symbol may be encoded with a channel code.

FIG. **23**B illustrates time-domain relationships between multiple user data streams and associated orthogonal channel codes used to modulate each symbol in each data stream. A kth user transmits at least one data symbol d_{mfk} (where m is a data-symbol number in a particular code-period, f is a particular frame having a duration of at least one code period, and k is a user number that references a particular user) on at least one chip sequence C_{mfk}. The codes may be assigned with respect to any number of parameters, including data-symbol number m, frame number f, and/or user number k. The channel code duration is typically the same as the multiple-access code duration. The channel code bandwidth is typically less than or equal to the bandwidth of the multiple-access or spreading code C_{mfk}. Channel codes may be derived from the same set of codes used for multiple access. Each chip sequence is shown as a plurality of time-domain chips C_{nmfk}, where n indicates a chip position relative to other chips in the code. Although the chip waveforms are illustrated as overlapping waveforms, non-overlapping waveforms may be employed. Any form of chip shaping may be provided, including, but not limited to, raised cosine, sine, and/or CI chip shaping.

Each user may transmit data symbols in the same time interval by using different multiple-access codes. A single user may be provided with more than one multiple-access code, thereby increasing the effective bandwidth of that user's communication channel. A user may use a different multiple-access code and/or channel-code set relative to each adjacent data symbol. A particular user may transmit multiple symbols in a given time interval by using multiple orthogonal channel codes. A user may transmit multiple data bits per symbol by employing an M-ary modulation scheme, such as QAM, QPSK, etc.

FIG. **24** shows relative symbol durations between a user's data symbols d_1, d_2, . . . , d_m, channel-code symbols $cc_{mn'}$ (where n'=1, 2, . . . , N'), and direct-sequence or CI-code symbols c_1, c_2, . . . , c_N for a channel code having a longer duration than the direct-sequence or CI code. A kth user transmits one data symbol d_m corresponding to a particular channel code in one channel-code period. Multiple data symbols d_m may be transmitted simultaneously by employing multiple simultaneous channel codes. Each channel-code symbol $cc_{mn'}$ has the same duration as the direct-sequence or CI-code period. Each data symbol d_m is spread over multiple direct-sequence or CI-code periods. A particular user may employ multiple direct-sequence and/or channel codes to increase throughput or reduce probability of error. In one embodiment of the invention, there is at least a one-to-one correspondence between channel codes and data symbols. In another embodiment, data symbols, such as binary or M-ary data symbols, are impressed upon individual channel codes. Similarly, multiple-access codes may comprise different levels of code granularity. For example, wideband codes may provide spreading or inter-cell isolation, whereas relatively narrowband codes may provide intra-cell orthogonality.

Although the channel-code symbols $cc_{mn'}$ and the data symbols d_m are shown as rectangular symbols, these symbols may be shaped in the time domain. For example, the symbols may be shaped with respect to some form of chip shaping, such as raised cosine, Gaussian, sinc, and/or CI chip shaping. The symbols may simply be tapered in the time domain. Frequency-domain windowing may be employed to provide a predetermined time-domain chip profile. Either or both the channel-code symbols $cc_{mn'}$ and the data symbols d_m may convey M-ary signals, such as polyphase, multi-magnitude, or hybrid signals.

FIG. **51** illustrates channel-code chips c_{nk} (where n indicates a chip position relative to other chips in a code vector and k is a user number that references a particular user) and a data symbol d_m applied to multiple carrier frequencies in a multiple-access system. The channel-code chips c_{nk} map at least one data symbol d_m to multiple frequencies. The code vector may be a direct-sequence code, a CI code, or any other appropriate symbol alphabet.

In one set of embodiments of the invention, the channel-code chips have the same duration as the data symbol d_m. A multiple-access code used herein preferably has the same code length (i.e., the same number of carriers). In one embodiment, frequency-domain multiple-access coding is provided to the carrier frequencies as MC-CDMA, LIMA, or any other frequency-domain multiple-access coding. In another embodiment of the invention, multiple-access coding is provided in the time domain in the form of direct-sequence coding, CI coding, and/or TDMA. In yet another embodiment of the invention, modulation on each carrier frequency is characterized by multi-tone CDMA or multi-carrier direct-sequence CDMA. In another set of embodiments of the invention, multiple-access coding is characterized by CI/DS-CDMA and FIG. **33** indicates CI carriers for a particular CI/DS-CDMA code or code chip.

Multiple channel codes may be used simultaneously as a means for multiple access or increased throughput. Data symbols may be encoded with respect to an alphabet defined by the possible channel codes. Data symbols may be encoded with respect to modulation of the channel codes. Data symbols may be encoded with respect to a combination of a channel-code alphabet and impressed modulation.

FIG. **52** illustrates an application of multi-level coding of the present invention. A plurality N' of communication channels are indicated by frequency-domain code vectors $C_1=[c_{11}, c_{12}, \ldots, c_{1N}]$ to $C_{N'}=[C_{N'1}, C_{N'2}, \ldots, C_{N'N}]$. In a given time interval, a data symbol do may be transmitted on each channel. In one embodiment of the invention, at least one super-code vector $C^o=[c^o{}_1, \ldots c^o{}_{M=N'}]$ is applied across the frequency-domain code vectors C_1 to $C_{N'}$. Each frequency-domain code vector C_n is multiplied by a super-code chip $c^o{}_m$. Super-code vectors are preferably orthogonal or quasi-orthogonal with respect to each other. A particular super-code vector may correspond to a channel code or a multiple-access channel. Super codes may be changed relative to some predetermined time interval, such as the duration of a data symbol d_m.

FIG. **53** illustrates a multi-level coding method of the invention that spreads a data symbol do over multiple frequencies f_0 to f_{N-1} and time intervals t. An nth multiple-access channel or a channel code is defined by a code vector $C_n=[c_{n1}, c_{n2}, \ldots, c_{nN}]$. The code vector C_n may be an MC-CDMA code, a CI code, a CIMA code, etc. A super-

code chip c^o_m from some super-code vector $C^o=[c^o_1, \ldots, c^o_M]$ of length M multiplies the code vector C_n over some predetermined time interval t. Preferably, the time interval t is some integer multiple of the normal symbol duration $T_s=1/f_s$, where f_s is the frequency separation between carrier frequencies. The super-code vector C^o spreads a data symbol d_m over M time intervals t. The super-code vector C^o is preferably one of a family of orthogonal or quasi-orthogonal code vectors. In one embodiment of the invention, each super-code vector may represent a particular data symbol. In another embodiment of the invention, each super-code vector represents a multiple-access channel.

FIG. **54**A illustrates a method of sub-channel coding. Chips $[c_{n1}, c_{n2}, \ldots, c_{nN}]$ of at least one code C_n are provided to a plurality N of subchannels, such as spatial sub-channels. The code sequence G provides a data symbol or multiple-access channel with sub-channel (e.g., sub-space) diversity. If a small number of the subchannels have poor link quality, the integrity of the coded data symbol or channel is not significantly compromised. The effects of inter-symbol interference can be reduced by a multicarrier implementation, such as OFDM or some CI-based technique. Inter-symbol interference may be mitigated by spreading and/or interleaving each data symbol d_m in the time domain.

FIG. **54**B shows a subchannel coding technique combined with time-domain coding. Super codes C^o may be applied to orthogonal bases, such as subchannels, sub-channel codes, CI codes, direct-sequence codes, and/or any orthogonal or quasi-orthogonal diversity-parameter values. In this case, at least one super code C^o is applied to a particular sub-channel code C_n over multiple time intervals. The application of the super code C^o increases data symbol d_m duration. Alternatively, a super code C^o may be applied in the frequency domain to provide frequency diversity.

Super codes may provide channel coding and/or multiple-access coding. Although non-overlapping time intervals, frequencies, and subchannels are illustrated in the preferred embodiments, coding for multiple access and channel coding may be applied to any orthogonal or quasi-orthogonal diversity-parameter values.

CI Channel Coding Systems

The following descriptions of transmitters and receivers adapted to perform CI channel coding reference functional diagrams that correspond to systems and methods of the invention.

FIG. **55** shows an embodiment of a transmitter adapted for combined channel coding and multiple access. A data source **5500** provides a stream of data bits to a symbol processor **5502**. The symbol processor **5502** groups the data symbols to generate a sequence of data words wherein each data word represents a symbol value. The symbol values may be processed via error-correction coding and/or interleaving by an optional error-correction coder **5504**.

Error correction coding may be performed with Reed-Solomon codes, hybrid Reed-Solomon/binary codes, erasure codes, turbo codes, CI codes, etc. Error correction coding typically involves providing some sort of parity-check symbols to the data symbols. Bi-orthogonal coding has the extra requirement of correcting the binary element of the data. Interleaving may be performed to reduce the problems associated with error bursts. Error correction may be aided by changing the direct-sequence code on each symbol in order to randomize the effect of multipath on each symbol. In several preferred embodiments, the effects of multipath are mitigated by using CI. Either or both forward error correction and automatic re-transmission request may be performed.

A coder (or CI coder) **5506** translates the input data into symbol waveforms. The coder **5506** may modulate an appropriate phase change between the symbols. Modulation can take the form of minimum-shift keying or any other continuous-phase modulation. The coder **5506** may incorporate coherent M-ary PSK or M-ary DPSK. The coder **5506** may translate the input data with respect to a stored set of waveforms. The coder **5506** may select a corresponding logic in a waveform generator (not shown). For bi-orthogonal or differentially bi-orthogonal coding, phase inversion may be performed by complementing the symbol waveforms.

A frequency spreader **5512** combines the symbol waveform(s) with a direct-sequence or CI waveform generated by a DS/CI code generator **5510**. The frequency spreader **5512** may include some sort of combining device, such as an exclusive OR logic gate or equivalent device. The output of the frequency spreader **5512** is processed by an RF modulator **5514** that provides an RF transmit signal that is optionally processed and coupled into a communication channel by a transmitter **5516**.

The order of modulation provided by modules **5510**, **5512**, and **5514** may be changed. RF modulation **5514** may be implemented in stages and include IF processing and associated filtering. RF modulation **5514** may include any form of direct conversion including frequency-conversion techniques of the present invention. Various modules may be coupled to the DS/CI code generator **5510**. For example, the data source **5500**, the error-correction coder **5504**, and/or the coder **5506** may be coupled to the DS/CI code generator **5510** to impress data, error-correction coding, and/or channel coding into the direct-sequence and/or CI codes generated by the DS/CI code generator **5510**.

FIG. **56** illustrates a receiver corresponding to one embodiment of the invention. A_n input data sequence is provided to a correlator **5606**. A synchronizer **5602** controls the timing of various receiver components, including the correlator **5606**, a multiple-access/spread-spectrum reference-code generator **5603**, and a channel reference-code generator **5604**. Various implementations of the correlator **5606** may be provided. Optional components not shown in FIG. **56** may include time-tracking, synchronization-detection, level-control, a delay-lock loop, a comparator, and threshold detection-systems.

The synchronizer **5602** may include a matched filter, an aided-acquisition correlator, and/or a threshold-detection circuit. Synchronization typically involves two primary steps. Acquisition involves bringing the spreading signals into coarse alignment. Tracking involves continuously maintaining optimal fine alignment via feedback.

A demodulator **5608** performs a maximum likelihood decision or some other approximation that determines which orthogonal waveform(s) was (were) transmitted. The correlator **5606** provides the demodulator **5608** with a number M of correlation values corresponding to the M-ary signal input to the correlator **5606**. Any phase-shift data impressed upon the orthogonal waveforms can be demodulated by the demodulator **5608** via comparison with at least one phase reference.

Demodulated data symbols are coupled to a data processor **5612**. After demodulation, each demodulated signal is decoded for errors if error-correction coding is employed. The data symbols are then processed to form a bit stream. The data processor may include an optimal-combining receiver, a multi-user detector, an interference canceller, a decision processor, and/or one or more feedback loops to

control receiver function in response to some performance measurement, such as BER, SNR, probability of error, received signal power, etc.

Systems and methods of the invention may be characterized by various modes of operation. Mutually orthogonal binary waveforms or other signal alphabets may be synchronously modulated onto one or more CI-based signals. Synchronous modulated implies that transitions of the channel-code waveforms (i.e., the signal alphabets) and the multiple-access or spreading waveforms occur simultaneously. Thus, channel-code waveforms having a bandwidth less than or equal to the bandwidth of the multiple-access or spreading waveforms do not increase the bandwidth of the composite waveform.

In one embodiment, orthogonal binary waveforms are modulated onto at least one CI-code waveform. In another embodiment, orthogonal waveforms are modulated onto at least one signal having a CI-based sub-layer. Another set of embodiments includes modulating a signal set, such as one or more orthogonal waveforms, onto a CI/DS-CDMA waveform.

Orthogonal or quasi-orthogonal CI codes may be synchronously modulated onto one or more waveform sets. In one embodiment, at least one CI code set or CI-encoded information signal is modulated onto a wave set of at least one CI code. Another embodiment includes modulating CI-coded waveforms onto any type of spread-spectrum or multiple-access waveform. One particular set of embodiments includes modulating at least one CI-coded waveform onto at least one CI/DS-CDMA code set.

In one set of embodiments, the DS/CI code generator **5510** and the multiple-access/spread-spectrum reference-code generator **5603** are adapted to generate CI-based signals, such as CI codes or CI-based multiple-access signals. CI-based signals include CI/DS-CDMA signals, which can have binary or polyphase chip sequences. CI-based signals may include any type of CI sub-carrier architecture, such as signals characterized by orthogonal circular (and/or elliptical) polarizations. In these embodiments, the coder **5506** and the channel reference code generator **5604** are adapted to generate one or more waveforms indicative of a signal alphabet, such as a set of orthogonal, bi-orthogonal, or trans-orthogonal waveforms. Waveforms generated by the coder **5506** may include binary, polyphase, and or continuous-phase signals. The coder **5506** may generate conventional channel codes that are then modulated onto CI-based signals.

In another set of embodiments, the DS/CI code generator **5510** and the multiple-access/spread-spectrum reference-code generator **5603** are adapted to generate conventional spread-spectrum or multiple-access waveforms, such as any of various binary chip sequences. In these embodiments, the coder **5506** and the channel reference code generator **5604** are adapted to generate one or more CI-based signaling alphabets. CI-based signaling alphabets may include one or more CI codes. A CI-based alphabet may include any signaling alphabet constructed from a superposition of CI signals.

A pulse-shaping filter may be provided to the DS/CI code generator **5510** or the RF modulator **5514**. The DS/CI code generator **5510** and the multiple-access/spread-spectrum reference-code generator **5603** may be adapted to provide a different code to each adjacent symbol in a sequence of symbols. Error-correction coding may be employed to further reduce error rates. Coherent or non-coherent detection may be performed at the receiver.

CI Receiver Processing for Single-Carrier Signals

In one aspect of the invention, a received single-carrier or multicarrier signal is decomposed into a plurality of orthogonal, overlapping carrier components. These components can then be processed to obtain benefits of parallel processing and frequency-domain processing. The selection of carrier components may depend on one or more signal characteristics, channel characteristics, and/or receiver characteristics. Methods and systems adapted to decompose a received signal into CI components may be adapted to other embodiments and aspects of the invention described herein. For example, a wideband single-carrier signal may be decomposed into a plurality of narrowband CI components to facilitate array processing.

Various embodiments of CI are characterized by a mapping process performed by a receiver that maps time-domain samples of a high-bandwidth signal into a parallel set of low-bandwidth, long-duration symbols. FIG. **57**A shows a frequency-domain profile **5701** of a high-rate digital transmission represented by a time-domain profile **5710** shown in FIG. **57**B. The time-domain profile **5710** may be more accurately characterized by Gaussian or raised-cosine symbols.

The wideband signal spectrum **5701** may be decomposed into a plurality N of narrowband signals **5702**, as shown in FIG. **57**C. However, if the narrowband signals **5702** do not overlap in the frequency domain, some of the received signal energy (and thus, a substantial amount of the information) is lost. The lost signal energy is illustrated by a plurality of gaps **5703** between the narrowband signal spectrum **5702** and the wideband signal spectrum **5701**.

A preferred embodiment of the invention provides for decomposition of a received signal into a plurality of overlapping narrowband carrier signals. FIG. **58**A illustrates N modulated orthogonal carrier components. When a received signal is decomposed into carrier components, each carrier frequency f_n is associated with a complex-valued symbol v_n. In this case, a sample period $T_s=1/f_s$ provides overlapping frequencies f_n that are incrementally spaced with a frequency separation offs between adjacent carriers.

The sample period E is a predetermined time interval in which samples are collected and processed, such as in a Fourier transform operation. This duration T specifies a set of frequencies f_n that are orthogonal to each other. How the samples collected within each sample period T are processed (e.g., selected and/or weighted) determines a receiver's sensitivity to particular frequencies.

Each carrier signal appears to be modulated with a complex data symbol v_n that is actually a complex-weighted superposition of a plurality of data symbols s_m. Each symbol v_n has a symbol period of $T_s=1/f_s$. A corresponding frequency spectrum in FIG. **58**B shows the N frequency components. Depending on the particular embodiment of the invention, the carriers may or may not be incrementally spaced in frequency. Subsets of the modulated carriers may or may not overlap. An nth symbol v_n corresponding to an nth carrier frequency f_n, which results from a superposition of complex weighted w_{np} data symbols s_m, is expressed by:

$$v_n=\Sigma_{n,m=1}w_{nm}s_m$$

The vector representations v_n may be combined and processed using matrix operations to separate the data symbols s_m. Appropriate techniques involving any combination of estimation, optimization, interferometry, and/or cancellation may be used to separate the data symbols s_m.

FIG. **58**C illustrates N' modulated carrier components. In this case, N'>N. Thus, the frequency separation/s of the

carriers is smaller than f_s. Consequently, the symbol v_n period T's is longer than T_s. The frequency separation/s and the symbol period T's are expressed by the following equations:

$$f'_s = f_s N/N'$$

$$T'_s = T_s N'/N$$

A frequency-domain spectrum of the carrier components shown in FIG. **58**C is shown in FIG. **58**D.

A transmission method of the invention provides a transmitter with a multicarrier signal having selected frequency components intended to facilitate separation and processing of the received data symbols. On the receive side, factors that may play a part in selecting carrier frequencies as part of a decomposition process include number of parallel operations, duration and frequency of sampling, and transformation characteristics between transmitted symbols u_p and received carrier symbols v_n.

FIG. **58**E exemplifies a spectral profile selected for a particular communication channel. Information signals are transmitted and/or received in a plurality of spectral ranges **5811**, **5813**, **5815**, and **5817**. The following spectral ranges are avoided: a spectral range **5812** allocated to another user, application, or system, a spectral range **5814** experiencing a deep fade, and a spectral range **5816** experiencing jamming or interference. A transmitter may be adapted to avoid transmitting in undesirable spectral ranges. A receiver may be adapted to avoid receiving signals in undesirable spectral ranges. In either case, the desired spectral ranges may be decomposed into CI carriers.

FIG. **59**A illustrates a method of generating CI carriers as part of a transmission process. A channel-estimation step S**901** characterizes the communication channel and identifies desirable and undesirable spectral regions. Channel estimation may be performed with respect to multiple channels. Channel estimation may be performed with signals received from remote transceivers. Alternatively, remote transceivers may perform channel estimation and communicate those estimates to the local transceiver.

CI carriers are generated in a CI carrier generation step S**905** based on channel estimates. Pre-transmission processing S**906** is performed prior to transmitting **5907** the carriers into a communication channel. Pre-transmission processing S**906** may include predistortion, A/D conversion, modulation, multiplexing, multiple-access processing, up conversion, amplification, filtering, coding, beam forming, etc.

FIG. **59**B illustrates a method of generating CI carriers as part of a receiving process. A channel-estimation step S**901** characterizes the communication channel and identifies desirable and undesirable spectral regions. Channel estimation may be performed with respect to multiple channels. Channel estimation may be performed with the aid of signals received from remote transceivers. Alternatively remote transceivers may perform channel estimates and communicate those estimates to the local transceiver.

A received signal is decomposed **5904** into a plurality of CI carriers. Carrier properties, such as frequency selection, frequency spacing, and complex weighting are selected, at least in part, with respect to the channel estimates. Optionally, the carriers may be processed before being combined in a combining process **5906**. The combining process **5906** may be directed by channel estimates. Combining **5906** may be performed using any appropriate optimal-combining technique, such as MMSE combining. Alternatively, other combining techniques may be used. The combined signals are then conveyed to a receiving process **5908** that may further process the combined signals. Decomposition of a received signal into narrowband CI components permits low-speed, parallel processing. In addition to simplifying demodulation of a high-rate signal, CI carrier processing can simplify many data-processing applications (such as error detection, error correction, virus detection, verification, decoding, and/or other security protocols) that typically require high-rate processing. This simplification is enabled by slower data-processing requirements. The combining of multiple low-speed processes produces high aggregate data rates. Similar benefits can be provided to other signal-processing operations, such as interference mitigation, noise mitigation, correlation, matched filtering, coding/decoding, beam forming, etc.

FIG. **60**A illustrates a CI receiver adapted to process received single-carrier signals. Single-carrier signals include a single carrier signal modulated with an information signal, a single unmodulated carrier, and/or any received multicarrier signal that can be processed as a single-carrier signal.

A single-carrier receiver of the invention includes an orthogonal-frequency filter **6001** coupled to an optimal combiner **6002**. Additional signal-processing units (not shown), such as one or more decoders, formatters, beam formers, demodulators, demultiplexers, despreaders, channel compensators, etc., may be coupled to the combiner **6002**. The orthogonal-frequency filter **6001** shown in FIG. **60**A includes an optional filter **6010**, a sampler **6011**, and a digital filter **6012**, such as a Fourier transform processor.

The orthogonal-frequency filter **6001** is adapted to receive at least one input single-carrier and/or multicarrier signal. The input signal may be processed prior to being coupled into the orthogonal-frequency filter **6001**. For example, a signal received by a receiver system (not shown) coupled to a communication channel (not shown) may be amplified, filtered, demultiplexed, demodulated, modulated, and/or down converted prior to being coupled into the orthogonal-frequency filter **6001**. Optionally, the receiver system (not shown) may perform beam forming, interference cancellation, despreading, demultiplexing, channel compensation, multiple-access processing, A/D processing, and/or D/A processing.

The input single-carrier signal may optionally be processed by the filter **6010**. The filter **6010** may include a passband filter, such as to provide anti-aliasing. The filter **6010** may include one or more filters, such as low-pass, high-pass, and/or notch filters. The filter **6010** may be adapted to select one or more communication channels, reject interference, compensate for channel distortion, and/or avoid deep fades.

The sampler **6011** performs digital sampling. A sampler, such as the sampler **6011**, may include one or sample-parameter controllers (not shown) to select and/or adapt sample parameters, such as sample rate, sample width, sample duration, sample interval, sample shape, and/or sample weights. The sampler **6011** may optionally be integrated into a filter, such as the digital filter **6012**. The selection and/or adaptation of various sample parameters can be performed to affect the frequency response of the orthogonal-frequency filter **6001**. Furthermore, the sampler **6011** may optionally include a digital filter (not shown) to provide a predetermined frequency response.

One advantage of a digital receiver system includes the ability to adapt the sample rate to operate over a wide range of data rates. An adjustable anti-aliasing filter combined with an adjustable-rate sampler may be provided to appropriately process a wide range of input signal bandwidths. Alternatively, a fixed sample rate and static analog filter may

be combined with a digital system adapted to use multi-rate signal processing algorithms to accommodate a predetermined range of signal bandwidths and sample rates.

The sampler **6011** may include one or more samplers. Samples may be stored in a storage system (not shown). Samples may be processed (e.g., selected, weighted) prior to, or following storage. The sampler **6011** may include one or more quantizers (not shown), such as noise-rejecting quantizers.

The digital filter **6012** may include one or more filters to process samples produced by the sampler **6011**. The filter **6012** may include a filter bank. The filter **6012** may include any type of signal processor adapted to perform a Fourier transform operation. For example, the filter **6012** may perform one or more FFTs, DFTs, and/or OFFTs. The filter **6012** may include one or more filters with simple delays and/or sophisticated filters having complex amplitude and phase responses.

FIG. **60**B illustrates a CI receiver embodiment adapted to process received single-carrier signals. The single-carrier receiver includes an orthogonal-frequency filter **6001** coupled to an optimal combiner **6002**. The orthogonal-frequency filter may **6001** include one or more optional analog filters **6010**.1 to **6010**.N, one or more samplers **6011**.1 to **6011**.N, and one or more integrators **6012**.1 to **6012**.N. The numbers of analog filters **6010**.1 to **6010**.N, samplers **6011**.1 to **6011**.N and integrators **6012**.1 to **6012**.N may differ from each other.

The analog filter(s) **6010**.1 to **6010**.N may select one or more frequency channels. Similarly, the sampler(s) **6011**.1 to **6011**.N, and/or integrator(s) **6012**.1 to **6012**.N may select one or more frequency channels. A plurality of samplers may be coupled to a single analog filter. A plurality of samplers, such as samplers **6011**.1 to **6011**.N, may be provided by a single sampler that collects samples and a selector (not shown) that selects collected samples to provide different samples rates and/or sample intervals. The integrators **6012**.1 to **6012**.N may include combiners (e.g., adders), accumulators, and/or storage devices.

FIG. **61** illustrates basic components of a repeater that converts a received signal into overlapping, orthogonal CI components, processes the components, and recombines the processed components prior to transmitting the combined components. The repeater includes an orthogonal-frequency filter **6101**, a sub-carrier processor **6102**, and an inverse orthogonal-frequency filter **6103**.

The orthogonal-frequency filter **6101** is a filter that is adapted to decompose a received signal into a plurality of CI components. The filter **6101** may down convert the received signal into one or more baseband and/or IF signals. Various methods of down conversion may be performed, such as mixing, passband sampling, or any appropriate zero-intermediate-frequency process. The down-converted signals may be converted to digital signals in an A/D process prior to, during, or following down conversion. The sub-carrier processor **6102** may be adapted to filter one or more CI components, or otherwise mitigate noise and/or interference. The processor **6102** may perform channel compensation of transmitted and/or received signals. The processor **6102** may perform pre-distortion processing. The processor **6102** may be adapted to perform various data-processing applications.

The inverse orthogonal-frequency filter **6103** may be adapted to combine the processed signals prior to transmitting the signals into a communication channel (not shown). The filter **6103** optionally performs amplification. The filter **6103** may include an up sampler, an inverse Fourier transform, an up converter, a filter bank (such as a reconstruction filter bank), an amplifier, a D/A converter, an array-processing system, and/or any other appropriate pre-transmission system or device.

FIG. **62** illustrates basic components of a CI receiver coupled to a plurality of array elements **6200**. The array elements **6200** may include one or more RF processors (not shown) adapted to perform RF-signal processing, such as amplification and filtering. A_n orthogonal-frequency filter bank (OFFB) **6201** is adapted to separate one or more single-carrier signals generated by the array **6200** into a plurality of CI carriers. A CI carrier may be a modulated carrier signal or a complex value related to at least one information signal value in a particular CI carrier band. One or more filters in the OFFB **6201** may be coupled to each element of the array **6200**. The OFFB **6201** may be adapted to perform typical front-end processes, such as, but not limited to, A/D conversion, down conversion, demodulation, and channel selection.

Various signal processing functions may be applied to the CI carrier signals in an optional processor **6202**. These processes may include one or more of the following; channel compensation, interference mitigation, carrier weighting, multi-user detection, demodulation, demultiplexing, despreading, A/D conversion, down conversion, beam forming, interferometry, matched filtering, convolution, and decoding. The CI components are combined in a combiner **6203**. The combiner **6203** may perform one or more types of signal combining, including optimal combining.

FIG. **63** illustrates basic components of a matched-filter CI receiver adapted to process received single-carrier signals. Received single-carrier signals are processed in a down converter **6301**. Down-converted signals are digitized in an A/D converter **6302** prior to being processed in an OFFB, such as an FFT **6303**. In some applications, the A/D converter **6302** and the down converter **6301** may be embodied by an anti-aliasing filter (not shown) and a passband sampler (not shown).

The FFT **6303** separates the received single-carrier signal into a plurality of CI component signals that are correlated with a plurality of reference component signals. A CI reference generator **6310** generates the reference component signals and provides the signals to a correlator **6304**. The correlator **6304** output may be coupled to one or more additional signal processing systems (not shown).

An embodiment of the CI reference generator **6310** includes a single-carrier reference-signal generator **6311** coupled to an OFFB, such as an FFT **6312**. The FFT **6312** separates the single-carrier reference into a plurality of reference component signals.

The correlator **6304** may include a plurality of matched filters (not shown) adapted to process each CI component signal/reference component signal pair. In one embodiment, the FFT **6303** may be provided with a processor (such as the processor **6202** shown in FIG. **62**) to compensate for channel effects and/or interference. In an alternative embodiment, a processor and a combiner (such as the processor **6202** and the combiner **6203** shown in FIG. **62**) are coupled between the FFT **6303** and the correlator **6304**, and the CI reference generator **6310** is adapted to generate a single-carrier reference signal. The correlator **6304** is adapted to correlate the processed and combined received signal with the reference signal.

FIG. **64**A illustrates a CI receiving method adapted to process a single-carrier signal. Received signals are optionally down converted **6401** to one or more baseband or IF signals. Down conversion **6401** may include anti-aliasing filtering and passband sampling. Down conversion **6401**

may include selecting and/or adjusting sample widths and/or integration times. Down-converted signals may optionally be filtered **6402**. Filtering **6402** may include channel selection.

A received single-carrier analog signal is converted to a digital signal in an A/D conversion step **6403**. The digital samples are provided to an OFFB step **6404** that separates the digital signal into a plurality of CI carriers or CI-carrier values. The carriers or carrier values are optionally processed in a processing step **6405** before being combined in a combining step **6406**. Processing **6405** and combining **6406** may be characterized by optimal combining. The processing step **6405** may include one or more of the following; channel compensation, interference mitigation, noise mitigation, weighting, multi-user detection, demodulation, demultiplexing, despreading, A/D conversion, down conversion, beam forming, interferometry, matched filtering, convolution, and decoding.

FIG. **64**B illustrates basic steps of a CI reception method. A received single-carrier signal is decomposed into a plurality of CI components in a decomposition step **6410**. The received signal may be an analog or a digital signal. An analog signal is typically decomposed into a multicarrier analog signal or a plurality of complex values representing carrier values. A digital signal may be decomposed into a plurality of analog carriers whose superposition represents time-domain characteristics of the digital signal. The received signal may be a multicarrier signal. However, the decomposed carriers do not need to correspond to the received carriers.

The decomposed signal components may be processed in an optional processing step **6411** prior to combining **6412**. Various processing and combining steps may be performed, as described throughout the specification.

FIG. **64**C illustrates basic steps performed by a CI receiver. Channel estimation **6420** is performed using blind adaptive techniques and/or training signals. Channel selection **6421** is performed based on channel estimation and/or multiple-access considerations. Received signals are decomposed **6422** into CI component signals, which may optionally be processed in one or more processing steps **6423**. The CI components signals are combined in a combining step **6424**.

Software-Defined Implementation of CI Systems

The primary issue facing the wireless communication industries is how to use the available spectrum most efficiently given current channel conditions and user demands. Existing wireless systems do not address this issue effectively because the physical-layer functionality is fixed while channel conditions and network traffic can change rapidly.

Recently, the concept of an adaptable network based on software-defined transceivers has been introduced. However, the implementation of this concept has been limited by conventional technologies. Currently, software-defined radio is limited to unsophisticated switching schemes between dedicated hardware components, thus, providing only a primitive form of interoperability between only two or three transmission protocols.

One of the goals of software-defined networks is to enable a more dynamic organization of resources. In order to achieve this goal, software radio should enable dynamic adaptations of all communication layers, including the physical layer, which is typically implemented in hardware. As a result of the limitations of conventional radio technologies, prior-art software radio development is directed primarily toward interoperability problems resulting from different cellular standards. The implementation of CI-based technologies provides the adaptability and low complexity necessary to implement a software-defined solution for wireless networking.

CI systems and methods described herein have applicability to wireless and guided-wave systems including, but not limited to, base stations, mobile transceivers, fixed subscriber units, routers, gateways, patches, and repeaters. Adaptable CI implementations of the invention may include providing communication between devices that utilize different transmission standards. CI systems may provide associated control operations, such as identifying a particular transmission protocol used by a particular device, reserving channels for transmission, monitoring channel use (including channel reservation and channel release), requesting data transmissions and/or state information from remote devices, attaching tags to data streams for identification and/or access control, and providing instructions to remote transceivers to adjust or control processing, transmit status information, and/or identification.

A CI-based software radio can extend adaptive link-layer techniques to the physical layer. This enables more efficient use of the spectrum by dynamically adjusting physical-layer characteristics to current channel conditions, network traffic, and application requirements. CI can significantly improve wireless network performance and functionality by adapting to different requirements for bandwidth, error rate, latency, link priority, and security.

Embodiments of a CI-based communication system may include interactive capabilities between the physical layer and higher layers such that a response to changing conditions and operational requirements can be directed to an appropriate physical-layer function. For example, a base station in a mobile wireless network can dynamically create channels depending on the number of mobile units in its coverage area and their service requirements. When additional units enter the area, system bandwidth can be assigned accordingly.

In ad-hoc networks, base station functions (e.g., routing, power control, synchronization, geo-location services, etc.) may be distributed among subscribers and repeaters. CI is an ideal technology for mitigating multipath effects, which can be particularly sever in ad-hoc networking environments. The performance benefits of CI can be used to greatly reduce subscriber-unit emissions for those units that perform routing and relay functions. CI can also be used to adapt base-station and access-point functions to maintain link quality and perform load balancing (e.g., managing power budgets for devices acting as routers and relays, managing system spectrum allocations, and adjusting cell boundaries to adapt to changing user demands, power budgets, and spectrum use.

Bandwidth can be dynamically allocated to up-stream and down-stream channels depending on network traffic characteristics. Units requiring real-time or broadband services may be assigned to dedicated channels, whereas units having bursty data requirements may be assigned to a shared channel.

The proposed CI network adjusts time-domain and frequency-domain characteristics of transmissions by applying weights to the CI carriers. Thus, CI carriers can be processed to produce signals having various physical-layer characteristics:

Multiple-access protocols (e.g., DS-CDMA, TDMA, OFDM, MC-CDMA)

Channel codes

Modulation types (e.g., phase modulation, frequency modulation, amplitude modulation, time-offset modulation, etc.) and modulation levels (e.g., binary, M-ary)

Multiplexing (e.g., TDM, FDM, CDM)

Formatting (e.g., frame length, headers, payload length, etc.)

Source coding

Frequency agility (e.g., frequency hopping, variable aggregate bandwidth, frequency selectability, etc.)

Conventional software-based radios can provide adaptability to different communication standards. However, conventional software-based systems have the associated complexity of performing many physical-layer and related processes via separate functional processes. This complexity necessitates multiple processors, resulting in greater system cost and complexity than conventional hardware-based systems.

Alternatively, a CI-based software-defined radio simultaneously performs many processing functions via sub-carrier selection and weighting. The selection of CI carrier frequencies and the application of weights consolidates many of the physical-layer processes, which are typically performed in multiple stages using different signal-processing techniques.

FIG. **65** illustrates how basic physical-layer functions can be combined into three processes: CI carrier and weight calculation **6511**, CI carrier selection **6512**, and CI carrier weighting **6513**. A selection of appropriate carriers and the application of carrier weights can provide basic physical-layer transceiver processes, such as formatting and source coding **6501**, encryption **6502**, channel selection **6503**, channel coding **6504**, multiplexing **6505**, modulation **6506**, spread-spectrum processing **6507**, and multiple-access processing **6508**. In one set of embodiments, the physical-layer processes are performed via software-controlled processes. Optionally, A/D conversion **6509** and frequency conversion **6510** may be performed via harmonic and/or sub-harmonic processes **6515**. A/D conversion **6509** may be integrated into frequency conversion **6510** and/or Fourier processes **6514**.

CI-based systems process wideband signals as a superposition of narrowband signals. In addition to enabling slow, parallel processing, which facilitates the implementation of software-based processing and simplifies the required microprocessor architecture, a CI transmitter can process carriers to improve performance in the following ways:

Apply pre-distortion weights to compensate for multipath fading.

Eliminate carriers having deep fades and/or high interference.

Adapt to different spectrum allocations.

Operate across non-contiguous frequency bands.

Achieve wideband frequency-diversity benefits for a narrowband data channel.

Similarly, a receiver can process received CI carriers in the following ways to achieve various performance and system benefits:

Apply post-distortion weights to compensate for multipath fading.

Disregard carrier frequencies having deep fades and interference.

Filter noise and/or interference on each carrier.

Perform multi-user detection to mitigate interference.

Perform space-frequency processing to achieve spatial diversity and/or enhance bandwidth efficiency.

Various sub-layer processes may be implemented in software. This enables a CI-based system to be reprogrammed such that various processing functions (e.g., pulse shaping, sub-carrier selection, sub-carrier weighting, coding, modulation, power control, spatial processing, multiplexing, multiple access, combining, decision, feedback, process control, etc.) can be adapted to different applications and system requirements.

FIG. **66** illustrates an embodiment of a CI-based software-defined radio. A software implementation of a CI-based transceiver may include one or more signal processing hardware components **6603.1** to **6603.***j* and one or more CI-based signal processing software components **6601.1** to **6601.***i*. The software components **6601.1** to **6601.***i* may reside on one or more of the hardware components **6603.1** to **6603.***j* or on one or more additional hardware components that are not shown. For example, the software components **6601.1** to **6601.***i* may reside on a computer main frame or a workstation. At least one of the hardware components **6603.1** to **6603.***j* may be coupled to at least one of the software components **6601.1** to **6601.***i* by at least one interface **6602**. The interface **66021** may optionally couple together hardware and/or software components.

The software components **6601.1** to **6601.***i* may include at least one local and/or remote computer program adapted to process signals received from the hardware components **6603.1** to **6603.***j*. The software components **6601.1** to **6601.***i* may include one or more application programs for performing digital signal processing. One or more software components **6601.1** to **6601.***i* may provide control signals to one or more hardware components **6603.1** to **6603.***j* to select, adapt, or alter signal processing. The interface **6602** may include a bus or network (not shown). The interface **6602** may include one or more radio interfaces.

The hardware component(s) **6603.1** to **6603.***j* typically include a transmitter and/or receiver system, and a storage medium (e.g., disk drive, tape drive, CR Rom, DVD, flash memory, or any other storage device) for storing application programs and data. Hardware and/or the software may perform A/D conversion, as necessary. In some applications, modulation and/or demodulation may be performed digitally with any combination of software **6601.1** to **6601.***i* and hardware **6603.1** to **6603.***j* components.

In one set of embodiments of the invention, control signals are provided to the hardware components **6603.1** to **6603.***j* over one or more communication channels normally processed by the software radio. For example, a software component (such as at least one of the software components **6601.1** to **6601.***i*) residing at a remote receiver location may receive signals transmitted by the radio, process the received signals, and convey some control information in the data stream (e.g., in a header or pilot channel) to the hardware components **6603.1** to **6603.***j*. Much of the signal processing in a radio network may be performed by a single processing system (such as a base station) to reduce the cost and complexity of mobile transceivers. Alternatively, signal-processing operations may be distributed throughout the network in a way that balances processing and/or communication-resource (e.g., spectrum use) loads.

One or more software components **6601.1** to **6601.***i* may be replaced to provide different signal processing and/or control features. In another set of embodiments of the invention, software is uploaded to a remote transceiver via one or more communication channels normally processed by the software radio. This simplifies software updates and enhances signal-processing versatility of the network.

Conventional software-based radios can provide adaptability to different communication standards. However, conventional software-based systems have the associated complexity of performing many physical-layer and related processes via separate functional processes. This complexity can necessitate multiple processors, resulting in greater system cost and complexity than conventional, substantially hardware-based, systems.

Alternatively, CI-based software-defined radio simultaneously performs many processing functions via sub-carrier selection and weighting. CI-based protocols greatly exceed the performance (e.g., throughput, system capacity, bandwidth efficiency, power efficiency, probability of error, interference mitigation, and range) of any conventional software radio while enabling backward compatibility with all conventional transmission and multiple-access protocols. Furthermore, CI provides a framework to migrate all transmission protocols to a common high-performance platform that is suitable for all applications.

FIG. **67** illustrates basic baseband-processing components of a CI transceiver. A transmit data stream is processed by an encoder/interleaver system **6710** that provides parallel data streams to an IFFT processor **6711**. In-phase and quadrature-phase transmit signals are generated by either the IFFT processor **6711** or one or more subsequent signal-processing systems (not shown).

Received data signals are separated into sub-carrier components by an FFT processor **6721**. Sub-carrier values are combined by a combining system **6722** prior to being decoded in a decoder/de-interleaver system **6723**. Various control signals may be generated throughout the receiver processing operations. For example, performance measurements (e.g., BER, SNR, SNIR, etc.) of received data symbols may be used to adjust various operations, such as combining. Received data symbols may be used to adjust gain control of either or both of the transmit side and the receive side of the transceiver. The combining system **6722** may generate control signals to adjust the function of the encoder/interleaver system **6710** and/or the decoder/de-interleaver system **6723**. Similarly, other control schemes that are well known in the art may be performed by the transceiver.

In a CI transceiver, the combiner **6722** may analyze one or more signal characteristics (e.g., bit rate, modulation type, modulation characteristics, symbol constellation, processing gain, and directionality), one or more link characteristics (e.g., priority, security requirements, quality of service requirements, application requirements, information type, spectrum use, channel separation, coverage, and network topology), and/or one or more signal measurements (e.g., SNR, SNIR, probability of error, BER, soft decisions, signal power, Doppler effects, phase jitter, channel estimation, and synchronization). Based on this analysis, the combiner **6722** may be adapted to select and/or adapt one or more transceiver systems and/or functions described throughout the specification. Various processing characteristics that the combiner **6722** may select and/or adapt include filter parameters, channel selection, interference filtering, channel compensation, sample rates, sample widths, number of samples per sample interval, sample-interval duration, sample selection, sample grouping, decimation, quantization, synchronization, local oscillator amplitude, reference signal phase, gain, detector threshold, constellation, processing gain, modulation, demodulation, multiplexing, demultiplexing, multi-user detection, multiple access, formatting, source coding, beam forming, null steering, interferometry, combining technique, waveform shaping, coding, and/or system resource allocation (e.g., CPU use, memory, spectrum, power, etc.).

Software may be used to adapt the basic baseband-processing components to constraints imposed by the propagation environment, network load, quality of service, link priorities, differentiated security requirements, spectrum-use regulations, power constraints, latency requirements, interference, and jamming. Furthermore, the baseband-processing components shown in FIG. **67** may be adapted to provide additional processing functions, such as up conversion, down conversion, and demodulation.

In CI-based systems, as well as in software radio, modulation parameters (e.g., type of modulation, modulation level, etc.) may be adjusted with respect to one or more constraints, such as bandwidth efficiency, probability of error, latency per bit, and power consumption. Coding may be controlled with respect to similar parameters including probabilities for detected and/or undetected errors. Code control may include selecting and/or adjusting any combination of code types, individual codes, code lengths, code generation, and decoding. A unique aspect of CI is that it enables modulation and coding-related constraints to be addressed via sub-carrier selection and weighting, thus, reducing or obviating the need for adjusting modulation and coding parameters.

FIG. **68** illustrates transmission methods **6810** and reception methods **6820** of the present invention. Steps within the methods **6810** and **6820** can be regarded as functional blocks or systems within a CI transceiver. Various systems and methods not shown are implied. For example, various steps and components may be synchronized.

Synchronization may include open loop and/or closed loop transmitter synchronization. Phase synchronization may be performed via phase-locked loops. Synchronization can include carrier synchronization, sub-carrier synchronization, symbol synchronization, frame synchronization, and/or network synchronization. Filtering, amplification, as well as other signal-processing steps and systems may be included within the steps shown in FIG. **68**.

Signals from an information source (not shown) are provided to a formatting step **6801** followed by a source-encoding step **6802**. Encoded signals are encrypted **6803** and provided with channel coding **6804** before being multiplexed **6805**. A modulation step **6806** is performed before spreading **6807** and multiple-access processing **6808**. A transmission step **6809** processes and transmits the resulting signals into a communication channel 99.

Transmitted signals are coupled out of the channel 99 in a reception step **6819**. The received signals are processed in a multiple-access step **6818**. The signals are despread **6817**, demodulated **6816**, and demultiplexed **6815** prior to channel decoding **6814**. The decoded signals are decrypted and processed in source decoding and formatting steps **6812** and **6811** before being coupled to an information sink (not shown).

In one set of embodiments, at least some of the steps illustrated in FIG. **68** and their corresponding system components can be combined. In other set of embodiments, one or more of the steps and corresponding system components may be omitted. For example, essential transmitting steps include formatting **6801**, modulation **6806**, and transmission **6809**. Essential receiving steps include reception **6819**, demodulation **6816**, and formatting **6811**. All other steps shown in FIG. **68** are optional.

The formatting step **6801** may process a source signal (e.g., data, a message, an information signal) to make it

compatible with digital signal processing. Data, a message, or an information signal describes a signal whose spectrum extends from (or near) d.c. up to a finite value. This is also referred to as a baseband or low-pass signal.

FIG. **69**A illustrates how digital, text, and analog signals are formatted for different information signals. Digital information is typically passed through to a waveform-encoding step **6824**. However, in some applications, digital information may be reformatted. Text information is first encoded into a sequence of bits in an encoding step **6823**. Groups of k bits may be combined to form symbols from an alphabet of $M=2^k$ symbols.

An analog signal is sampled in a sampling step **6821** to produce a discrete pulse-amplitude-modulated waveform. Sampling **6821** can include impulse sampling, natural sampling, sample and hold, over sampling, under sampling, as well as any other form of sampling. Preferably, sampling **6821** is provided as part of a CI-based method or system. For example, CI sampling, orthogonal frequency Fourier transforms, and/or other CI-based procedures or components may include at least one sampling method or system. A_n anti-aliasing filter (not shown) may be provided prior to sampling. Post filtering may be performed following sampling **6821** to remove aliased signal components. The sampled signal is passed to a quantizer **6822** prior to being coded **6823**.

Pulse-code modulated (PCM) symbols may be generated from quantized pulse amplitude modulated signals. Analog signals are sampled and uniformly or non-uniformly quantized to one of L levels. Each quantized sample is then digitally encoded into a length log **2**L codeword. PCM waveform types include non-return-to-zero, return-to-zero, phase-coded, and multi-level binary. Different waveform types within each PCM classification, as well as other PCM waveform types, may be generated by providing appropriate weights to CI carriers. Similarly, multi-level signals may be generated by appropriate CI-carrier weighting.

Pulse-shape selection is typically based on various parameters, including spectral characteristics, feasibility of synchronization, interference and noise immunity, and implementation costs and complexities. Various pulse shapes, including raised cosine, sinc, etc., can be provided by appropriately weighting CI carriers. Roll-off factors can be controlled by adjusting CI carrier weights. Uniformly weighted CI carriers result in a sinc-like function. Various windowing techniques may be used to generate CI superpositions having predetermined time-domain characteristics.

Pulse overlapping may be performed, such as to generate substantially orthogonal symbol positions, information-channel positions, and/or multiple-access channels. Pulse overlapping may be performed via appropriate CI carrier weighting. Pulse overlapping may also be performed via suitable time-domain delay and overlapping methods. Although pulse overlapping is shown with respect to CI signals, any pulse shapes may be overlapped. Furthermore, pulse shapes may be adjusted to reduce interference between overlapping pulse shapes.

Source coding **6802** forms efficient descriptions of information sources that improve the SNR for a given bit rate or improve the bit rate relative to a given SNR.

Source coding can include differential pulse code modulation, block coding, synthesis/analysis coding, and/or redundancy-reducing coding. CI can easily be integrated into all types of coding. CI also provides diversity benefits that reduce signal degradation due to noise, interference, and distortion. CI diversity benefits can simultaneously enhance throughput and SNR. CI codes include multicarrier-based direct-sequence CI codes, polyphase CI codes, poly-amplitude CI codes, or any combination thereof.

The encryption step **6803** provides link privacy and user authentication. Various data-encryption techniques may be integrated into a CI carrier weighting process. Furthermore, various physical-layer encryption techniques may be used. For example, DSSS and FHSS can provide some security while enabling processing gain and multiple access. CI direct-sequence and frequency-hopping code security may be enhanced by adjusting code sequences, code lengths, or a combination of physical signal parameters and/or processes used to encode and/or encrypt information.

Diffusion describes a process of smoothing out statistical fluctuations in a transmission signal. For example, the pseudo-random nature of some direct-sequence codes provide a Gaussian-like energy distribution in the frequency domain. CI may be used to effect diffusion by minimizing PAPR, enabling high processing gains, and lowering spectral power densities by spreading information signals across non-contiguous frequency bands.

Channel coding **6804** improves communication link performance by enabling the transmitted signals to better withstand the effects of various channel impairments, such as fading, noise, and interference. Channel coding **6804** may include channel estimation, which can be performed by processing the complex carrier amplitudes of received CI signals. Channel coding **6804** may be implemented by applying appropriate weights to CI carriers to generate predetermined time domain channel codes. Similarly, CI carrier weighting may be performed to generate signals having other predetermined diversity-parameter characteristics.

Waveform coding may utilize CI codes. For example, waveform codes may include orthogonal and/or bi-orthogonal CI codes. Similarly, trans-orthogonal or simplex CI codes may be used. CI coding may also be combined with higher-order (M-ary) modulation to provide waveform coding in bandwidth-limited channels (i.e., where bandwidth expansion is not possible). For example, Trellis-coded CI modulation may be used. Structured sequences add parity digits to data such that the parity digits can be employed for detecting and/or correcting specific error patterns. Error-correcting codes (e.g., forward-error correction or error detection codes) may be based on CI coding. CI coding may be applied to block coding and convolutional coding. Polyphase CI codes may be implemented as cyclic codes.

The multiplexing step **6805** controls a user's access to a fixed communication resource. Multiplexing provides the means to efficiently allocate portions of the communication resource to a number of users. Basic multiplexing and multiple-access techniques include frequency division, time division, code division, space division, and polarization division. Each of these techniques can be performed in a CI-based system by appropriate selections and/or adjustments of CI carriers.

CIMA can be represented as a type of multiplexing based on interferometry division. Although CIMA resembles code division multiple access because its phase spaces can be regarded as polyphase codes (particularly, time-domain CI codes), CIMA can be adapted to CDMA, TDMA, and frequency division multiple access.

The modulation step **6806** involves choosing a modulation type to achieve a desirable balance between various objectives, such as maximizing throughput, minimizing probability of error, optimizing bandwidth efficiency, improving SNR, and reducing system costs and complexity. Modulation may be coherent or non-coherent. Modulation

may be analog or digital. Modulation may include phase modulation, amplitude modulation, frequency modulation, or any of various hybrid modulation techniques. Modulation may include continuous-phase modulation.

Modulation is provided in a CI-based system by modulating one or more CI carrier values. CI may be referred to as a form of multicarrier modulation. For example, phase modulation is provided to a CI superposition signal by phase-modulating the individual carrier components. Amplitude modulation is performed by adjusting one or more CI carrier amplitudes. Frequency modulation may be performed by any combination of selecting CI carrier frequencies and adjusting the carrier values.

The spreading step **6807** may include redundantly modulating data symbols over a plurality of carriers. Frequency-domain spreading may be provided via conventional direct-sequence coding and/or CI coding. This type of coding may be generated by any combination of selecting and adjusting the CI carriers. CI carriers may be selected to span discontinuous frequency bands, avoid interference and/or jamming, and/or mitigate the effects of multipath fading.

Multiple access **6808** may include any number of polling and access algorithms. For example, carrier sense or token ring multiple access techniques may be employed. Physical layer multiple access is preferably employed at the CI-carrier level. Framing can involve providing a predetermined number of symbols in a fixed time interval. In CI systems, framing can be performed by selecting a number of CI carriers that is related to the number of symbols in a frame. The frequency separation between carriers may be related to the inverse of the frame duration. Data symbols are positioned in the frame via carrier weighting, which may be adjusted at frame-duration intervals.

Headers, trailers, training sequences, payload segments, and other symbol groupings (even discontinuous groupings) may be regarded as subframes and processed in the same way as frames are processed. In one set of embodiments, subframes may be processed and then combined temporally. In another set of embodiments, each subframe may be processed as a subset of carriers. In yet another set of embodiments, each subframe is processed simultaneously as a calculation or application of weights to at least a subset of CI carriers. The calculations or weights are combined to generate an aggregate carrier-weight set that generates a superposition signal indicative of the frame. Higher-than-physical-layer techniques are typically performed by systems that may provide control signals to adjust carrier weighting and/or selection to implement the physical-layer controls for multiple access.

The transmit step **6809** may preprocess the modulated signals to optimize the signals for transmission in the channel 99. Basic components of a transmitter typically include a frequency up-conversion stage, a power amplifier, and an output coupler (e.g., an antenna). The transmit step **6809** may include selecting or adjusting transmitted signal frequencies to mitigate interference, reduce the effects of channel distortion, provide power control, and/or conform to spectrum allocations. The transmit step **6809** may provide carrier weighting for beam forming or other spatial interferometry applications. The transmit step **6809** may filter or predistort the transmitted signals. The transmit step **6809** may further include one or more adaptation steps (not shown) that provide for adjustment of transmission and/or transmit-signal characteristics based on feedback or blind adaptive processing.

The receive step **6819** couples transmitted signals out of the channel **6819** and optionally converts the received signals into a form that facilitates IF and/or baseband processing. Basic components of a receiver include an input coupler for receiving signals from the channel 99, a low-noise amplifier, and a down-converter stage that down converts received signals to IF or baseband. The receive step **6819** may include selecting or adjusting received signal frequencies to mitigate interference, reduce the effects of channel distortion, provide channel selection, and/or optimize some performance measurement. Weights may be applied to received signals for beam forming, spatial interferometry, and/or optimal combining. The receive step **6819** may include adaptive processing and/or probing techniques that adjust one or more physical parameters of the received signals. The receive step **6819** may generate commands based on channel estimates to control transmission characteristics of a local or remote transmitter.

The multiple-access step **6818** selects one or more signals by processing CI carriers. Alternatively, conventional demultiplexing techniques can be used. A CI superposition signal has similar time-domain characteristics as a conventional single-carrier signal.

Frequency-division demultiplexing can be performed by selecting predetermined CI carriers following a Fourier transform or other filtering operation. Code-division demultiplexing can be performed by frequency-domain decoding. Demultiplexing in the spatial domain can involve providing weights to carriers from each of a plurality of receiver elements to separate desired signals from interfering signals. Similarly, spatial processing can be performed via frequency-diversity interferometry.

Time-division demultiplexing can be performed by matched filtering, orthogonal frequency Fourier transforms, or equivalent signal-processing techniques applied to CI carriers. An advantage of CI-based reception of time-domain signals is that each symbol is processed over a time interval that is substantially longer than the apparent symbol (e.g., pulse) duration. The symbols are also processed in parallel. These signal-processing advantages enable the adaptation of conventional parallel processing to CI systems. Low-speed parallel processing also facilitates the implementation of software-based applications (such as error detection, error correction, authorization, verification, and other security-related applications) for high-speed communication networks.

The despreading step **6817** can involve spread-spectrum decoding and/or carrier selection and grouping. Decoding can take the form of code-division demultiplexing. Since CI carriers corresponding to a particular channel or user can be distributed over one or more frequency bands, carrier selection follows a filtering operation that separates a received CI signal into its carrier components.

The demodulation step **6816** may include coherent or non-coherent detection. Detection may include sampled matched filtering, envelope detection, differential detection, correlation, etc. These techniques can be performed with respect to individual carriers or with respect to a superposition of the carriers. In some cases, an orthogonal sample-and-sum operation can provide filtering and demodulation.

The demultiplexing step **6815** can be provided to the CI carriers in a combining step. Channel decoding **6814**, as well as other steps in the receiver **6820** may include carrier selection, time interval selection (e.g., integration period), weight generation, carrier weighting, and/or combining.

The decryption step **6813** provides any necessary physical-layer and/or data-layer decryption. Physical layer decryption may include carrier-frequency selection, spread-spectrum decoding, carrier-phase decoding, time-base

decoding (e.g., pulse-position decoding, time-hopping decoding, space-time decoding, etc.), signal de-masking, polarization decoding, and/or any other diversity parameter related decoding. Data-layer decoding may be performed via carrier processing. For example, a data decryption key may be translated into complex carrier weights that are provided to CI carriers or signal values derived from the carriers. Alternatively, data decryption may be performed following CI carrier processing.

The source-decode step **6812** and/or the formatting step **6811** reduces a received waveform to a set of numerical values. This operation can be performed with a linear filter coupled to a sampler. Similarly, a matched filter or correlator may be used. Signal detection provides a comparison of the value set to a threshold level or a constellation of values.

FIG. **69**B illustrates different embodiments of the formatting step **6811** relative to the type of information being processed by the receiver **6820**. Signals processed by a waveform detector **6831** are output for formatting **6811**. The formatting step **6811** passes digital information, performs decoding **6832** for textual information, and provides an additional step of low-pass filtering **6833** for analog information. The formatted information may be provided to an information sink (not shown).

A receiver may process a received signal by one or more detection schemes, including matched filtering, optimal combining, and multi-user detection. CI can be used in one or more of these detection schemes. In one example, CI sampling provides a simplified form of matched filtering. Formatting **6811** may include source coding and decoding processes, such as block coding, synthesis/analysis coding, redundancy-reducing coding, etc. CI coding may be used in source coding and decoding processes.

CI Sampling

Principles of CI may be applied to many different types of signal processing. In one set of embodiments of the invention, sample values are collected and processed according to mathematical principles of CI. In one aspect of the invention, correlation and filtering (such as matched filtering) may be performed without multiplication. In another aspect of the invention, various types of spectrum analysis and synthesis may be performed to provide a substantial reduction or elimination of complex multiplications and/or additions. In another aspect of the invention, phase and/or amplitude adjustment is provided to the samples to compensate for interference, noise, and/or channel distortion (such as multipath effects).

Applications of CI to sampling include processing received CI carrier signals and/or separating a received signal into a plurality of orthogonal CI signals. The process of decomposing a signal into one or more orthogonal carrier components involves selecting an appropriate sampling interval (i.e., symbol duration T_s) relative to the carrier-frequency separation f_s. Similarly, various CI techniques for generating CI-based signals include selecting a symbol duration T_s, corresponding to the carrier-frequency separation f_s.

FIG. **70** shows three orthogonal waveforms **7001**, **7002**, and **7003** separated in frequency by integer multiples of a separation frequency f_1. In some cases, the waveforms **7001**, **7002**, and **7003** may be sub-carrier modulations. Similarly, the waveforms **7001**, **7002**, and **7003** may be characterized by orthogonal circular (or elliptical) polarization spin frequencies. Data symbols may be impressed onto each waveform within a symbol interval $T_s=1/f_s$. The symbol interval and/or adjacent intervals may include guard intervals and/or cyclic prefixes, which are well known in the art.

In order to separate a data symbol modulated on a particular waveform from interference contributed by other waveforms, the set of waveforms is first sampled at a sampling frequency f_{sample} that equals a desired waveform frequency f_n, or some harmonic or sub-harmonic thereof. The desired waveform's frequency f_n can be expressed as:

$$f_n=f_o+nf_s$$

where f_o is a base or carrier frequency and n is some integer. In this case, frequencies of the adjacent waveforms can be expressed as:

$$f_{n\pm1}=f_o+(n\pm1)f_s$$

A number N of samples are represented in FIG. **70** by equally spaced time intervals **7010**.0 to **7010**.N corresponding to an integer multiple of a desired waveform's period. In this example, the sample intervals **7010**.0 to **7010**.N intersect the peaks of a desired waveform. However, the sample intervals **7010**.0 to **7010**.N intersect the other waveforms at various parts of their cycles. An important aspect of the invention involves selecting the time interval (or symbol duration T_s) over which samples are combined. The symbol duration T_s defines the frequency spacing $f_s=1/T_s$ of orthogonal waveforms. When N samples collected over a period T_s are combined, a desired signal can be separated from interfering signals modulated on orthogonal waveforms.

One type of sampling that may be performed with CI sampling methods (as illustrated in FIG. **70**) is known as under sampling, which is described by the well-known Passband Sampling Theorem. An improvement provided by CI sampling consists of combining samples obtained during one or more symbol intervals T_s to separate at least one desired symbol from symbols impressed on other waveforms.

The following explanation illustrates a simple case in which symbols are demodulated from one particular sub-carrier frequency in the presence of other sub-carrier frequencies. In this case, $f_{sample}=f_n$. FIG. **71**A is a normalized complex-plane representation of how the sampling rate $f_{sample}=f_n$ relates to the desired waveform's frequency f_n. Since $f_{sample}=f_n$, the samples always occur on the same part of the complex plane, such as on the real axis at **1**. The number of samples Ns per symbol interval T_s is expressed by:

$$N_s=f_{sample}T_s=(f_o+nf_s)/f_s$$

The number of samples per waveform period ($1/f_n$) is 1.

FIG. **71**B and FIG. **71**C are normalized complex-plane representations of how the sampling rate f_{sample} relates to frequencies of the adjacent waveforms. The number of samples per period of the adjacent waveform having frequency can be expressed as:

$$N_{n-1}=\frac{f_{n-1}}{f_{sample}}=1-\frac{f_s}{(f_o+nf_s)}.$$

FIG. **71**B shows each subsequent sampled value shifted by:

$$\phi_{n-1} = -\frac{f_s}{(f_o + nf_s)} 2\pi \text{ radians.}$$

Since there are $N_s=(f_o+nf_s)/f_s$ samples per symbol interval T_s, the vector samples fill one full rotation of the normalized complex plane, as shown in FIG. **72**. Thus, the vector sum of the samples is zero.

The number of samples per period of the adjacent waveform having frequency f_{n-1} can be expressed as:

$$N_{n+1} = \frac{f_{n+1}}{f_{sample}} = 1 + \frac{f_s}{(f_o + nf_s)}$$

FIG. **71**C shows that in the complex plane, the sampled values shift by an amount:

$$\phi_{n+1} = \frac{f_s}{(f_o + nf_s)} 2\pi \text{ radians.}$$

The N_s samples collected throughout the symbol interval T_s also precess through one full rotation of the complex plane, but in the opposite direction. The vector sum of these samples (also represented by FIG. **72**) is zero.

The number of samples per period of any adjacent waveform having a frequency $f_{n\pm n}$ can be expressed as:

$$N_{n\pm n'} = \frac{f_{n\pm n'}}{f_{sample}} = 1 \pm \frac{n' f_s}{(f_o + nf_s)}$$

In the complex plane, the sampled values shift by an amount:

$$\phi_{n\pm n'} = \pm \frac{n' f_s}{(f_o + nf_s)} 2\pi \text{ radians.}$$

N_s samples collected throughout the symbol interval T_s precess through n' rotations of the complex plane and cancel unless $f_{n\pm n'}$ is an integer multiple of f_n. The case in which min (where m is some integer) can be avoided by providing appropriate frequency adjusting to either or both signal frequencies and sample frequencies. Thus, the vector sum of the samples is zero.

In one aspect of CI sampling, orthogonal frequency channels are easily separated using only sampling and adding processes. One application of this invention includes frequency-division demultiplexing. Coherent CI sampling may be performed by receivers designed for multicarrier transmission protocols, including CI, OFDM, and MC-CDMA.

In-phase and quadrature-phase samples may be generated by sampling at a quarter-wave offset to the sampling period of a first set of samples. FIG. **73** illustrates two sets of samples having the same desired frequency and a $\pi/2$ phase offset between them. Both in-phase and quadrature-phase samples of a particular frequency produce the same vector sum of zero for orthogonal frequencies when samples collected over a corresponding time interval T_s are combined.

Any appropriate sampling method may be used to generate in-phase and quadrature-phase samples for the purpose of this invention. In one embodiment, a delay offset is provided to one of two identical timing signals used to trigger a sample-and-hold circuit. In another embodiment, a high-rate timing signal is used to trigger a sample-and-hold circuit and then undesired samples are discarded before combining. In another set of embodiments, an input signal may be under sampled and the in-phase and quadrature-phase samples may have a $\pi/2$ phase offset relative to at least one desired frequency component f_n. A combining process may include adding and/or subtracting samples. A combining process may optionally include weighting.

FIG. **74**A illustrates the combined values of 110 CI samples for each of 400 frequencies in intervals of one cycle per symbol period T_s. Since the sampling rate is 110 samples per symbol period T_s, non-zero sums occur at 110 cycles-per-symbol intervals. All other integer cycles-per-symbol frequencies correspond to integer-valued rotations around the complex plane that sum to zero.

FIG. **74**B illustrates the combined values of 110 CI samples for each of 800 frequencies spaced at 0.05 cycles-per-period intervals and centered at 110 cycles per symbol period. The sums corresponding to non-integer cycles-per-symbol frequencies have non-zero values.

FIG. **74**C illustrates a plot of sums of samples collected at a particular sample frequency for different sampled signal frequencies. The sums are from a plurality of samples collected over a given symbol interval T_s. The signal frequencies are centered at 110 cycles per symbol and extend 8 cycles per symbol on both sides of the center frequency.

A center peak **7400** may correspond to a signal frequency that is a harmonic or sub-harmonic of the sample frequency. Zero values, such as illustrated by zero-crossing positions **7401** to **7407**, occur at integer cycles-per-symbol frequencies relative to the center frequency. The zero-crossing positions, such as positions **7401** to **7407**, indicate frequencies that are orthogonal to the center frequency. When generating orthogonal sub-carrier frequencies, it is desirable to position the frequencies at zero crossings, such as illustrated in FIG. **74**C. The zero-crossing positions depend on the symbol interval T_s over which the samples are combined, and thus, can optionally be adjusted with respect to adjustments to the symbol interval T_s.

FIG. **74**C also illustrates contributions of various frequencies to the combined samples. Signals modulated onto frequencies that are not centered at zero-crossing positions contribute non-zero values to the combined samples. In some spectrum-analysis applications, samples that are combined at one or more sample frequencies may be weighted and/or combined with samples collected at one or more different frequencies. Zero-crossing positions, as well as side-lobe height and main-lobe width can be selected and/or adjusted by providing appropriate complex weights to the samples.

FIG. **75** illustrates sums of samples collected at a particular sample frequency f_n for different sampled signal frequencies. A peak **7500** occurs when the sampled signal frequency equals the sample frequency f_n. The sum at sample frequency f_n is represented by FIG. **76**A, which illustrates each sample as a normalized vector mapped in a complex plane. Because the sample and sampled signal frequencies are equal, each sample coincides with the same location of each period of the sampled signal. In this case,

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all the vectors map onto each other in the positive real axis (i.e., +1), resulting in totally constructive combining.

A first zero crossing **7501** is illustrated in FIG. **75**. The sampled signal frequency equals the sample frequency f_n plus one cycle-per-symbol duration. Thus, the sampled signal frequency f_{n+1} is orthogonal to the sample frequency f_n. The sample sum at f_{n+1} is represented by a complex-plane mapping illustrated in FIG. **76**B. Because the sample frequency f_n and the sampled signal frequency f_{1+1} differ, the sample values intersect different parts of the sampled signal. Since the frequencies f_n and f_{n+1} are orthogonal and differ by one cycle per symbol duration, the sample values map to uniformly spaced vectors over a unit circle. This results in a vector sum of zero.

A first side-lobe peak **7502** illustrated in FIG. **75** corresponds to a sampled signal frequency that equals the sample frequency f_n plus one and one half cycles per symbol. The sampled signal frequency $f_{n+1.5}$ is not orthogonal to the sample frequency f_n. The vectors representing the sample values fill one and one half rotations throughout the complex plane. The vectors in the one-half plane shown in FIG. **76**C combine substantially constructively to produce the side-lobe peak **7502**. Since approximately two-thirds of the vectors are distributed uniformly throughout one rotation (and thus, cancel), the side-lobe peak **7502** is substantially lower than the main-lobe peak **7500**.

A second zero crossing **7503** is represented by a vector mapping illustrated in FIG. **76**D. The sampled signal frequency equals the sample frequency f_n plus two cycles per symbol. Thus, the frequencies f_n and f_{n+2} are orthogonal and the sample values map to vectors uniformly distributed around two full unit circles in the normalized complex plane. In this case, the vectors shown in FIG. **76**D overlap other vectors.

A second side-lobe peak **7504** corresponds to a sampled signal frequency that equals the sample frequency f_n plus two and one half cycles per symbol. Four fifths of the corresponding vectors are mapped over two rotations in a normalized complex plane and thus, cancel. The remaining vectors are distributed over a half rotation in the complex plane, as illustrated by FIG. **76**E. The vector sum produces the peak **7504**, which is lower than the first side-lobe peal **7502**.

Additional zero crossings and side-lobe peaks, as well as other sums, may be represented by the vector-mapping techniques previously described herein. These techniques may be used to describe, as well as construct, signals having similar characteristics. For example, CI signals, array beam patterns, diffraction patterns, and other types of interference patterns may be described by vector maps and/or constructed using processes that correspond to vector mapping.

FIG. **77**A is a functional diagram that illustrates one aspect of coherent CI sampling as it applies to several apparatus and method embodiments of the present invention. The general nature of the functional diagram is the basis of a large number of embodiments of this aspect of the invention.

An input signal $\Sigma s_n(f,t)$ includes multiple signal components having orthogonal frequencies. Other diversity parameters of the components may also be orthogonal. In some cases, orthogonal frequencies may refer to polarization spin frequencies, subcarrier modulation frequencies, array pattern scan frequencies, direct sequence code repetition rates, and/or frequencies that characterize cyclic properties of any other diversity-parameter values.

The input signal is processed in a sampler **7701**, which is a device or process that samples an input signal with respect to one or more diversity parameters. In one set of embodiments, the sampler **7701** uses at least one reference timer signal no produce samples in the time domain. The reference timer signal(s) τ may be generated internally or externally with respect to the sampler **7701**. The sampler **7701** may generate one or more sets of samples with respect to one or more diversity parameter values (e.g., timing signals, carrier frequencies, etc.).

In one embodiment, each set of samples corresponds to a different sampling rate. In another embodiment, a first set of samples is collected with respect to one sampling rate f_{sample} and additional sample sets are generated as subsets of the first set. Thus, the subset frequencies f_{sample} (n) are less than the sampling rate f_{sample}. In at least one embodiment, the sampler **7701** may sample the input signal at a sampling frequency f_{sample} corresponding to one or more frequencies of the input signal. In at least one embodiment, the sampler **7701** may under sample and/or over sample one or more signal components of the input signal.

Samples from the sampler **7701** are input to a combiner **7702**. The combiner **7702** is adapted to sum or otherwise combine two or more samples. The combiner **7702** combines at least one set of samples that corresponds to at least one symbol interval T_s. The symbol interval T_s is provided with respect to the relationship $T_s=1/f_s$ such that at least one data symbol on at least one carrier can be separated from interfering data symbols on one or more carriers that are orthogonal to the desired carrier(s). Thus, the process of summing the selected samples over a predetermined symbol interval T_s provides for filtering of orthogonal carriers that are not aliased by the sampling process. In some applications, sampling and summing may be performed to decompose a single-carrier signal into a plurality of predetermined CI carriers. In other applications, a received multicarrier signal may be decomposed into a different set of carrier signals or carrier-signal values.

The sampler **7701** and/or combiner **7702** may include a storage device (not shown) to store samples before combining them. The combiner **7702** may separately combine subsets of samples and/or it may combine all of the samples together. An output signal $s(f_n,t)$ represents the combined samples output by the combiner **7702**. In one embodiment, the value of the output signal corresponds to at least one frequency component f_n of the input signal and the sampling frequency f_{sample}. The sampling frequency f_{sample} may have the same value as f_n, a harmonic off, or a sub-harmonic off, in order to extract the value(s) of the input signal associated with f_n. In particular, this combination of sampling and combining can be used to demodulate data symbols impressed on one or more frequencies f_n without requiring complex digital processing.

The sampler **7701** and/or the combiner **7702** may include a weighting device (not shown) capable of applying weights to the samples and/or sums of the samples. The weights may be complex valued. In some embodiments, weight values may be provided by shifting or otherwise adjusting the order of the samples. These weights may be used to compensate for channel effects and/or signal coding. An optimal-combining process may control the weights to enhance reception of desired signals in the presence of noise and/or interference.

The combiner **7702** may preferentially weight and/or combine certain combinations of samples with respect to the waveform and/or coding of the received signal. Weights may be applied to the received samples to compensate for any mismatch between the sampling frequency f_{sample} and the frequency f_n of at least one desired signal component. If a

desired frequency component is over sampled, some of the samples may be disregarded to enhance reception (e.g., improve SNR, SNIR, BER, probability of error, etc.) of the desired signal.

Although FIG. **77**A illustrates one type of CI sampling that is useful for separating data symbols impressed on multiple orthogonal frequency channels, variations to this method and apparatus may be employed. Furthermore, CI sampling may be used to separate data symbols modulated onto other orthogonal diversity parameters, such as polarization, time, spreading code, phase space, subspace, angle of arrival, etc.

FIG. **77**B illustrates a functional diagram for an apparatus and method of the present invention. An input signal $\Sigma s_n(f,t)$ may include multiple signal components characterized by frequencies that are orthogonal. Alternatively, the input signal $\Sigma s_n(f,t)$ may include one or more single-carrier signals. The input signal $\Sigma s_n(f,t)$ is processed by a sampler **7701** that includes in-phase and quadrature-phase sampling units **7701**I and **7701**Q, respectively. The sampler **7701** receives at least one pair of timing signals $\tau(0)$ and $\tau(\pi/2)$ having a relative phase offset of $\pi/2$. Each pair of timing signals $\tau(0)$ and $\tau(\pi/2)$ may correspond to a different CI carrier frequency f_n. Thus, a timer (not shown) may perform appropriate frequency-dependent processing to produce quarter-wave phase offsets $\pi/2$. Each sampling unit **7701**I and **7701**Q generates a plurality of samples at one or more sample frequencies f_{sample}.

The samples are combined in a combiner **7702**. In this case, the combiner **7702** includes in-phase and quadrature-phase combining units **7702**I and **7702**Q. Sample sets corresponding to one or more symbol intervals T_s are combined. In one embodiment, the samples are combined separately with respect to at least one predetermined sample frequency over at least one predetermined symbol interval T_s. In another embodiment, the samples are combined without respective to any periodic sampling frequency. Samples may be selected at random, pseudo-random, or otherwise non-periodic intervals. Combining may be coherent or non-coherent.

The combiner **7702** outputs in-phase and quadrature signals $s_1(f_n,t)$ and $s_Q(f_n,t)$ that may optionally be processed in at least one signal processor **7703**. The in-phase and quadrature-phase signals $s_1(f_n,t)$ and $s_Q(f_n,t)$ correspond to one or more frequency components f_n and symbol values occurring in time interval T_s. Optionally, these signals may be combined coherently or non-coherently in the processor **7703**. In one embodiment, the processor **7703** generates an output signal $s(\phi,A,f_n,t)$ having a particular phase ϕ and amplitude A corresponding to a CI carrier frequency f_n and a symbol interval T_s. The phase ϕ and/or amplitude A may be used to identify a transmitted symbol. Phases ϕ may be represented by time offsets. Alternatively, or additionally, phases ϕ and amplitudes A may be processed to characterize the propagation channel and generate receiver and/or transmitter channel-compensation weights. In other embodiments, the processor **7703** may produce a modulated signal that may optionally be demodulated.

Various method and apparatus embodiments of the invention are summarized by the following functional descriptions:

Type 1: Sampling orthogonal carrier frequencies.

An input signal including a set of orthogonal carriers is sampled at one or more sample rates f_{sample} that include at least one CI carrier frequency f_n and/or some subharmonic thereof.

The samples are summed (or otherwise combined) over at least one symbol interval T_s.

In the case where multiple sample rates f_{sample} are employed, samples corresponding to each sample rate f_{sample} may be combined separately. Sampling and/or summing may include accumulating or storing the samples. If samples are collected at multiple frequencies f_{sample}, the samples may be separated with respect to sample frequency f_{sample} before being stored and/or combined. In one set of embodiments, samples corresponding to a particular sampling frequency f_{sample} are preferably summed separately from samples corresponding to other sample frequencies. Samples collected at multiple frequencies f_{sample} may be sorted, arranged, rearranged, shifted, or stored in a predetermined order.

Sampled values may be stored in a predetermined order and the stored values may be further sampled, selected, or rearranged prior to combining. Any type of signal having orthogonal carrier (or sub-carrier) frequencies may be CI sampled, including OFDM, MC-CDMA, LIMA, CI, circular polarized, Discreet Multitone, FDM, WDM, ultra-dense WDM, MC DS-CDMA, and multi-tone signals. The orthogonal carrier frequencies may be up converted or down converted in frequency prior to sampling. Combined samples may be multiplied by a complex weight. Similarly, samples may be weighted prior to combining.

Type 2A: Sampling a CI Signal.

The phase of each sample frequency f_{sample} is set to at least one particular phase space.

Samples collected at each sample frequency f_{sample} are summed over at least one symbol interval T_s.

One or more of the sums are multiplied by a complex weight (optional).

Sums corresponding to a particular phase space are summed.

A decision process determines symbol value(s) associated with each phase space.

Type 2B: Sampling a CI Signal.

The phase of each sample frequency f_{sample} is set to at least one particular phase space.

Samples at all sampling frequencies f_{sample} for the particular phase space are summed over at least one symbol interval T_s.

A decision process is used to determine what symbol(s) was modulated onto each phase space.

Type 2C: Sampling a CI Signal.

The phase of each sample frequency f_{sample} is set to a particular phase space or set of phase spaces. For example, in-phase (I) and quadrature-phase (Q) samples may be collected.

Samples collected at each sampling frequency f_{sample} are summed over at least one symbol interval T_s. I and Q samples may be summed separately.

One or more of the sums are multiplied by a complex weight (optional).

Magnitude and/or phase for each frequency f_{sample} is determined from the corresponding sum(s).

A decision process determines on or more symbol values associated with each frequency f_{sample}.

A decision process may determine the value associated with each phase space (optional).

Multiple phase spaces may be evaluated in parallel. The sample frequencies f_{sample} may include one or more subharmonics of the orthogonal carrier frequencies f_n. The sample frequencies f_{sample} may include subharmonics of one or more of the orthogonal carrier frequencies f_n. Each sample frequency f_{sample} may include harmonics of one or

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more of the orthogonal carrier frequencies f_n. The process of summing the samples may be preceded by selecting or discarding some of the samples.

Type 3: Deriving low-rate samples from a set of samples collected at a higher rate.

A received waveform is sampled at some high sampling rate f_h.

Samples are selected with respect to at least one desired sample phase and at least one desired sample frequency f_1, where $f_1<f_h$. Samples corresponding to a desired sampling rate (or some harmonic or subharmonic thereof) are selected. Selective decimation may be performed.

The selected samples are summed.

A decision process is optionally provided to determine what symbol(s) was modulated onto at least one frequency, at least one phase space, or any combination thereof.

Type 3 CI sampling may result in slightly poorer precision (due, at least in part, to quantization error) compared to other types of CI sampling. However, the reduced complexity of using a single sampling frequency f_h can be weighed against the slight performance degradation (which appears to be negligible for relatively high sample rates f_h). Sample weights may depend on proximity of actual samples (corresponding to f_h) to desired samples (corresponding toll).

Groups of samples may be selected. For example, samples straddling a desired sample point may be combined. Samples may be discarded if they do not fall within a predetermined proximity to desired sample points. For example, only sample points that are within some time period of the desired samples may be summed. Samples may be selected to minimize probability of error, SNR, BER, signal-to-interference, SNIR, or optimize some other performance measurement that characterizes the quality of the estimated data symbols. The received signal may be up converted or down converted prior to sampling. Sampling may be integrated into a down-conversion process, such as passband sampling. In any of the CI sampling cases, a received signal may be filtered prior to or following sampling.

FIG. **78**A shows part of a coded CI waveform **7800** that may be processed using a CI algorithm, such as an algorithm based on the Type 3 CI sampling method. The waveform **7800** shown is distorted relative to a multipath channel distortion model. The signal is constructed from **10** carriers having a frequency spacing of f_s=100 kHz. The algorithm samples the received CI waveform at 10 MHz to generate 100 sample points across the 10-μsec symbol interval T_s. Typically, more than 100 sample points would be generated across a symbol interval T_s. In this case, there are 10 phase spaces and thus, 10 symbols occurring within the symbol interval. Alternatively, quasi-orthogonal pulse shaping may be used to provide up to 20 symbols.

The algorithm collects samples from the sampled waveform corresponding to the 10 phase spaces and the 10 frequencies associated with each phase space. The most appropriate of the 100 sample points is selected for each sample of each phase-space/frequency combination. The selection of sample sets to be summed may be performed only once. The combinations may be used for subsequent sets of samples as long as the sample rate and the desired phase-space/frequency combinations are not changed. Samples corresponding to each phase space are summed to provide a signal representing one of the transmitted symbols. As the granularity of the sampling (i.e., the sample frequency f_h) is increased, greater precision is achieved with respect to measuring received data symbols. FIG. **78**B shows a table that illustrates **10** transmitted data symbols and the corresponding non-normalized received signal for each of the 10 phase spaces.

Individual sample values may be added or subtracted depending on the part of a desired waveform cycle with which they correspond. This adaptation is implied by the term combining, as used herein. Samples having low values typically have relatively low SNRs. Accordingly, some applications may remove samples having values below a predetermined threshold. In some combining embodiments, sample values may be weighted with respect to a multi-level step function. The step function typically has the same frequency (and possibly phase) of at least one desired carrier signal. The step-function levels may approximate (either closely or roughly) the desired waveform's amplitude. Appropriate weighting and/or selection processes are also implied by the function of combining for both channel compensation and step-function processes.

Although impulse sampling is illustrated herein for simplicity, various forms of sampling may be provided, such as sample and hold. Other sampling techniques may be employed within the scope of the invention. Natural sampling (such as described in B. Sklar, *Digital Communications, Fundamentals and Applications*, Prentice-Hall, Inc., New Jersey, 1988, which is incorporated by reference) involves multiplying a band-limited waveform by a pulse train or switching waveform. Sample widths may be provided to collect substantial amounts of the received waveform energy. In some applications, sample widths may be on the order of half the wavelength of a desired waveform in a multicarrier signal. In other applications, sample widths may be approximately half the wavelength of a predetermined CI waveform component into which a received signal is processed. In some applications, sub-harmonic (i.e., passband) sampling may be performed to provide a combined down-conversion/filtering operation. Furthermore, the sampling processes disclosed herein may be integrated into Fourier or similar transform operations.

In one set of embodiments, signals are filtered with respect to at least one orthonormal basis by inputting a multicarrier signal (defined by the at least one orthonormal basis) into a processor (not shown) adapted to correlate the input signal with a sum of values pertaining to the at least one orthonormal basis. This process is distinguishable from combining correlations of the input signal with various values of the orthonormal basis. Various types of orthonormal bases may be used, such as wavelet, Fourier, Hadamard-Walsh, Laplace, and Lorentz, as well as other orthonormal bases.

CI OFFT

The Fourier transform of a time-domain signal into its frequency-domain components is expressed by:

$$X(f)=\int_{-\infty}^{\infty}x(t)e^{i2\pi ft}\delta t.$$

The corresponding discreet Fourier transform (DFT) equation is expressed by:

$$X(f_n)=\sum_{k=0}^{K-1}x_k e^{-i2\pi f_n kt_o}$$

where K is the number of time-domain samples collected over a period of $T_s=Kt_o$. Several simplifications can be made when orthogonal frequencies are processed. The orthogonal frequencies f_n are expressed by:

$$f_n=f_o+nf_s$$

and the sampling period is $T_s=1/f_s$.

When orthogonal frequencies are sampled and processed with a DFT, a value in a particular frequency bin f_n corresponds to time-domain samples X_k multiplied by complex values $e^{i2\pi f_n kt_s}$. Since multiplication with a complex value is computationally intensive compared to most signal-processing operations, it is desirable to replace complex multiplications with simpler operations, such as adding and shifting. This is accomplished by replacing the complex value $e^{i2\pi f_n kt_o}$ (or any sinusoid representing a component of the complex value) with at least one periodic step function $\Gamma(t,f_n,\phi)$ having frequency f_n. For example, a periodic two-level step function having at least one predetermined ϕ is expressed by:

$$\Gamma(t,\ f_n,\ \phi)=\begin{cases}-1(\cos(2\pi f_n t+\phi)<0)\\+1(\cos(2\pi f_n t+\phi)>0)\end{cases}$$

Other types of step functions may be used. For example, step-function values do not need to be constrained to values of ±1. Step functions having more than two levels may be employed. Step functions may have multiple phases ϕ. For example, in-phase and quadrature-phase step functions may be employed.

The step function $\Gamma(t,f_n,\phi)$ can be expressed as a sum of harmonic sinusoids. For example:

$$\Gamma(t,\ f_n,\ \phi)=\sum_{n=1,3,5,\ldots}\frac{\sin(2\pi f_n t+\phi_n)}{n}.$$

FIG. **79**A illustrates two periods of a step function **7901** constructed from a superposition of 100 odd-harmonic sinusoids generated with respect to the step function $\Gamma(t,f_n,\phi)$. FIG. **79**B illustrates a portion of a Fourier transform **7910** of the step function **7901**. The Fourier transform **7910** shows 13 of the 100 component frequencies and their relative magnitudes on a logarithmic scale.

The step functions $\Gamma(t,f_n,\phi)$ are used in place of the periodic complex values $e^{i2\pi f_n kt_o}$ to simplify the DFT of a signal. This improvement is suggested by the DFT equation, which shows that the complex multipliers $e^{i2\pi f_n kt_o}$ corresponding to frequency bin f_n are periodic with respect to f_n. In one set of preferred embodiments, the sampled signal is band-limited such that only the f_n frequency component of the step function $\Gamma(t,f_n,\phi)$ contributes to values of $X(f_n)$ in the orthogonal-frequency Fourier transform (OFFT) equation shown as follows:

$$X(f_n)=\sum_{k=0}^{K-1}x_k\Gamma(t,\ f_n,\ \phi)$$

The OFFT equation is similar to the DFT equation in its ability to quantify values in particular frequency bins. The OFFT is simpler than other Fourier transform techniques because it replaces the complex values $e^{i2\pi f_n kt_o}$ with step-function values, such as ±1, which can be implemented in an adding process. Thus, the OFFT replaces complex multiplies with additions.

In the orthogonal-frequency case, the continuous form of the OFFT is the CI Orthogonal-Frequency Fourier Integral, or CIOFFI:

$$X(f_n)=\int_0^{1/f_s}\cos(2\pi f_{n'}t+\phi_{n'})\Gamma(t,\ f_n,\ \phi)$$

where the cosine term represents at least one of the received carriers having frequency $f_{n'}$. Assuming equality between all phase $\phi_{n'}$ and ϕ values, the continuous-form OFFT can be expanded as:

$$X(f_n)=\frac{1}{2\pi f_{n'}}\left[\sin2\pi f_{n'}t\Big|_0^{\frac{1}{4}f_n}-\sin2\pi f_{n'}t\Big|_{\frac{1}{4}f_n}^{\frac{3}{4}f_n}+\ldots+\sin2\pi f_{n'}t\Big|_{\frac{1}{4}f_n+\frac{2n-1}{2f_n}}^{0}\right]$$

and simplified to:

$$X(f_n)=\frac{1}{2\pi f_{n'}}\sum_{k=0}^{K-1}(-1)^k\sin\frac{2\pi n'y}{n}\Big|_{-\frac{1}{4}+\frac{k}{2}}^{\frac{1}{4}+\frac{k}{2}}$$

where y is a dimensionless variable. Further simplification yields:

$$X(f_n)=\frac{1}{\pi f_{n'}}\sin\frac{\pi n'}{2n}\sum_{k=0}^{K-1}(-1)^k\cos\left(\frac{\pi n'k}{n}+\phi_m\right)$$

The phase term ϕ_m indicates the possibility of a phase-modulated information signal or a phase-space channel.

When the OFFT sample frequency f_n equals the received carrier frequency (e.g., n=n'), the OFFT equation reduces to:

$$X_{n=n'}(f_n)=\frac{1}{\pi f_n}\sum_{k=0}^{K-1}(-1)^k\cos(\pi k+\phi_m)$$

For each value of k, a π rotation of the vector (represented by the cosine term) is flipped by the −1 term. Thus, each kth vector maps onto a vector direction defined by the phase term Consequently, the terms of the OFFT that correspond to n=n' combine constructively.

When the OFFT sample frequency f_n does not equal the received carrier frequency $f_{n'}$ (e.g., n≠n'), the OFFT equation is written as:

$$X_{n\neq n'}(f_n)=\frac{1}{\pi f_n}\sin\frac{\pi n'}{2n}\sum_{k=0}^{K-1}(-1)^k\cos\left(\frac{\pi n'k}{n}+\phi_m\right)$$

For simplicity, it may be assumed that the number of samples K collected is approximately some integer multiple of the sampled signal's cycles per symbol interval. The approximation works well for large numbers of samples. Similarly, K can simply be set to some integer multiple of the sampling frequency f_n. Each value of $X_{n\neq n'}(f_n)$ is a constant-valued vector having an incremental angular offset of πn/n'. After an integer number of full rotations, the sum of the K vectors is substantially zero. Thus, the terms of the OFFT that correspond to n≠n' combine destructively.

For f_o=0, and n≠n', constructive combining occurs under the following conditions:

$$n=(2m+1)n' \; m=1,2,3,\ldots$$

The ranges of sampling and carrier frequencies can be expressed by a start frequency f_i and an end frequency f_f.

$$f_i=f_o+0f_s=n_of_s$$

$$f_f=f_o+(n-1)f_s=(n_o+n-1)f_s$$

where the value of no may be integer or fractional. This sets boundary conditions on n and no according to the following equation:

$$n<2n_o$$

Alternatively, the boundary conditions may be exploited in such a way as to perform Fourier transform operations via under sampling.

FIG. **80**A is a frequency-domain representation that indicates a sampling frequency **8000**, which is a frequency component of a step function. In this case, the frequency component **8000** is a start frequency f_i that is orthogonal to a plurality of received frequency components **8001** to **8006**. Frequency component **8006** is designated as an end frequency f_f. If a received frequency component **8010** is a harmonic or subharmonic of a step-function component (such as frequency **8000**), an OFFT or CI-sampling process that incorporates frequency **8000** is non-zero. Thus, OFFT and CI sampling may utilize harmonic and/or sub-harmonic frequencies relative to at least one frequency component of a sampled signal.

In one embodiment of the invention, it is preferable to provide for band limiting of a received signal such that only one frequency component of the applied step function has a non-zero OFFT or CI-sampling result. A step-function component and a received signal component may be related as harmonics or subharmonics. In another embodiment of the invention, the step function is adapted (e.g., filtered) to a given signal's frequency band.

FIG. **80**B illustrates a frequency distribution of an alternate embodiment of an OFFT. Data symbols are redundantly modulated onto a plurality of uniformly spaced carrier frequencies, such as frequencies **8000**, **8010**, and **8020**. CI sampling or an OFFT are provided with respect to one or more step-function frequencies that equal one or more of the frequencies **8000**, **8010**, and **8020**. Alternatively, the step-function frequencies include one or more harmonics and/or subharmonics of the frequencies **8000**, **8010**, and **8020**. One or more additional step functions may be employed in an OFFT or CI-sampling process corresponding to another set of frequencies (such as frequencies **8001**, **8011**, and **8021**) that are orthogonal to the first set of frequencies **8000**, **8010**, and **8020**.

FIG. **81** shows three sinusoidal waves **8101**, **8102**, and **8103** having uniformly spaced frequencies f_1, f_2, and f_3, and a step function **8111** having a frequency equal to the frequency f_1 of wave **8101**. The value of a frequency bin from a discreet Fourier Transform is represented by:

$$y_p=\sum_{k=0}^{K-1} x_k e^{-i2\pi kp/K}$$

In an OFDM system that employs BPSK modulation, the frequency-bin values are ±1. Similarly, other modulation schemes may be processed. A simpler way to determine these values is to replace the exponential term in the above function with a step function. This eliminates the need for complex multiplications. The value of a frequency bin from the improved Fourier Transform is:

$$y_p=\sum_{k=0}^{K-1} x_k \Gamma[\tau_n=1/f_n]$$

where the values of the step function are $\Gamma[\tau_n=1/f_n]=\pm 1$. The step-function values vary with respect to the cycles of an nth frequency, f_n.

In FIG. **81**, the step function **8111** is set in phase with the wave **8101** having frequency f_1. In one embodiment of the invention, a value corresponding to frequency bin f_1 is obtained by adding and/or subtracting the sampled waveforms in a manner indicated by the step function **8111**. The contributions to frequency bin f_1 due to each of the three frequencies f_1, f_2, and f_3 are exemplified by sums of one thousand sample values shown as follows:

$$f_1=637.5046$$

$$f_2=-0.9994$$

$$f_3=-0.1402$$

The value corresponding to bin f_1 is positive or negative depending on the BPSK data value of the wave having frequency f_1.

Each frequency is expressed by:

$$f_n=f_o+nf_s$$

where f_o is an offset frequency and f_s is a shift frequency. In some cases it was found that by increasing f_o, the values corresponding to undesired bins were reduced.

Various mathematical relationships involving f_o, f_s, and/or n may be used to enhance the magnitude of the ratios of desired values to undesired values.

In order to measure complex values for each bin, in-phase and quadrature-phase step functions are used:

$$Re(y_p)=\sum_{k=0}^{K-1} x_k \Gamma[\tau_n=1/f_n,\ \phi=0]$$

$$Im(y_p)=\sum_{k=0}^{K-1} x_k \Gamma[\tau_n=1/f_n,\ \phi=\pi/2]$$

In order to sample CI waves at a particular phase space O, a set of step functions corresponding to each of the carriers for that particular phase space may be used:

$$C_m = y_p(\phi_m) = \sum_{n=1}^{N} \sum_{k=0}^{K-1} x_k \Gamma[\tau_n = 1/f_n, \phi = \phi_m]$$

The values obtained for each frequency bin may optionally be multiplied by one or more complex weights w_n prior to combining in order to compensate for fading and/or interference:

$$C_m = y_p(\phi_m) = \sum_{n=1}^{N} w_n \sum_{k=0}^{K-1} x_k \Gamma[\tau_n = 1/f_n, \phi = \phi_m]$$

Without, the complex weight w_n, the result is similar to a simple matched filter that is matched to a CI pulse.

FIG. **82** shows a step function **8211** of a particular phase space superimposed over three sinusoidal waves **8201**, **8202**, and **8203** characterized by different phases of the same frequency f_n. A first sinusoid **8201** has the same phase as the step function **8211**. The other two sinusoidal waveforms **8202** and **8203** contribute interfering terms to the desired value obtained in frequency bin f_n from the first waveform. Similarly, at other frequencies, waveforms corresponding to interfering phase spaces (such as waveforms **8202** and **8203**) contribute interfering terms. However, the sum of bin values over all of the frequencies corresponding to a desired phase space results in destructive combining of the interference from other phase spaces and constructive combining of the desired signal.

The table shown in FIG. **83** illustrates the summed values of three frequency bins of a three-carrier signal generated for a desired phase space and for the two remaining undesired phase spaces. A set of quasi-orthogonal phase spaces may be employed. However, this results in some cross correlation between the first set and the second set of phase spaces.

FIG. **84** illustrates basic components of a CI-OFFT receiver. A received signal is optionally processed by a band limiting filter **8401** to limit the frequency band of the signal. The band limiter **8401** may act as an anti-aliasing filter and/or a channel selector. Received signals are processed by a sampler **8402** adapted to generate one or more sample sets with respect to step-function characteristics provided by a step-function generator **8408**. The step-function generator **8408** may control one or more sampling parameters of the sampler **8402**, such as sample width, sample shape, number of samples, sampling interval, sample grouping, sample-set size, etc. Sample parameters may be adapted to provide filtering.

Samples generated by the sampler **8402** may optionally be stored in a storage device **8403**, such as computer memory. A selector/accumulator **8404** selects and groups samples in a combining process. A symbol-interval selector **8409** may control selection criteria, such as symbol duration T_s, and number of samples per symbol interval. The symbol duration T_s, corresponds to a particular number of step-function periods over which samples are combined. In an OFFT process, the combination of symbol durations and step-function periods are adapted to decompose a received signal into orthogonal components. The resulting signals may optionally be coupled to a processor **8405** adapted to perform one or more receiver processes. In some cases, the orthogonal components may be combined in a combiner (not shown).

In an alternative embodiment of the invention, the sampler **8402** provides unformatted samples to the selector/accumulator **8404**. The selector/accumulator **8404** is adapted to generate one or more sample sets with respect to step-function characteristics provided by the step-function generator **8408**. In this case, the selector/accumulator **8404** may control symbol duration T_s (i.e., carrier separation f_s) and step-function frequency (i.e., carrier selection). The selector/accumulator **8404** may optionally provide weights to the samples (such as to adapt to step-function levels, compensate for channel effects, mitigate interference, perform demodulation, and/or provide for any other signal-processing objectives). The selector/accumulator **8404** may optionally discard or replace sample values that exceed and/or fall below a predetermined threshold power level.

The principles of the OFFT may be applied to any algorithmic or numerical implementation of a Fourier transform. Computations in OFFT algorithms and/or inverse-OFFT algorithms may exploit symmetry and/or periodicity properties of one or more step functions, such as step function $\Gamma(t)$. Such computations used to simplify transform operations are known as divide-and-conquer techniques. Any of various types of radix-2 and/or radix-4 algorithms may be employed in OFFTs and/or inverse OFFTs. The principles described herein may be applied to or adapted to any of the fast Fourier transforms. The principles described herein may be applied to any inverse Fourier transform.

The principles of CI Sampling and it applications to digital filtering are fundamental in nature. Step functions (which may take the form of integrators, accumulators, recursive structures, adders, storage systems, etc.) or equivalent functions having harmonic content are used to process band-limited signals. Step-function processing is simpler to implement in the time domain than sinusoid-based processing. Band limiting allows step functions having appropriate harmonic content to replace sinusoids in a variety of signal-processing applications. Accordingly, CI sampling may be implemented in a variety of algorithms and applications, including, but not limited to, sigma-delta modulation, correlation, convolution, resonant filters, sinc filters, invertible transform operations, frequency conversion, filter banks, and analysis/synthesis filters.

Inverse CI-OFFT

In an inverse CI-OFFT process, data symbols are impressed onto one or more carrier signals by generating time-domain symbols that are summed relative to a function representing a sum of a plurality of values pertaining to at least one orthonormal basis. In one embodiment, the orthonormal basis values in the function's sum include only one carriers in a multicarrier signal. In another embodiment, the orthonormal basis values in the function's sum include more than one carrier in the multicarrier signal.

In one specific example of the invention, data symbols are impressed onto one or more carrier frequencies of a multicarrier signal by combining one or more information symbols relative to a step function having one or more frequencies. The periodicity of each step function preferably corresponds to a frequency of the multicarrier signal. In some applications, the multicarrier frequencies correspond to one or more harmonics of one or more step functions.

Step-function values may include at least two of the following set of normalized values: 1, 0, and −1. Alternatively, the step function values may be derived from a

constellation of more than two values. Step-function values may be incremental or non-incremental.

FIG. **85** illustrates a plurality of five-level step functions **8501** to **8509**. The step-function frequencies are orthogonal over the interval shown. FIG. **86**A illustrates a pulse **8601** resulting from a superposition of the step functions **8501** to **8509**. In one case, high-frequency components of the superposition pulse **8601** may be filtered using a low-pass filter (not shown) to produce a filtered baseband pulse **8602** illustrated in FIG. **86**B.

Step functions may be modulated with at least one information signal to produce an information-modulated pulse. In one application, each step function is modulated (or otherwise impressed) with at least one information signal. The step functions may be modulated via CI coding. In one example, the step-function carriers are provided with a plurality of interfering information signals and the carriers are combined to produce a plurality of superposition pulses that characterize each of the information signals. In some applications, the carriers may be provided with phase offsets (for example, to enhance security and/or reduce PAPR) prior to combining. Low-frequency and/or high-frequency components of the combined signals may be selected and/or removed via filtering. In one set of applications, selection of high-frequency components of the combined signals may provide for frequency up-conversion.

FIG. **87**A illustrates a combined signal **8701** resulting from a superposition of a plurality of step functions having a frequency offset f_o. FIG. **87**B illustrates a low pass filtered superposition signal **8702** after high-frequency components have been removed from the combined signal **8701**.

FIG. **88**A illustrates a superposition pulse **8801** generated from a plurality of binary step functions (not shown). FIG. **88**B illustrates a filtered superposition pulse **8802** generated by low-pass filtering the pulse **8801**.

FIG. **89**A illustrates a functional embodiment of an inverse CI-OFFT system of the invention. Information symbols from an input information stream are modulated by a modulator **8901** onto a plurality of step functions generated by a step-function generator **8904**. The step functions may be weighted by an optional weight generator **8905** prior to being combined in a combiner **8902**. The step functions may be weighted to provide coding (such as to provide carrier-phase offsets and/or to implement a direct-sequence type of coding), compensate for channel distortion, generate array-processing weights, or perform any other physical-layer processing. The combined signal may be filtered to provide a band-limited signal and/or provide for frequency up-conversion. The filtered signal is optionally provided to a transmission system (not shown) for coupling into a communication channel.

FIG. **89**B illustrates an alternative functional embodiment of an inverse CI-OFFT system. A weight generator **8911** is adapted to provide weights to a step-function generator **8912**. The weights characterize at least one information signal. Optionally, the weights may be adapted to other physical-layer parameters, such as coding, channel compensation, array-processing weights. The weighted step functions are combined in a combiner **8913** and filtered by a filter **8914** prior to being coupled to a transmission system (not shown).

FIG. **89**C illustrates yet another embodiment of a functional embodiment of an inverse CI-OFFT system of the invention. An information stream is processed by a serial-to-parallel converter **8921**. The information symbols are combined in a combiner **8922** with respect to a plurality of functions, such as provided by a step-function generator **8924**. Optionally, the information symbols may be weighted and/or combined with respect to weights provided by a weight generator **8925**. The combined signals are processed by a filter **8923** prior to being coupled to a transmission system (not shown).

The methods and systems illustrated with respect to OFFT techniques (including inverse CI-OFFT) may be interpreted in many different ways. Signals may be generated and combined in many different ways with respect to OFFT techniques. Data symbols may be processed in many different ways that are analogous to step-function generation and combining techniques associated with OFFT techniques.

CI-Based Wavelets

In B. B Hubbard's *The World According to Wavelets* (2nd edition, A K Peters, Ltd., Natick, Mass., 1998), which is hereby incorporated by reference, the FFT is described as "the modern algorithm that has most transformed our society." Gilbert Strang states "whole industries are changed from slow to fast by this one idea." The primary advantage of the FFT is that it reduces the computational complexity relative to the DFT. For example, the FFT reduces the number of complex multiplications from N^2 to N log N. CI applications to Fourier transforms, as described herein, provide even more substantial reductions in complexity.

The Fourier transform provides a useful interpretation of the many physical phenomena. For example, the realization that an elementary particle does not simultaneously have a precise position and a precise momentum is a natural consequence of Fourier analysis. One of the principle arguments supporting wavelets is that Fourier analysis is poorly suited for brief signals or signals that change in time. Drawbacks to Fourier analysis are based on the observation that since the building blocks of Fourier analysis are sines and cosines that oscillate for all time, Fourier analysis is not effective in describing signals having changing frequencies.

A windowed Fourier transform may be used to analyze a signal in both time and frequency by detecting frequencies of the signal in each of a plurality of time segments. The windowed Fourier transform replaces the Fourier transform's sinusoidal wave with a product of a sinusoid and a window function that is localized in time. However, small windows are blind to low-frequency components of the signal and large windows do not provide adequate time resolution.

Many parallel interpretations can be made between the Fourier transform and other transforms. For example, the discreet wavelet transform is analogous to the DFT. Consequently, aspects of the present invention pertaining to Fourier transforms can be extended to variations of the Fourier transform and other transforms as well. Transforms and inverse transforms that may be used in conjunction with the present invention include, but are not limited to, Abel, Bessel, Fourier, Haar, Hadamard, Hankel, Hartley, Hilbert, Hough, Laplace, Mellin, Radon, Slant, Walsh, Wavelet, and Weber transforms.

The wavelet transform replaces the Fourier transform's sinusoidal waves with a wavelet-window family generated by translations and dilations. The continuous wavelet transform (CWT) is expressed by:

$$\gamma(s,\tau)=\int\int f(t)\Psi^*_{s,\tau}(t)dt$$

The CWT equation illustrates how a function $f(t)$ is decomposed into a set of wavelet basis functions $\Psi_{s,\tau}(t)$. Optionally, the wavelet basis functions $\Psi_{s,\tau}(t)$ may be expressed by one or more sets of CI basis functions. The

variables s and rare scale and translation, respectively. The inverse wavelet transform is given by:

$$f(t)=\iint\gamma(s,\tau)\Psi_{s,\tau}(t)d\tau ds$$

The wavelets are generated from a single basic wavelet by scaling and translation:

$$\Psi_{s,\tau}(t)=\frac{1}{\sqrt{s}}\Psi\left(\frac{t-\tau}{s}\right)$$

When discreet wavelets are used to transform a continuous signal, the result is a series of wavelet coefficients. It is preferable that the discreet wavelets behave like an orthonormal basis. Selection of the basic wavelet can make discreet wavelets substantially orthogonal to their dilations and translations:

$$\int\Psi_{j,k}(t)\Psi_{m,n}(t)dt=\begin{cases}1, & j=m, k=n\\ 0, & \text{otherwise}\end{cases}$$

An arbitrary signal can be constructed from a sum of the orthogonal wavelet basis functions weighted by wavelet transform coefficients:

$$f(t)=\sum_{j,k}\gamma(j,k)\Psi_{j,k}(t)$$

A set of orthogonal code vectors can be obtained from rows and/or columns of the matrix $\Psi_{j,k}(t)$.

In addition to using the orthogonal wavelet basis to define orthogonal code vectors, the orthogonal basis functions may be defined as carriers in the definition of CI. For example, multiple orthogonal basis functions may be modulated with the same data symbol with respect to one or more CI codes. Multiple CI encoded data symbols may each modulate the multiple orthogonal basis functions with respect to an orthogonal phase space. In this context, a phase space is defined as a set of signal parameters (such as phases) that allow signals impressed onto the same set of carriers to be separated via interferometry.

CI can provide a multicarrier basis to wavelets. Thus, CI can be used to provide multi-resolution analysis to analyze one or more signals at different frequencies with different resolutions. CI-based pulses can be used to provide good time resolution and poor frequency resolution at high frequencies and good frequency resolution and poor time resolution at low frequencies. This approach is useful when the signal being analyzed has high frequency components for short durations and low frequency components for long durations.

A CI-based wavelet is represented by a superposition of finite-duration CI waveforms, such as sinusoids. The duration of a CI wavelet may equal the symbol duration $T_s=1/f_s$ or some fraction of T_s. Wavelet functions with different regions of support that are used in a transformation process can be derived from one a CI-based function. Translation is related to phase space, as a pulse position is defined by a unique set of sub-carrier phases. Scaling is related to the inverse of a CI pulse's effective carrier frequency f_{eff}. The effective carrier frequency f_{eff} may be adjusted by appropriate selection and/or weighting of individual CI carrier frequencies f_n or selection of the offset frequency f_o. Similarly, the CI-based mother wavelet may be changed simply by adjusting carrier selection and/or carrier weighting. Because wavelets can be expressed as a linear combination of CI sub-carriers, various sub-carrier groups may be used as basis vectors for wavelets.

CI wavelets having various scales and translations are multiplied with a signal being analyzed. The product is nonzero where the signal falls in the region of support of the wavelet, and it is zero elsewhere. Each product represents a superposition of correlation values of a given set of CI subcarrier basis functions having complex weights corresponding to a particular CI wavelet. By shifting the wavelet in time, the signal is localized in time, and by changing the scale, the signal is localized in effective frequency f_{eff}.

The wavelet transform has good time and poor frequency resolution at high frequencies, and good frequency and poor time resolution at low frequencies. However, a high-frequency (i.e., small scale) CI-based wavelet can be decomposed into a plurality of narrowband sub-carrier components to provide high frequency resolution. Similarly, multiple low-frequency (i.e., large scale) wavelets can be combined relative to at least one predetermined phase space to provide a superposition signal characterized by high time resolution.

Required sampling rates correspond to CI sub-carrier frequencies. At lower frequencies, the sampling rate can be decreased, which saves a considerable amount of computation time. Nyquist's sampling rate is the minimum sampling rate that allows the original continuous time signal to be reconstructed from its discrete samples. Discretization can be done in any way without any restriction as far as the analysis of the signal is concerned. If synthesis is not required, even the Nyquist criteria does not need to be satisfied. The restrictions on the discretization and the sampling rate become important if, and only if, the signal reconstruction is desired.

FIG. **90** illustrates a wavelet **9000** constructed from a plurality of CI carriers, such as CI carriers **9001** to **9007**. CI carriers may be used to construct any wavelets, including, but not limited to, Morlet, Mexican hat, Meyer-Lemarier', Daubechies, and Malvar wavelets. CI wavelets may include various types, including continuous, discreet, frame, orthogonal transform, quasi-orthogonal transform, and bi-orthogonal transform wavelets.

In the case of a continuous transform, any function having a zero integral can be a wavelet. A feature of orthogonal CI carriers that is exploited by the present invention is that each carrier has a zero integral. Thus, the CI carriers can be implemented as sinusoidal basis functions for any wavelet.

Orthogonal wavelets are a special case of discreet wavelets. Orthogonal wavelets provide a representation of a signal without redundancy and lend themselves to fast algorithms. CI-based wavelets can be orthogonalized with respect to phase space, scaling, and/or frequency shift. Orthogonal CI wavelets may share the same carriers and the carrier phases may allow the wavelets to be orthogonal. CI carrier weights may be adjusted to generate different wavelet types, adjust scaling, and/or provide time shifts. CI-based wavelets can also be processed via fast algorithms, including FFTs, OFFTs, wavelet transforms, and CI sampling algorithms.

FIG. **91** illustrates a Morlet wavelet packet **9100** that represents a superposition of CI carriers, such as CI carriers **9101** to **9107**. In conventional wavelet systems, a wavelet packet represents a product of a wavelet and an oscillating function. The wavelet part is responsive to abrupt changes and the oscillating function reacts to regular oscillations. The packet width, frequency, and position can each be varied

independently. The CI packet **9100** width can be varied by adjusting CI carrier **8602** weights. The oscillating function in the CI wavelet packet **9100** may be represented by an effective carrier frequency f_{eff}. Techniques for selecting and adjusting the effective carrier frequency f_{eff} are described throughout the specification. In some applications, a carrier-frequency offset/0 may be provided to the CI carrier frequencies f_n to select or adjust the effective carrier frequency f_{eff}. The CI packet **9100** position can be shifted by shifting the carrier phase space.

FIG. **92**A illustrates three overlapping CI pulses **9201**, **9202**, and **9203**. The oscillations in the pulses **9201**, **9202**, and **9203** have frequencies f_1, f_2, and f_3, respectively. The pulses **9201**, **9202**, and **9203** combine to provide a superposition signal **9210** shown in FIG. **92**B characterized by an approximately linear frequency ramping from f_1 to f_3.

The oscillation in a CI pulse is referred to as an effective carrier. The effective carrier frequency f_{eff} is related to the weighted average of carrier frequencies that comprise the CI pulse. The amplitude of pulse **9201** is near its maximum at time whereas the amplitudes of pulses **9202** and **9203** are near zero. Thus, the oscillation frequency of pulse **9210** is approximately f_1 at time t_1. The amplitude of pulse **9201** tends toward zero and the amplitude of pulse **9202** approaches its peak value as the time approaches t_2. Thus, the oscillation frequency of pulse **9210** smoothly transitions from f_1 to f_2 over the time period of t_1 to t_2. The amplitude of pulse **9202** drops toward zero and the amplitude of pulse **9203** increases over the period of t_2 to t_3. Consequently, the oscillation frequency of pulse **9210** smoothly transitions from f_2 to f_3.

FIG. **92**C illustrates a plurality of CI carriers **9220** to **9229** that combine to generate the superposition signal **9210** shown in FIG. **92**B. The carriers **9220** to **9229** are characterized by predetermined frequencies, frequency separations, magnitudes, and phases necessary to produce a superposition signal (such as signal **9210**) having predetermined transient features. In some applications, time-varying weights may be applied to the carriers.

A first group of carriers **9220**, **9221**, **9222**, and **9223** combine to generate a portion of the superposition signal **9210** that is characterized by frequency f_3. A second group of carriers **9224**, **9225**, and **9226** combine to generate a portion of the superposition signal **9210** that is characterized by frequency f_2. A third group of carriers **9227**, **9228**, and **9229** combine to generate a portion of the superposition signal **9210** that is characterized by frequency f_3. Transition regions of signal **9210** between the frequencies f_1, f_2, and f_3 are characterized by varying proportions of superposition signals relative to the carrier groups. In some cases, one or more carrier sets may provide non-negligible contributions across most of a superposition signal and/or to a plurality of non-contiguous sections of a superposition signal.

Time offsets of various features of the superposition signal **9210** are characterized by one or more carrier phase offsets. The scale of the superposition signal corresponds to a scale factor associated with the carriers. Amplitude variations in the superposition signal **9210** may correspond to a set of carrier phases and/or magnitudes. Consequently, time offsets and scales in wavelet processing can be represented by corresponding CI carrier phase offsets and/or amplitudes. Correlation values corresponding to particular wavelets (indicated by scale, offset, and wavelet type) may be converted to correlation values corresponding to one or more predetermined CI carriers. A wavelet interpretation of transmitted and/or received signals may be conveyed as a CI interpretation. Conversely, CI interpretations may be converted to wavelet interpretations.

FIG. **93** illustrates a conversion between a set of wavelet parameters (τ_n, s_n) to a set of CI parameters (f_n, w_n). A wavelet **9301** is characterized by a time offset Zn and a scale s_n. The wavelet **9301** is also characterized by a superposition of CI carriers **9302** having predetermined frequencies f_n and corresponding carrier weights w_n.

In some applications, a correlation value associated with a particular wavelet may be expressed by a set of weighted carriers. If multiple wavelets are generated from the same set of carriers, each wavelet correlation value maps into the same set of carriers. Each of the corresponding carrier weights can be derived from a superposition of weighted wavelet correlation values. Prior to superposition of the weighted wavelet correlation values used to generate a carrier weight corresponding to a particular carrier frequency f_n, each wavelet correlation value is weighted with the carrier weight w_n of carrier frequency f_n associated with the corresponding wavelet.

FIG. **94**A illustrates a CI-based wavelet (i.e., superposition signal) **9400** characterized by a high time resolution (i.e., a narrow time-domain signal). FIG. **94**B illustrates a plurality of narrowband CI carriers **9401** to **9407** that are components of the superposition signal **9400** shown in FIG. **94**B. FIG. **94**C is a frequency-domain illustration of the carriers **9401** to **9407** shown in FIG. **94**B. Each frequency-domain component **9401** to **9407** is characterized by high frequency resolution (i.e., a narrow frequency-domain signal). Consequently, a CI-based wavelet provides the means to perform analysis with high resolution in both the time and frequency domains.

The inverse relationship between time and frequency illustrated by the Fourier transform exemplifies the Heisenberg Uncertainty Principle. However, interferometry methods of the present invention exploit phase space to circumvent the inherent resolution trade offs between coupled measurements, such as time and frequency. Consequently, the interferometry techniques of the present invention may be extended to various probability-distribution applications. These applications may include various types of sensing and analysis.

FIG. **95**A illustrates a portion of a particular signal **9500** characterized by multiple frequencies and transient signal characteristics. Each of a plurality of narrowband CI signals **9501.1** to **9501**.N shown in FIG. **95**B is correlated (or similarly processed) with the signal **9500** to provide a plurality of correlation values $c_1(f_1)$ to $c_N(f_N)$.

Each correlation value $c_1(f_1)$ to $c_N(f_N)$ provides a measure of correlation between the signal **9500** and one of the CI signals **9501.1** to **9501**.N. In some applications, each narrowband CI signal **9501.1** to **9501**.N includes in-phase and quadrature-phase components. Similarly, the correlation process may include in-phase and quadrature phase processing. The correlation values $c_1(f_1)$ to $c_N(f_N)$ may include any combination of in-phase and quadrature-phase correlation values. In some cases, each correlation value $c_1(f_1)$ to $c_N(f_N)$ may include separate in-phase and quadrature-phase components.

FIG. **95**C illustrates a superposition signal **9502** resulting from a sum of the CI signals **9501.1** to **9501**.N. The superposition signal **9502** is characterized by a pulse bounded by a narrow time interval $\Delta t=t_2-t_1$. A Δt-width signal **9503** illustrates the portion of the signal **9500** that

contributes substantially to a correlation value resulting from a correlation between superposition signal **9502** and signal **9500**.

An nth correlation value $c_n(f_n)$ characterizes the presence of a corresponding narrowband frequency component f_n over a relatively long time interval t'_1-t'_2. The correlation values $c_1(f_1)$ to $c_N(f_N)$ may be combined to produce a combined correlation value $c(t_1:t_2)=\Sigma c_n(f_n)$. When the correlation values $c_1(f_1)$ to $c_N(f_N)$ are combined, contributions of signal **9500** outside of the time interval $\Delta t=t_2-t_1$ substantially cancel. Contributions of signal **9500** within the time interval $\Delta t=t_2-t_1$ combine substantially in phase.

In some applications, complex-valued weights may be provided to the correlation values $c_1(f_1)$ to $c_N(f_N)$ prior to combining. The weights may be provided to select predetermined time intervals Δt, time-interval width, and/or effective superposition signal **9502** shape. The correlation values $c_1(f_1)$ to $c_N(f_N)$ may be generated with respect to some filtering function, such as an FFT.

A CI-based wavelet may be provided with the transmission and/or reception benefits of a multicarrier signal. CI processing, as described throughout the specification and in the documents incorporated by reference, may be performed with respect to CI-based wavelets.

FIG. **96**A illustrates one aspect of the invention in which wavelet parameters (such as scale factors, translations, and/or wavelet type) are modulated or otherwise impressed onto CI signals for transmission. The wavelet parameters are generated **9601** or otherwise acquired prior to being used to shape a CI waveform in a step of providing CI symbols with wavelet parameters **9602**. The wavelet parameters may be used to shape one or more CI superposition signals and/or adjust CI symbols that are conveyed on one or more diversity parameters. The CI signals are processed for transmission **9603**. This processing **9603** typically includes preparing a baseband or IF signal for coupling into a communication channel. The transmission-processing step **9603** may include predistortion processing, channel selection, coding, interleaving, up conversion, filtering, amplification, mixing, and/or any other processes typically performed prior to transmission.

FIG. **96**B illustrates an alternative method of transmitting wavelet parameters over a communication channel. Wavelet parameters are provided in a wavelet-generation step **9601**. The wavelet parameters are converted to CI carrier weights using an appropriate wavelet-parameter-to-CI-carrier-weight conversion **9604**. The wavelet parameters may be CI encoded. The CI symbols representing the wavelet parameters are processed in a transmission-processing step **9605** prior to being coupled into a communication channel (not shown). In this case, the CI weights may be conveyed via CI transmission signals or any other form of transmission signaling.

FIG. **96**C illustrates yet another method of conveying wavelet parameters as a CI-based signal. Wavelet parameters are provided (i.e., generated and/or acquired) in a wavelet-generation step **9601**. The wavelet parameters or wavelets generated with respect to the wavelet parameters are converted to CI waveforms in a conversion step **9606**. The CI waveforms are processed in a transmission processing step **9603** prior to being coupled into a communication channel.

In digitally implemented CI systems, synthesis of a superposition of the various modulated carriers may be performed via a mathematical transformation that generates a sequence of numbers representing the amplitude of the signal as function of time. For example, a superposition signal may be generated by applying an inverse Fourier transformation to a symbol vector generated from CI symbols to be transmitted. Similarly, the symbols are recovered at a receiver using the corresponding inverse transformation. In addition to receiving and separating multicarrier signals with a filter bank, a transceiver can perform transmit-side operations (e.g., modulation, multiplexing, etc.) using a digital filter bank.

The computational workload inherent in synthesizing and analyzing a multicarrier signal is related to the number of subbands. For example, if fast Fourier transforms are employed, the workload is of order N log N, where N is the number of sub-bands. Similar relationships exist for other transforms. Thus, in some applications it is advantageous to minimize the number of subbands. Sub-band selection may be made with respect to channel estimation. For example, characteristics, such as coherence length, may be used to optimize sub-channel (i.e., CI carrier) bandwidth(s) and spacing. Other technical considerations, such as interference, transmitter complexity, receiver complexity, transceiver power, transmitted power density, etc., may be used to determine sub-channel parameters.

At the receiver, the signal from the communication link may be decoded by a plurality of finite impulse response (FIR) filters that are matched to the transmitted waveforms. Synchronization errors between the transmitter and receiver may be corrected with weights determined from transmitted training signals. The receiver may include a phase-compensation circuit that includes a second bank of FIR filters that measure the amplitude of each carrier after the signal has been phase shifted.

Various types of filter banks may be implemented. For example, filter banks may be constructed with narrow-band lapped transforms. Any type of matched filter and/or correlator may be implemented. The decomposition of a signal into frequency subbands may be performed by a tree-structured filter. Such a filter includes two or more levels of filter banks that can be adapted to implement a time-domain to frequency-domain transformation. To implement a variable-channel-width system, a transformation that breaks the available frequency band into subbands of differing width is required. This may be performed using a non-uniform filter-bank transform.

The reverse transformation can be performed by an analogous filter bank. A multi-level tree filter may perform the frequency-domain to time-domain transformation. The symbols to be sent on the finer subbands are first combined using a first set of synthesis filters to provide signals representing the larger subbands. These symbols, together with those from other bands, are then combined by a synthesis filter to provide the time-domain signal that is sent on the communication link.

FIG. **97**A illustrates a CI reception method of the invention. A generation step **9701** provides for the generation of a plurality of CI carriers. The carriers are correlated with at least one receive signal to produce one or more correlation values in a correlation step **9702**. An optional combining step **9703** may be provided to combine a plurality of correlation values.

In the generation step **9701**, CI carriers may be provided with in-phase and quadrature-phase components. The CI carriers may be provided with one or more phase spaces. The CI carriers may be provided with complex weights to compensate for channel distortions. Carrier weights may be provided to compensate for interference. In some applica-

tions employing receiver arrays, carrier weights may be provided for beam forming. In any of these cases, the carrier weights may be adaptive.

The correlation step **9702** may include correlating each CI carrier with one or more received signals. In one set of embodiments, the correlation step **9702** may be adapted to provide correlation between a superposition of the CI carriers and the received signal. Superpositions of the CI carriers may take the form of one or more wavelets. CI carrier weights may correspond to various wavelet scales, translations, and/or shapes (i.e., wavelet types). The CI-based wavelets may include orthogonal wavelets.

In some embodiments of the invention, the received signal may be separated into CI carriers prior to correlation. Carrier weights may be provided to received-signal carriers to compensate for interference and other channel effects. Carrier weights may be provided for beam forming. Correlation, or equivalent processes, may be performed via equivalent processes, including, but not limited to, summing samples over a predetermined time interval, weighting and combining samples, sample-and-accumulate processes, etc.

FIG. **97**B illustrates an alternative CI reception method. A received signal is decomposed into a plurality of CI components in a decomposition step **9711**. The CI components may be processed in an optional channel-compensation step **9712**. Processing may include providing complex weights to the CI carriers. The CI components are correlated with a CI reference in a correlation process **9713** or some equivalent process. In the case in which multiple correlation values are generated by the correlation process **9713**, the values may optionally be combined in a combining process **9714**. Combining may include providing weights to the correlation values.

FIG. **97**C illustrates steps of a CI reception method. A decomposition step **9721** provides for decomposition of at least one received signal into a plurality of frequency components, such as CI signals. The decomposition step **9721** may provide a plurality of oscillating signals characterized by predetermined frequency and bandwidth values. The frequency components may be characterized by complex values that indicate magnitude and phase. The frequency components may include orthogonal and/or quasi-orthogonal components. The frequency components may include overlapping and/or non-overlapping components.

Channel compensation weights may optionally be provided to one or more frequency components in a channel-compensation step **9722**. CI weights may optionally be provided to the components in a weighting step **9723**. CI weights may be provided to the frequency components to select a particular phase space in a combining step **9724**. The combining step **9724** may include adaptive combining.

Adaptive reception and transmission techniques pertaining to CI wavelets (as well as CI in general) may be based on blind-adaptive frequency-domain reception. Various reception techniques may be employed to exploit frequency selectivity that affects multiple carriers in a multipath environment. The technique is blind in the sense that transmitted carrier symbols (e.g., carrier weights) may be unknown. Received carrier symbols may be estimated without calibration and feedback. In one set of receiver embodiments, optimal combining (i.e., an optimal beam pattern in the frequency domain) is based on certain statistical properties of the received signals. Optimal combining is performed by solving an optimization equation.

FIG. **98** illustrates a CI transceiver of the invention. A receiver system **9801** couples a transmitted signal out of a communication channel (not shown). One or more typical receiver-side signal processing techniques (including filtering, mixing, down conversion, amplification, A/D conversion) may be performed on the received signal. A filter bank, such as an FFT **9802**, separates the received signal into a plurality of frequency components. The components are provided with weights in a receiver weighting system **9803**. The weights may include one or more types of weights, such as channel-compensation weights, decoding weights, demultiplexing weights, MUD weights, array-processing weights, wavelet-processing weights, etc. The weighted carriers are combined in a combiner **9804**. The combined signals may be processed in a data processor **9805**. The data processor **9805** may be part of a blind-adaptive processor **9806** that is adapted to generate and/or adapt weights relative to one or more performance parameters, including channel estimates, confidence measures, data estimates, signal power, probability of error, BER, SNR, and SNIR.

In one embodiment of the invention, the blind-adaptive processor **9806** is adapted to process a plurality of information-bearing CI symbols produced from a plurality of carriers. The processor **9806** may work in conjunction with the combiner **9804** to combine the carriers and estimate transmitted data. The combining process may include wavelet processing. The processor **9806** may work in conjunction with the data processor **9805** to provide a channel estimate based on the data estimate. The processor **9806** may employ a time-varying channel-estimation filter (not shown). The processor **9806** provides channel compensation to the received CI carriers and/or symbols. Channel compensation may be based on a statistical characterization of interference, such as a covariance matrix.

In some applications, the processor **9806** may provide predistortion weights to transmitted carriers. A data stream is optionally processed by a transmit data processor **9807**. The data processor **9807** may perform wavelet processing. A transmitter weighting system **9808** is adapted to weight data symbols provided to frequency bins of a frequency-domain-to-time-domain converter, such as an IFFT **9809**. Time-domain signals generated by the IFFT **9809** are provided to a transmission system adapted to prepare the time-domain signals for transmission into a communication channel.

Wavelets, such as CI wavelets, may be used to convey data symbols, code symbols, etc. Symbols may be conveyed via phase shifts, amplitudes, frequencies, polarizations, or any suitable combination of modulation techniques. Orthogonal wavelets, such as wavelets orthogonalized by scaling and/or time offsets, may be used to convey different data symbols and/or different communication channels. CI-based wavelets may be orthogonalized via each wavelet's effective carrier frequency. Data symbols may be spread over multiple orthogonal wavelets via some appropriate form of coding, such as direct-sequence and/or CI coding.

In some applications, quasi-orthogonal wavelets, such as overlapping wavelets, may be used to convey data symbols and/or communication channels. Methods of processing overlapping wavelets may be performed in the same manner as that overlapping CI waveforms (e.g., CI pulses) are processed. Processing may include either or both time-domain and frequency-domain processing.

Wavelets may be provided with coding using one or more coding techniques. In one set of applications, each code uses the same wavelets. A code may be provided as a set of phase shifts (e.g., a polyphase CI code or a binary-phase direct-sequence code) or some other diversity-parameter values applied to the wavelets. An orthogonal channel may consist of a set of codes applied to orthogonal or quasi-orthogonal wavelets. In one set of embodiments, the wavelets may each

have the same duration with orthogonal effective carrier frequencies applied to the wavelets relative to some code.

In an alternative set of embodiments, each code is composed of a plurality of wavelets having different scales (e.g., durations). The order of the wavelets determines each code. In a special case, each code chip has the same duration. The number of wavelets representing each chip depends on the duration of the particular wavelet compared to the duration of the chip. Orthogonal wavelets may be provided wherein the wavelet scales are related by multipliers that are powers of two.

CI Adaptability

The present invention increases flexibility and adaptability by providing scaling of operating parameters and/or signal characteristics in a CI system. FIG. **99** illustrates a control circuit **9901** adapted to process one or more system requirements **9911** and, optionally, one or more channel characteristics **9912**. The control circuit **9901** provides adjustment to one or more CI parameters **9902** in a CI transceiver **9903**. CI parameter adjustment and/or selection affects one or more transceiver operating parameters **9921**.

The control circuitry **9901** may scale a transmitted bit rate by scaling the CI symbol duration, the number of carriers, the carrier spacing, and/or the number of bits per symbol per carrier. This permits the scaleable CI system to operate in various communications environments requiring various operating parameters and/or characteristics. By scaling the operating parameters and/or characteristics of the CI system when control circuitry **9901** determines that different operating parameters and/or characteristics are necessary or advantageous, the control circuitry **9901** can dynamically change the operating parameters and/or characteristics, thereby providing compatibility or the desired performance. For example, dynamically scaling the bit rate enables widely varying signal bandwidths, adjustment of delay-spread tolerances, and adaptability to different SNR requirements. A scaleable CI system is particularly suitable for applications in mobile wireless communications, as well as other applications that support a variety of services in a variety of environments.

In accordance with aspects of certain embodiments of the scaleable CI modulation system, a CI modulation system can be designed with an upper limit on the number of carriers and a variable symbol duration. The control circuitry can dynamically scale the number of carriers below the upper limit to decrease the signal bandwidth and the transmission rate while delay-spread tolerance remains the same. The control circuitry **901** can also dynamically increase the symbol duration to decrease the transmission rate and the signal bandwidth and provide an increase in delay-spread tolerance. The control circuitry **9901** may be adapted to adjust the transmission rate by changing the type of modulation. In accordance with other embodiments, a scaleable coded CI modulation system achieves variable transmission rates using adaptive coding where different coding schemes are used to improve the link reliability and/or to decrease the peak-to-average power ratio.

In accordance with yet other embodiments of the scaleable CI modulation system, scaleable transmission rates permit asymmetric data rates between mobile units and base stations. For example, the mobile units can have lower data rates than the base stations by allocating only a fraction of the total number of carriers to each mobile, while the base stations transmit on all carriers simultaneously. Additionally, during data downloading, for example, a mobile unit could have a larger downlink data rate than uplink data rate. In accordance with other aspects of a scaleable CI system, mobile units and base stations using the same antennas for both transmit and receive operations can benefit from adaptive antennas without any additional processing requirements at the base station, thereby keeping the mobile units as simple as possible. The scaleable CI modulation system can use an adaptive antenna at the base by sending feedback through the uplink when uplink and downlink channel characteristics are not identical.

Power control may be performed by either or both CI transmitters and CI receivers on each carrier or on subgroups of carriers. Alternative to power control, certain carriers may be selected to optimize one or more operational parameters, such as throughput, probability of error, received signal power, transmitter power efficiency, SNR, QOS, etc. CI carriers may be selected with respect to the types of services being provided. For example, different qualities of service corresponding to different-priority links and/or different link services may be criteria for selecting CI carriers. In one case, carriers having little distortion and interference may be selected for services (such as data links) that do not tolerate high BER. In another case, a transmission may be divided into sections and sent on two or more groups of carriers. An important section, such as addressing information, may be sent on higher-quality channels than the channels on which the payload data is sent. Addressing and other control information is typically less tolerant to errors than payload data. Thus, important parts of a transmission may be transmitted on orthogonal phase spaces and/or on carriers having little distortion and fading.

Another aspect of the invention employs a medium access contention (MAC) protocol that is highly beneficial in wireless networks, and particularly in CI-based wireless networks that employ a fixed minimum burst size. In one embodiment, a MAC protocol is a demand-assigned protocol that maximizes utilization of the allocated frequency spectrum (i.e., the bus medium). Each data communication device (DCD) in the network communicates with a central access point (AP). Multiple DCDs may request access from the AP in the same request access (RA) burst. In one embodiment, each of the multiple DCDs transmits its access request to the AP within a frequency-domain channel in the RA burst that is orthogonal to the frequency domain channels used by the other DCDs requesting access. In another embodiment, each of the multiple DCDs transmits its access request to the AP within a phase-space channel in the RA burst that is orthogonal to the phase-space channels used by the other DCDs requesting access. Alternatively, other orthogonal diversity-parameter values may be employed. Each DCD includes channel training information in the access request burst to allow the AP and/or DCD to adapt to rapid variations in channel characteristics.

Ad-Hoc CI Networking

FIG. **100**A illustrates a plurality of subscriber units **10001** and **10002** (e.g., mobile or fixed subscriber units) in a network having a plurality of access points **10011** to **10015** (e.g., base stations). At least one of the subscriber units **10001** is adapted to transmit a pilot signal or known training signal that is received at the plurality of access points **10011** to **10015**. Signal paths **9931** to **9935** corresponding to a pilot transmission from the subscriber unit **10001** and the access points **10011** to **10015** are shown. The propagation environment ensures that the set of pilot signals received by the access points **10011** to **10015** is unique for each subscriber's location. The uniqueness of the propagation environment may be exploited to provide or enhance coding. The access points **10011** to **10015** are adapted to process the received pilot signals. Processing operations may depend on various

characteristics of the received pilot signals, including absolute and/or relative signal power levels. For example, a predetermined number of access points **10011** to **10015** may be selected to process signals for a given subscriber unit based on the received pilot signal power.

At least one of the access points **10011** to **10015** is adapted to perform channel analysis to characterize the propagation environment of the transmissions between the subscriber unit **10001** and the access point(s). Channel analysis may include delay-profile and/or flat-fading characterizations. The propagation environment may be employed as a unique identifier for each subscriber unit. Channel weights calculated from channel estimates may be utilized in multiple-access codes, encryption codes, and/or authentication and verification procedures.

Channel analysis may be used to generate filter weights and/or array-processing weights at the access points **10011** to **10015** to process received and/or transmitted signals. The access points **10011** to **10015** may include single-antenna systems or multi-antenna systems, such as antenna arrays. Received signals may be compared to some local or global timing reference, such as to analyze phase offsets and/or signal timing.

FIG. **100**B illustrates a plurality of access points **10011** to **10015** adapted to transmit channel-compensated signals **9941** to **9945**. The transmissions **9941** to **9945** exploit the propagation channels between the access points **10011** to **10015** and at least one subscriber unit **10001** to constructively combine at the at least one subscriber unit's **10001** location.

In one set of embodiments of the invention, transmission weights are generated from the reciprocal of a channel matrix that characterizes the propagation environment between one or more access points (such as access points **10011** to **10015**) and the at least one subscriber unit **10001**. Channel weights may be provided via any combination of deterministic (i.e., training) and blind-adaptive processing. Channel weights may be selected and/or adapted to optimize coherent combining of access-point transmissions to one or more subscriber units. Similarly, the channel weights may be selected and/or adapted to optimize coherent combining of signals received from one or more subscriber units. Any of various optimal combining techniques may be employed.

Channel weights may be adapted to generate beam-pattern nulls at one or more undesired subscriber units or interference sources (not shown). Channel weights may be adapted to provide time-varying channel compensation. Thus, beam steering, null steering, or any other time-dependent adaptive array processing may be performed. Appropriate combinations of carrier selection and carrier weighting may be provided to achieve simultaneous directionality and diversity benefits. In some applications, the access points **10011** to **10015** shown may be replaced by subscriber units acting as routers, relays, and/or array elements of an adaptive transceiver array.

FIG. **101** illustrates a plurality of access points **10011** to **10015** connected to a network **10200**, such as an optical-fiber or wireline network. A central processor **10201** is adapted to process signals received and transmitted by the networked access points **10011** to **10015**. In this case, the access points **10011** to **10015** may be "dumb terminals," wherein most or all of the signal processing is performed by the central processor **10201**. For example, the central processor **10201** may perform channel analysis and generate access-point weights to optimize communication with the subscriber units (not shown). The access points **10011** to **10015** may perform only basic signal-processing functions, such as RF processing and frequency conversion.

The central processor **10201** may provide base-station functionality, such as power control, code assignments, and synchronization. The central processor **10201** may provide network load balancing, including providing for balancing transmission power, bandwidth, and/or processing requirements across the network. Base-station functionality may be controlled by individual access points or subscriber transceivers assigned to act as base stations. Array processing may be performed in a distributed sense wherein channel estimation, weight calculation, and optionally, other network processing functions (such as load balancing) are computed by a plurality of spatially separated processors (e.g., access points and/or subscriber units) adapted to work together. A central processor (such as central processor **10201**) may optionally be provided to control data flow and processing assignments throughout the network.

Other types of networks, including wireless networks, may connect the access points **10011** to **10015**. One or more of the access points **10011** to **10015** may be replaced by subscriber units (not shown) adapted to perform as routers, repeaters, and/or elements of an antenna array.

In this case, the entire access-point network **10011** to **10015** is adapted to operate as an antenna array. In most applications, a portion of the network may be adapted to serve a particular subscriber transceiver. The network may be adapted to perform long baseline interferometry. The central processor **10201** and/or the access points **10011** to **10015** may be adapted to perform other signal-processing operations, such as, but not limited to, waveform shaping, error detection, error correction, power control, channel selection, multiple access control, multiplexing, modulation, formatting, synchronization, coding, etc. In alternative embodiments of the invention, the central processor **10201** is replaced by a distributed computing system (not shown) that may reside at a plurality of subscriber units, repeaters, and/or access points.

FIG. **102** illustrates a network architecture in which a plurality of subscriber units **10201** to **10205** are adapted to function as routers and/or repeaters. Each network node (e.g., subscriber unit **10201** to **10205**, access point (not shown), etc.) may be adapted to function as a router and/or repeater. As the network evolves, the nodes adapt the routing tables to optimize throughput. As network loads change, the nodes perform load balancing to ensure a predetermined range of bandwidth and transmit-power loads across the network. One or more paths to each subscriber unit may be selected or modified to optimize loads across the network, minimize transmission power, and/or ensure received signal quality. In one aspect of the invention, multiple transmission paths to the subscriber units are employed to achieve one or more objectives, such as reducing the effects of fading, reducing transmission power in some of the relays, and/or distributing transmission power across the network.

Information intended for a particular subscriber unit (e.g., subscriber unit **10210**) is passed through the network along a chain of subscriber units **10201**, **10202**, and **10203**. One or more subscriber units (e.g., units **10204** and **10205**) provide a final radio link **10224** and **10225** for the transmission.

The transmission signals may include multiple addresses corresponding to at least one path to the intended subscriber unit(s). The transmission may include multiple addresses corresponding to a plurality of devices that provide the final RF link to the desired subscriber. Alternatively, the transmission may include only the destination address of the desired subscriber. More than one destination address may

be included for a particular transmission. The transmission signal may be duplicated only when the paths diverge. For example, a message with addresses to units **10204** and **10205** is duplicated by transceiver **10203**. Alternatively, a broadcast message may include a plurality of addresses and the network may be adapted to propagate a single version of the message to all of the addresses.

In one set of embodiments, a data message is provided that includes a plurality of destination addresses. Processing instructions, such as transmission weight values, may be included in the data message. A single copy of the message is routed through nodes that form a path that is common to all of the destination addresses. The message is duplicated where the paths to the destination addresses diverge. The addresses may include any combination of codes and network header data bits. The codes may include any combination of polyphase CI codes, CI-based codes, and channel-specific spatial interferometry codes. For example, the channel characteristics for each subscriber may be exploited to provide addressing and/or multiple-access coding. CI codes may be implemented across one or more diversity-parameter spaces. Coding may include space-time coding, space-frequency coding, polarization coding, etc.

In some applications, CI codes may be adapted to accommodate changing numbers of users, different network topologies, load balancing, and varying network services. Code lengths, code orthogonality, number of codes per transmission, and/or chip values for one or more codes may be adapted. CI codes and/or network header addresses may be adapted to changing network conditions. In one set of embodiments, one or more network nodes (e.g., transceivers) may be adapted to process a predetermined set of addresses specified by codes and/or headers. A firewall may be implemented to isolate processing for transmissions routed through a transceiver from transmissions that are addressed to that transceiver. The nodes may perform error detection and/or error correction for each data stream prior to re-addressing and re-transmission.

In another embodiment of the present communication system, every subscriber has access to every transmitted message. Transmitted signals may be routed throughout the entire network. A transmitted message may be received by more than one unit and may be received while the unit is transmitting. CI coding may be employed to provide multiple access and thus, eliminate conflicts to increase system capacity. Similarly, channel-specific coding may be employed. In one aspect of the current embodiment, each transmission has a preamble that includes the code, which allows subscribers to synchronize with the transmission. Optionally, a tag may follow the preamble to identify the data payload.

In the current embodiment, each subscriber has access to the community transmissions. The system allows each subscriber to dynamically select for reception only those transmissions that are relevant to that subscriber. Individual subscriber transceivers may be equipped with adaptable or programmable decoders designed to select and decode one or more transmissions. The transceivers may be provided with a bank of decoders to decode and process multiple received signals simultaneously. The system further provides data inter-operability by use of a common CI-based waveform structure.

In one aspect of the invention, the communication signals are provided as coded sets of low-bandwidth subchannels. Thus, interference resulting from multipath and effective multipath due to retransmissions of information through the network is reduced to flat fades. Sub-carrier bandwidths may be adapted to the multipath channel in one or more parts of the network. Coding may be adapted with respect to one or more parameters, including geographical distributions of subscriber units and access points, channel conditions, link priority, security, subscriber services, number of subscribers, etc.

In one embodiment of the invention, base-station responsibilities are assigned to, or assumed by individual subscriber units. Base-station operations are coordinated with simultaneous coded transmissions of a communications channel and a control channel. Codes may include CI codes, CI-based coding, channel-specific coding, or any combination thereof. A time division duplexing method may be employed for transmit and receive operations to implement the necessary control functions for operation without a base station. Each subscriber unit can be assigned to be a network control station. By using time division duplexing for transmit and receive operations in a CI-based multiple access system the entire frequency bandwidth can be used, in contrast to base station operations having one set of frequencies for transmitting and another set of frequencies for receiving.

The subscriber unit that is acting as a network control station maintains power control and time synchronization normally performed by the base station. Power control is maintained within predetermined time intervals by a feedback control loop using proportional integration and differentiation to smooth control such that power oscillations are maintained within desired limits. The network control functions may automatically be transferred if the connection with the transceiver is terminated or there is a predetermined degree of signal-quality degradation. The network control station has channel control capabilities to assure transmission security. For example, the network control station may assign codes to the other subscriber units to change the security or priority of individual communication links.

FIG. **103**A illustrates a CI transceiver adapted to perform routing. Transmitted signals are received by a receiver system **10301** that outputs a baseband signal. The receiver system **10301** performs RF and (optionally) baseband processes typically performed to convert an RF signal to a baseband or intermediate frequency signal. For example, the receiver system **10301** may perform channel selection, filtering, amplification, frequency conversion, and A/D conversion.

A CI decoder **10302** is adapted to decode the baseband signal relative to one or more address codes intended for the transceiver. The decoder **10302** may select a signal relative to an address in a header prior to decoding. A signal processor **10303** may process the decoded signals prior to producing an output data stream. Signal processing may include one or more signal-processing operations, including, but not limited to, quantization, channel decoding, multiple access decoding, demultiplexing, formatting, demodulation, channel estimation, channel compensation, synchronization, filtering, error detection, error correction, signal-quality analysis, multi-user detection, phase-jitter compensation, frequency-offset correction, time-offset correction, etc.

A control system **10304** is adapted to select, adapt, or otherwise control the operation of one or more transceiver components. For example, channel estimates and/or signal-quality analysis performed by the signal processor **10303** may be processed in the control system **10304** to adapt decoding performed by the decoder **10302**. The control system **10304** may provide power control to the transmis-

sion system **10306** and/or otherwise provide network control. Similarly, CI coding may be adapted by the control system **10304**.

A CI coder **10305** is adapted to process input data bits to produce a coded signal that is coupled to a transmission system **10306**. The transmission system **10306** performs signal-processing operations typically performed to prepare a baseband signal for transmission into a communication channel. The transmission system **10306** may perform one or more processes, including, but not limited to, D/A conversion, modulation, filtering, amplification, frequency conversion, beam forming, etc.

Signals from the receiver system **10301** are coupled to a CI decoder **10312**, which may include a bank of CI decoders. The decoder **10312** decodes received signals that are to be retransmitted. The decoded signals are processed in a signal processor **10313**. The signal processor **10313** may perform similar signal-processing operations as signal processor **10303**. Furthermore, the signal processor **10313** may perform pre-processing operations prior to coding in a CI coder **10315**. The coder **10315** may include a CI coder bank. A control system **10314** is adapted to select, adapt, or otherwise control the operation of one or more of the transceiver components **10312**, **10313**, and **10315**.

The control system **10314** and the coder **10315** may provide channel-compensation and/or beam-forming weights to the coded symbols. Such weights may be regarded as part of the routing process. Since routing decodes some signals that are not intended for the transceiver, the router components **10312**, **10313**, **10314**, and **10315** are isolated from the rest of the transceiver by a fire wall **10310**.

Code division duplexing or cancellation division duplexing may be employed to permit reliable reception while concurrently transmitting. Alternatively, other types of duplexing may be employed. Pseudo-random time, frequency, and/or phase codes are typically used to avoid self-jamming. However, CI codes and CI-based waveforms enable the frequency-domain processing required for optimal performance in a multipath environment while providing data redundancy (i.e., channel coding) needed to mitigate errors. Optionally, additional channel coding (e.g., block, convolutional, TCM, turbo) may be provided to CI waveforms and/or CI coding.

FIG. **103**B illustrates an alternative embodiment of a CI receiver adapted to perform routing. Many of the system components shown in FIG. **103**B are similar to components shown in FIG. **103**A and thus, are identified by corresponding reference numbers. A portion of the baseband (or IF) signal(s) produced by the receiver system **10301** is optionally processed in a processor **10319** prior to being coupled into the transmission system **10306**. The processor **10319** may perform one or more baseband or IF processes, including, but not limited to, signal shaping, filtering, re-quantization, error detection, error correction, interference mitigation, multi-user detection, amplification, up sampling, down sampling, frequency conversion, D/A conversion, AGC, symbol remapping, etc.

FIG. **103**C illustrates a CI transceiver adapted to decode received signals intended for the transceiver and partially decode and route signals intended for one or more other transceivers. System components shown in FIG. **103**C are similar to components shown in FIG. **103**B, as indicated by similar reference numbers.

The CI decoder applies one or more decode signals to the received baseband signal. If the received baseband signal is coded with one or more codes including complex conjugates of the one or more decode signals, a sum of decoded baseband symbols over a code period combines coherently. The combined symbols have a value associated with one or more information signals. The combined symbols may be provided as a data output after one or more optional signal-processing operations.

Symbols generated by the CI decoder **10302** are optionally processed in processor **10319** prior to being coupled to a transmission system **10306** for re-transmission. CI-encoded signals not corresponding to complex conjugates of at least one of the decode signals (i.e., not intended for the transceiver) contribute a substantially zero value to the combined symbols. The processor **10319** may be adapted to remove one or more signal components intended for the transceiver. Since the signals intended for the transceiver provide a dc offset to the individual symbols generated by the CI decoder **10306**, these signals may be removed by filtering, cancellation, or some other dc-removal process.

FIG. **104**A illustrates a tree network that may be implemented in aspects of the present invention. Transmissions passed to one or more nodes in the network may be branched off, or routed, to a plurality of nodes. Routing may include processing any combination of network addresses conveyed in headers and network addresses conveyed by codes (e.g., spreading codes, multiple-access codes, channel codes, etc.).

Network addresses may provide routing information and/or directions. For example, multiple addresses may convey one or more paths between a source node and a destination node. Various types of control information may be included in a code. For example, certain codes may convey priority information or identify the type of data payload.

FIG. **104**B illustrates a network design that permits a plurality of communication paths to each node. Multiple network connections between a source node and a destination node may be provided for redundancy. Alternatively, each path may be selected based on one or more criteria, such as channel conditions and load balancing.

FIG. **104**C illustrates a network design adapted to provide array processing performance advantages. A plurality of nodes **10426**, **10427**, **10402**, **10420**, **10421**, and **10422** are adapted to provide complex-weighted transmissions to at least one destination node, such as nodes **10431** and **10432**. For example, a data sequence addressed to node **10431** is routed to nodes **10426**, **10427**, **10402**, **10420**, **10421**, and **10422**, which provide appropriate weights to the data transmission to generate a phase front **10441** that converges at the destination node **10431**. Similarly, appropriate delays or complex weights may be provided to transmissions to produce a coherent phase front **10442** that converges at destination node **10432**. Signals received by the nodes may be combined with respect to any combining technique, including optimal combining.

Nodes in a wireless network may generate weighted transmissions (or process received signals) to perform various types of array processing. Individual nodes may include one or more transceiver (e.g., antenna) elements. Array processing operations may include combinations of local and global processing. For example, diversity combining may be performed at each multi-element node and signals from each node may be combined in a central processor to perform sub-space processing. Other combinations of local and global processing may be employed.

Array processing may include space-time processing, space-frequency processing, beam forming, null steering, blind-adaptive processing, long baseline interferometry, frequency-diversity interferometry, etc. Array processing may be performed to achieve any combination of sub-space

processing (i.e., increased capacity) and diversity benefits (i.e., improved performance). Selection of transmitting and receiving nodes in an array-processing network can be adapted to changing node positions, network loads, throughput requirements, user services, bandwidth availability, frequency-reuse requirements, channel conditions, etc.

FIG. **105**A illustrates a concentric ring network configuration in which a base station **10500** or access point provides direct or indirect communication links to a plurality of subscriber units **10501** to **10535** arranged in a plurality of concentric-ring regions **10551** to **10553**. Subscriber units **10501** to **10506** in region **10551** are adapted to route signals to one or more subscriber units **10521** to **10535** in one or more regions, such as region **10553**. Similarly, subscriber units **10511** to **10518** in region **10552** may be adapted to route signals to subscribers in other regions. In some applications, one or more subscribers may be adapted to route signals to at least one other subscriber in the same region.

Region shapes and sizes may be adapted to numbers of users and/or the geographical distributions of the users. Similarly, regions may be adapted to balance network loads. For example, subscriber power consumption and processing requirements associated with routing signals through subscribers near the base **10500** can be mitigated by distributing routing operations over a larger number of subscribers. Thus, subscribers in regions **10551** and **10552** perform routing associated with a direct transmission from and/or to the base **10500**. Similarly, the number of subscribers in primary arteries of tree networks (or other networks) can be increased. Routing functions can be assigned to subscribers based on subscriber location, subscriber load, channel conditions, and network load. The network configuration illustrated in FIG. **105**A may be integrated with other network architectures, such as tree configurations.

FIG. **105**B illustrates a network configuration adapted to the geographic distribution of a plurality of subscribers **10521** to **10526** and **10531** to **10536** located along a roadway. In this case, there are two routing paths **10561** and **10562** provided by subscriber routing. Network configurations, including transmission paths, may be adapted to subscriber distributions and channel conditions. For example, urban channel environments are typically characterized by a waveguide grid. Thus, routing paths may be provided with a grid architecture in urban areas.

A transmission may include multiple levels of coding intended to be stripped off at each node along a predetermined path to a particular address. FIG. **106**A illustrates three nodes **10601**, **10602**, and **10604**. The first node is adapted to decode a one-rotation basic CI code by applying complex-conjugate decoding of the one-rotation code. A basic CI code on characterized by m rotations (m<N) is expressed by the following equation:

$$c_m = e^{im\phi'} \sum_{n=0}^{N-1} e^{imn2\pi/N} \hat{n}$$

The complex-conjugate decoding essentially unwinds the code. Similarly, nodes **10602** and **10604** are adapted to decode two-rotation and four-rotation codes, respectively. For simplicity, the rotations are provided in a common predetermined direction.

In one aspect of the invention, each node splits a received signal into at least two signals. At least one of the split signals is decoded at the node to extract any information intended for that node. A node may be associated with one or more addresses, or codes. At least one split signal is passed through the node without any decoding. Thus, node **10601** receives signals coded (or addressed) with one code rotation, node **10602** receives signals coded (or addressed) with two code rotations, etc.

In another aspect of the invention, a signal input to a node is not split prior to being decoded to extract any signals intended for that node. The decoded signal is then re-encoded with respect to the complex conjugate of the decoding operation. Thus, any unwinding associated with decoding is reversed prior to re-transmission of the coded information signal. Optionally, a node transceiver may cancel or otherwise remove signals addressed to itself prior to re-encoding.

In yet another aspect of the invention, coded transmissions are coded with respect to the intended path(s) to a predetermined address, thus obviating the need for splitting or re-encoding. For example, an information signal addressed to nodes **10602** and **10604** input to the first node **10601** is encoded with a pair of basic CI codes having three rotations and seven rotations, respectively:

$$r_{node901} = \sum_{n=0}^{N-1} (s_2(t)e^{i3n2\pi/N} + s_4(t)e^{i7n2\pi/N})\hat{n}$$

Decoding at the first node **10601** unwinds the coded signals by one rotation. The decode signal is characterized by C*(1), which is the complex conjugate of code C(1). Thus, node **10601** passes a coded information signal to node **10602** expressed by two-rotation and six-rotation codes:

$$r_{node902} = \sum_{n=0}^{N-1} (s_2(t)e^{i2n2\pi/N} + s_4(t)e^{i6n2\pi/N})\hat{n}$$

A sum of the decoded chips yields zero because there are no input signals coded with a single-rotation code. A sum of the chips generated at node **10601** is zero because the non-zero rotations cause the chip values to cancel. Decoding with decode signal C*(2) at node **10602** unwinds the coded signals by two rotations. Thus, a sum of the decoded signal at node **10602** coherently combines chip values associated with signal $s_2(t)$. Node **10602** produces a coded information signal expressed by:

$$r_{node904} = \sum_{n=0}^{N-1} (s_2(t) + s_4(t)e^{i4n2\pi/N})\hat{n}$$

The values $s_2(t)$ may optionally be removed (such as by cancellation, dc-offset removal, etc.) prior to transmission to node **10604**. A node transceiver at node **10602** may ensure non-zero chip values prior to transmission.

Coded signals received by node **10604** are processed with a complex-conjugate code C*(4) that unwinds the coded signal by four rotations. The resulting decoded signal is expressed by:

$$r_{node904'} = \sum_{n=0}^{N-1} s_4(t)\hat{n}$$

Decoding and summing the code chips at node **10604** coherently combines signal values $s_4(t)$ associated with a four-rotation code C(4).

FIG. **106**B illustrates a simple tree-style CI-based network. Nodes **10601**, **10602**, and **10604** are provided with decode signals corresponding to C*(1), C*(2), and C*(4), respectively. A branch node **10603** employs a decode signal C*(3) adapted to decode signals characterized by three rotations in a predetermined direction. A signal addressed with basic CI codes corresponding to rotations of seven, three, and six are input to node **10601**. Signals output by node **10601** to node **10602** correspond to rotations of six, two, and five. Node **10602** provides a decode signal of C*(2) to its input signal. Thus, the input corresponding to two rotations is decoded and the resulting value is processed at the node **10602**. The resulting output signal(s) from node **10602** is expressed by rotations as four, zero, three. The zero value may characterize a substantially null signal resulting from cancellation of the decoded signal at node **10602**.

Node **10602** may provide a broadcast signal to nodes **10603** and **10604**. Alternatively, node **10602** may duplicate the signal four, zero, three and provide a signal to each of the nodes **10603** and **10604**. In some cases, node **10602** may be adapted to separate its input signal into a plurality of components relative to addresses. Each component may be forwarded directly to its intended node. In some cases, separate signals may be provided via beam forming. In other cases, some form of multiple access, including header addresses, may be employed.

FIG. **106**C illustrates a simple multipath CI-based network. Node **10602** is provided with coded signals (expressed in rotations as 2,5,6,3,4). The value two is addressed to node **10602**. The values five and six are addressed to nodes **10603** and **10604**. A fourth node **10606** receives transmissions from nodes **10603** and **10604**. Thus, values three and four characterize paths through nodes **10603** and **10604**, respectively, that are addressed to node **10606**. Signals received and decoded at node **10606** may be combined coherently. Such combining may include optimal combining.

In some aspects of the invention, node **10606** may be provided with additional decode values (e.g., C*(5)) to enhance reception. Furthermore, two or more decode values (e.g., C*(6) and C*(5)) may be exploited in appropriate combinations to provide beam forming (or equivalent array processing) operations. Various combining operations may be provided to provide any combination of interference rejection, diversity enhancement, and sub-space processing (i.e., capacity enhancement).

FIG. **106**D illustrates a plurality of nodes **10601** to **10605** and at least two communication paths. A first communication path includes nodes **10602**, **10604** and **10605**. A second communication path includes nodes **10601**, **10603**, and **10605**. In this case, the two paths illustrate communication to node **5**. Alternatively communication paths may be provided indicating communications from node **10605**.

Signals arriving from the first communication path are encoded with at least one code $c_1(n)$. Similarly, the signals arriving from the second communication path are encoded with at least one code $c_2(n)$. In various applications of the invention, additional communication paths (not shown) may be provided.

The codes $c_1(n)$ and $c_2(n)$ may be address codes or they may include address codes. The codes $c_1(n)$ and $c_2(n)$ may be similar or different. Alternatively, the codes ci(n) and $c_2(n)$ may be separate (or different) from address codes. In some cases, address codes may be adapted to provide additional coding or achieve other objectives, such as, but not limited to, encryption, verification, authentication, identification, anti-jamming, and/or diversity benefits.

In one set of embodiments of the invention, redundant information signals or signals providing redundant information are routed along the multiple paths to the destination node **10605**. This can provide diversity benefits. The codes $c_1(n)$ and $c_2(n)$ may include similar or different channel codes. Signals provided along the multiple paths may be decoded (if necessary) and coherently combined in a receiver at the node **10605**. Combining may include one or more optimal-combining techniques. The number of transmission paths that are coherently combined is proportional to an effective processing gain of the combining process. Consequently, low-power information-bearing transmissions may be employed over the multiple transmission paths. Signals received from different paths may be processed via soft-decision processing to provide confidence measurements for symbol estimates and/or enhance channel compensation and/or decoding.

In another set of embodiments, each of a plurality of signals routed along different paths to a given node may provide necessary keys (or equivalent information) necessary for decoding. For example, signals routed along a first path may provide a coded information signal to a predetermined destination. Signals routed along a second path to the same destination may provide a decode sequence to decode the coded information signal. The codes $c_1(n)$ and $c_2(n)$ may include codes that are complex conjugates of each other. The first code $c_1(n)$ may include a public key and the second code $c_2(n)$ may include a private key wherein the two codes $c_1(n)$ and $c_2(n)$ contribute the necessary code keys for decoding a coded information signal transmitted along the first and/or second paths, or along a third path. Various pluralities of codes, paths, and/or coded information signals may be employed.

The process of providing multiple decoder keys across multiple transmission paths may be part of an authentication and/or verification process. The codes $c_1(n)$ and $c_2(n)$ may include channel-specific codes that characterize the channel between at least one transceiver and the destination node **10605**. The codes $c_1(n)$ and $c_2(n)$ may include channel compensation. Consequently, a channel analysis of received signals at the destination node **10605** will indicate the likelihood that the signals were transmitted from known nodes, such as nodes **10603** and **10604**. Similarly, channel analysis may be employed to determine the immediate originating node of a given transmission. The codes $c_1(n)$ and $c_2(n)$ may include beam-forming weights.

In some aspects of the invention, channel estimation may be performed on a signal received from a transceiver attempting to access the network. Various location-finding processes (e.g., direction-of-arrival determination, geo-location tracking, triangulation, etc.) may be implemented to determine the transceiver's location relative to a set or range of allowed locations. In some applications, identification of unauthorized users may be combined with location finding.

FIG. **106**E illustrates a node **10602** used in a plurality of crossing communication paths. Nodes **10601**, **10602**, and **10604** are part of a first communication path. Nodes **10611**, **10602**, and **10613** are part of a second communication path characterized by at least one unique diversity parameter value. In this case, the communication paths are distinguished by different carrier frequencies. Alternatively, communication paths may be differentiated by code, polarization, subspace, time, phase, subspace, or any combination thereof.

Although basic CI codes are illustrated in the exemplary network architectures, other types of codes (including, but not limited to, complex CI codes, Walsh codes, multi-code sets, multi-level (or stacked) codes, and/or codes derived from invertible transforms) may be implemented in the examples shown, as well as in variations, adaptations, permutations, and combinations of the exemplary network architectures. Network address codes may be employed for one or more additional functions, including, but not limited to, spread spectrum, multiple access, channel coding, and encryption. Network designs shown in the figures and described in the specification are intended to convey basic principles and various aspects of the invention. These network designs do not limit the scope of the invention. Consequently, various network designs may be considered as building blocks for complex network architectures.

Network designs and other aspects of the invention may be combined with prior-art network designs, systems, devices, protocols, formats, and/or methods. Such combinations are clearly anticipated and suggested. Aspects and embodiments of the invention may serve as portions of networks. Network designs, systems, and/or methods of the invention may be adapted to various types of networks, such as long-haul, short-haul, last-mile, local-area, metropolitan-area, sensor, RF-identification, tracking, ad-hoc, mobile radio, personal communication, cellular, airborne, air-ground, and/or satellite networks. Network architectures of the invention may include one or more types of multiple access. Network architectures of the invention may include any combination of addressing, including address codes and packet headers containing addresses.

FIG. **107**A illustrates a multi-level cellular architecture that may be employed by systems and methods of the present invention. At least one macro-cell **10721** is subdivided into one or more micro-cells **10731**. Various multiple-access techniques may be used to separate communications in different cells. For example, a predetermined code may be provided to transmissions within the macro-cell **10721**. Macro-cell codes may be provided for inter-cell multiple access or radio isolation. Micro-cell codes may be provided for intra-cell multiple access. Codes applied to transmissions may implement additional network functions, such as spread spectrum, encryption, authentication, channel coding, addressing, and/or interference mitigation.

In some applications, multi-level codes may be implemented. In some cases, macro-cell codes may provide greater processing gain than the micro-cell codes. For example, macro-cell codes may consist of long codes and micro-cell codes may consist of shorter channel codes and/or multiple-access codes. Either or both micro-cell codes and macro-cell codes may implement CI and/or CI-based coding. Coding may be implemented with, or as part of, array processing.

FIG. **107**B illustrates three cells **10721** to **10723** in a cellular network of the present invention. Each cell **10721** to **10723** employs a different long code C_{L1} to C_{L3}, respectively, to differentiate between communications in adjacent cells. Each cell **10721** to **10723** provides intra-cell communications with codes C_{s1-N} to differentiate between subscriber units in each cell. Coding may include CI and/or CI-based codes. Additional multiple-access techniques may be employed to provide for inter-cell and intra-cell multiple access.

FIG. **107**C shows a cellular architecture of the present invention that includes a plurality of cells **10721** to **10725** and a plurality of base stations **10701** to **10705** located on cell boundaries. The base stations **10701** to **10705** may include spatially sectorized antennas to provide communication to a plurality of cells. For example, base **10702** may be adapted to service users in cells **10721**, **10722**, and **10723**.

The base stations **10701** to **10705** may be adapted to route coded information across multiple cells. For example, coded data and/or control information is routed from base **10702** to base **10703**. A coded signal may be duplicated or decomposed for routing to multiple bases or subscriber units. For example, base **10703** transmits coded information to bases **10704** and **10705**. In some applications, subscriber units, such as subscriber units **10711** and **10712** may be employed to route information between two or more base stations. In any of the implementations of the invention, transmission paths through a network may be selected based on one or more criteria, including transceiver availability, transceiver locations, network loads, channel conditions, transmission-power requirements, etc.

FIG. **107**D illustrates a cellular network of the invention including a plurality of cells **10721** to **10730**, a plurality of base stations **10700** to **10709**, and a plurality of subscriber units, such as subscriber units **10761** to **10763** and **10771** to **10773**. In this case, the bases **10700** to **10709** are located inside each cell **10721** to **10730**. Other cellular architectures may be employed.

A base station (e.g., base **10700**) may route information directly to other bases (e.g., bases **10701**, **10702**, **10704**, **10705**, and **10706**). Such direct transmissions paths are indicated by transmission paths **10741** to **10745**. A direct transmission path l**0746** may be provided to a base (such as base **10709**) that is not adjacent to the originating base **10700**. A transmission between bases may be routed through intermediate bases. For example, base **10705** acts as a router for transmissions between base **10700** and bases **10707** and **10708**. Similarly, subscriber units (such as subscriber units **10771** and **10772** may be employed as routers for communications between bases (e.g., bases **10700** and **10703**), between subscribers, and/or between bases and subscribers.

FIG. **108**A illustrates a method for providing CI-coded transmissions of information and control signals. The method described in FIG. **108**A may be performed by a subscriber unit acting as a base station in a CI network. A CI code generation process **10801** provides CI codes and/or CI-based codes for at least one information signal and at least one control signal. A control signal may provide for one or more control functions, such as, but not limited to, power control, synchronization, code assignments, priority assignments, link assignments, channel assignments, duplexing control, training-signal generation, notice of transfer of control responsibilities, and request acknowledgement. Coding processes **10802** and **10803** encode the information signal(s) and control signal(s), respectively. A transmission process **10804** provides for transmission of the coded signals.

FIG. **108**B illustrates a method for managing network control in a CI network by one or more subscriber units adapted to function as base stations. A CI transceiver acting as a base station transmits CI-coded information and control signals in a transmission step **10810**. In a network identification and communication restriction step **10811**, CI codes can be used, at least in part, to address the communication and control channels. CI codes can be allocated to restrict communications between transceivers permitted to operate in the network. CI codes can also be used to identify a radio network and each of the radio devices, as well as the type of communications being transmitted.

A duplexing step **10812** provides for management of transmission and reception. Various types of duplexing may be employed, such as time-division duplexing, frequency-division duplexing, code-division duplexing, polarization-division duplexing, etc. A CI transceiver may include a plurality of CI decoders in parallel to allow reception of more than signal simultaneously. Similarly, transmission of coded signals may be performed simultaneous with reception when the transmitted CI codes differ from the code of the received signal. Furthermore, different CI codes may be used to encode transmissions to differentiate types of transmitted signals.

A network-control step **10813** indicates that at least one of the subscriber units becomes a network control station. A network control station initiates communications and maintains power control and time synchronization of the network in the same manner that a base station would normally function. A transfer step provides for transfer of network control from at least one subscriber to at least one different subscriber. The network control station can voluntarily transfer, or be commanded to transfer, power control and time synchronization of the network to any other radio in the network.

FIG. **108**C illustrates a network-control method of the present invention. A CI coding step **10821** provides different CI codes (such as may be used to spread a signal) to information and control signals. A network control station may provide time-division duplexing **10822** to regulate transmission and reception. A network-control step **10823** provides for network control by the network control station. Network control can include various operations, including, but not limited to, synchronization, power control, code assignment, channel assignments, channel coding, transmission-path selection, load balancing, and spectrum management.

FIG. **108**D shows a routing method of the present invention. A coding step **10831** provides a multi-address, CI-coded signal for transmission in a transmission step **10832**. The addresses may be provided by any combination of CI coding and header addressing. Transmitted signals may be routed via one or more paths through a network. A duplication step **10833** is provided when transmission paths through a node diverge. Duplicated signals are transmitted along their respective paths.

FIG. **109**A shows a relay method of the present invention. Received signal are decoded in a decoding step **10901** at each node. The decoding step **10901** involves applying a code to a received signal corresponding to the complex conjugate of the node's address code. A processing step **10902** processes information signals coded with the node's address codes. Processing **10902** may include summing the decoded symbols and performing hard and/or soft decisions. Information signals addressed to the node provide a dc offset to the symbols of the decoded signal. This offset may optionally be removed **10903** prior to transmitting **10905** the resulting decoded signals.

FIG. **109**B illustrates an alternative embodiment of a relay method of the invention. Some of the steps in the relay method shown in FIG. **109**B are similar to the steps shown in FIG. **109**A, as indicated by similar reference numbers. A reverse-decoding step **10904** provided between steps **10903** and **10905** applies the complex conjugate of any codes applied to the received signals in the decoding step **10902**.

FIG. **110**A illustrates a transceiver processing and routing method of the invention. A decoding step **11001** processes received signals with at least one complex-conjugate code corresponding to at least one address code associated with the transceiver address and/or one or more predetermined addresses. Decoding **11001** may include one or more decoding processes, such as channel decoding, multiple-access decoding, spread-spectrum decoding, and decryption. The decoding step **11001** may optionally include a level-detect function (not shown) to verify that a received signal is present prior to decoding.

A processing step **11002** is adapted to provide one or more signal-processing steps to the decoded signals. The processing step **11002** may estimate the values of information or control signals impressed onto address codes corresponding to the complex-conjugate code(s) provided in the decoding step **11001**. For example, an adding step (not shown) may provide for coherent combining of addressed information symbols. A decision step (not shown) may follow the adding step (not shown). If any signal values are present, they may be passed to an optional error detection/correction step **11011**.

Error detection/correction **11011** may employ parity checks, trellis demodulation, convolutional decoding, block decoding, and/or any other channel decoding or error-checking technique. Errors may be corrected via receiver-side processing. Alternatively, error detection may initiate a request for re-transmission. Error detection/correction **11011** may include re-quantization, channel estimation, channel compensation, predistortion of transmissions, multi-user detection, and/or optimal combining. Error detection/correction **11011** may include decision processing, including hard decisions and/or soft decisions. Decision processing may include iterative feedback processing, such as turbo decoding.

The signal values may be provided to an optional system-function step **11012**. Confidence measures from soft-decision processes may be used to adapt receiver parameters (e.g., the processing step **11002**), such as to optimize reception. Similarly, received control information may be used to adjust receiver parameters. System functions **11012** may include automatic gain control, adapting filter parameters, adjusting quantization constellations, and/or changing sampling parameters. System functions may also include removing symbols or values associated with one or more predetermined addresses from the input signal values.

The signal values may be provided to an optional network-function step **11013**. Network functions **11013** may be selected or adapted relative to received control information. Network functions **11013** may include routing, addressing, power control, synchronization, request re-transmission, multiple-access control, channel selection, authentication, verification, identification, link-priority assignments, load balancing, spectrum management, and/or error processing. Network functions **11013** may include adding, removing, and/or changing system control information.

Data and control information are re-encoded in a coding step **11004**. Re-encoding **11004** may include the application of one or more codes, including address codes, multiple-access codes, spreading codes, channel codes, and encryption. Coded signals are processed for transmission into a communication channel in a transmission step **11005**.

FIG. **110**B illustrates a transceiver processing and routing method of the invention. A received signal is duplicated in a duplication step **11000**. At least one duplicated signal is coupled into a decoding step **11021** that applies a complex-conjugate code to the received signal. The complex-conjugate code is related to the address code of the transceiver. The decoded signal is processed in a processing step **11022** to extract or otherwise estimate information values addressed to the transceiver.

At least one of the duplicated signals is input to a secure procedure **11010**. For example, the at least one duplicated signal is passed through a fire wall (not shown). A decoding step **11016** provides for decoding signals addressed to one or more destinations other than the current transceiver. A processing step **11018** is adapted to provide one or more signal-processing steps to the decoded signals. The processing step **11018** may estimate the values of information or control signals impressed onto address codes corresponding to the complex-conjugate code(s) provided in the decoding step **11010**.

Processed signals may be coupled to one or more optional processing steps, including error detection/correction **11011**, system function **11012**, and network function **11013** steps. The processed signals are encoded **11014** prior to being transmitted **11005**. Similarly, data input to the transceiver is encoded **11024** prior to being transmitted **11005**.

FIG. **111**A illustrates a method of receiving, processing, and re-transmitting signals. A receiving process **11101** provides reception of one or more signals received from one or more communication channels (not shown). The received signals are sampled in a sampling process **11103** with respect to a plurality of sampling parameters that are selected **11102** or predetermined.

Sampling parameters may include sample width, sample rate, sample duration, sample shape, and/or number of samples per symbol. One or more sampling parameters may be selected relative to characteristics of the received signal (s). For example, a multicarrier signal may be sampled in such a way as to generate symbols corresponding to the received sub-carrier channels. Alternatively, a single-carrier signal may be sampled with respect to a CI-signal generation algorithm adapted to generate a plurality of CI components from the single-carrier signal. Other signal characteristics that may be used to determine sampling parameters include carrier frequency, bandwidth, signal strength, noise, and/or interference levels.

The samples are provided for CI processing **11104** to generate a plurality of CI components. CI-component generation **11104** may include a Fourier transform operation. CI components may include CI signals and/or CI signal values. The CI components are combined in a combining process **11105** that may include a plurality of parallel combining processes. The combined CI components produce data symbols, such as data symbols indicative of high-rate, broadband, symbols received from a single-carrier signal.

The data symbols are processed in a data symbol processing step **11106** that may include one or more signal-processing steps **11110**, including, but not limited to, symbol analysis, symbol blocking, symbol insertion, interception of symbols, symbol-stream and/or packet addressing, symbol redirection, and/or symbol generation. The data symbol processing step **11106** may include a plurality of parallel processes. For example, a plurality of parallel low-speed CI combining processes that produce a plurality of data symbols can be coupled to a plurality of low-speed, data symbol processing steps.

A CI component generation step **11107** provides for generation of a plurality of CI components from the processed data symbols. Alternatively, a parallel-to-serial process (not shown) may be employed to generate a high-rate data-symbol sequence that is coupled to a transmission system **11108**. In the present example, CI components are provided to the transmission system **11108** for processing and coupling into at least one communication channel (not shown). The CI components may be processed with an inverse-Fourier transform to generate a high-rate, time-domain signal.

FIG. **111**B illustrates a system adapted to receive, process, and re-transmit signals according to the method outlined in FIG. **111**A. A receiver system **11121** processes transmitted signals received from one or more communication channels (not shown). The processed signals may optionally be filtered by an anti-aliasing filter **11122** prior to being coupled into a sub-carrier generator, such as a Fourier transform processor **11123**. CI components generated by the processor **11123** are provided to a combining system **11124** to generate a plurality of data symbols. The combining system **11124** may include a plurality of combiners adapted to operate in parallel. Similarly, a data processor **11125** may be adapted to process the data symbols via a plurality of simultaneous parallel operations.

A CI symbol generator **11126** generates a plurality of CI symbols from the processed data symbols. The CI symbols are impressed onto a plurality of carriers, such as by an inverse Fourier transform **11127**, which generates a high-rate, time-domain signal. Alternative one or more systems may be employed that generate a high-rate data stream from the processed data symbols. The data stream is provided to a transmission system **11128** adapted to process the data stream for transmission into at least one communication channel (not shown).

Scope of the Invention

In the preferred embodiments, several kinds of carrier interferometry, coding, filtering, and spatial processing are demonstrated to provide a basic understanding of applications of CI processing. With respect to this understanding, many aspects of this invention may vary. For example, signal spaces and diversity parameters may include redundantly modulated signal spaces. Descriptions of spatial processing may be applied to processing methods for non-spatial diversity parameters. Descriptions of systems and methods using spatial subspaces may be extended to systems and methods that use non-spatial subspaces.

For illustrative purposes, flowcharts and signal diagrams represent the operation of the invention. It should be understood, however, that the use of flowcharts and diagrams is for illustrative purposes only, and is not limiting. For example, the invention is not limited to the operational embodiment(s) represented by the flowcharts. The invention is not limited to specific signal architectures shown in the drawings. Instead, alternative operational embodiments and signal architectures will be apparent to persons skilled in the relevant art(s) based on the discussion contained herein. Also, the use of flowcharts and diagrams should not be interpreted as limiting the invention to discrete or digital operation.

In practice, as will be appreciated by persons skilled in the relevant art(s) based on the discussion herein, the invention can be achieved via discrete or continuous operation, or a combination thereof. Furthermore, the flow of control represented by the flowcharts is provided for illustrative purposes only. As will be appreciated by persons skilled in the relevant art(s), other operational control flows are within the scope and spirit of the present invention.

Exemplary structural embodiments for implementing the methods of the invention are also described. It should be understood that the invention is not limited to the particular embodiments described herein. Alternate embodiments (equivalents, extensions, variations, deviations, combinations, etc.) of the methods and structural embodiments of the invention and the related art will be apparent to persons

skilled in the relevant arts based on the teachings contained herein. The invention is intended and adapted to include such alternate embodiments. Such equivalents, extensions, variations, deviations, combinations, etc., are within the scope and spirit of the present invention.

Signal processing with respect to sinusoidal oscillating signals are described herein. Those skilled in the art will recognize that other types of periodic oscillating signals that can be used, including, but not limited to, sinusoids, square waves, triangle waves, wavelets, repetitive noise waveforms, pseudo-noise signals, and arbitrary waveforms.

The foregoing discussion and the claims that follow describe the preferred embodiments of the present invention. With respect to the claims, it should be understood that changes can be made without departing from the essence of the invention. To the extent such changes embody the essence of the present invention, each naturally falls within the breadth of protection encompassed by this patent. This is particularly true for the present invention because its basic concepts and understandings are fundamental in nature and can be broadly applied.

The invention claimed is:

1. A method of communication in a wireless communication network that employs a first set of complex-valued codes to encode data symbols to be transmitted, and employs a second set of complex-valued codes to recover transmitted data symbols from a received signal, the method comprising:

selecting a plurality of subcarriers to be transmitted;

encoding the data symbols with the first set of complex-valued codes to produce encoded data symbols;

applying the encoded data symbols to the plurality of subcarriers to produce a spread-Orthogonal Frequency Division Multiplexing (OFDM) signal; and

transmitting the spread-OFDM signal;

wherein the first set of complex-valued codes are complex conjugates of the second set of complex-valued codes.

2. The method of claim **1**, wherein selecting is responsive to spectrum allocation or is configured to provide for orthogonal frequency division multiple access.

3. The method of claim **1**, wherein selecting comprises selecting subcarrier frequency spacing.

4. The method of claim **1**, wherein an inverse discrete Fourier transform (IDFT) produces the spread-OFDM signal, and selecting comprises providing a set of zero and non-zero values to input frequency bins of the IDFT.

5. The method of claim **1**, wherein selecting comprises selecting subcarriers for control signaling or pilot tones.

6. The method of claim **1**, wherein the plurality of subcarriers are contiguous subcarriers or interleaved subcarriers.

7. The method of claim **1**, wherein encoding comprises multiplying a vector or matrix of data symbols with a vector or matrix comprising the first set of complex-valued codes.

8. The method of claim **1**, wherein applying comprises modulating the encoded data symbols onto the plurality of subcarriers.

9. The method of claim **1**, further comprising adding a cyclic prefix to the spread-OFDM signal before transmitting the spread-OFDM signal.

10. An apparatus for communication in a wireless communication network that employs a first set of complex-valued codes to encode data symbols to be transmitted, and employs a second set of complex-valued codes to recover transmitted data symbols from a received signal, the apparatus comprising:

at least one processor; and

a non-transitory computer-readable memory communicatively coupled to the at least one processor, the non-transitory computer-readable memory including a set of instructions stored thereon and executable by the at least one processor for:

selecting a plurality of subcarriers to be transmitted;

encoding the data symbols with the first set of complex-valued codes to produce encoded data symbols;

applying the encoded data symbols to the plurality of subcarriers to produce a spread-Orthogonal Frequency Division Multiplexing (OFDM) signal; and

transmitting the spread-OFDM signal;

wherein the first set of complex-valued codes are complex conjugates of the second set of complex-valued codes.

11. The apparatus of claim **10**, wherein selecting is responsive to spectrum allocation or is configured to provide for orthogonal frequency division multiple access.

12. The apparatus of claim **10**, wherein selecting comprises selecting frequency spacing of the plurality of subcarriers.

13. The apparatus of claim **10**, wherein an inverse discrete Fourier transform (IDFT) produces the spread-OFDM signal, and selecting comprises providing a set of zero and non-zero values to input frequency bins of the IDFT.

14. The apparatus of claim **10**, wherein selecting comprises selecting subcarriers for control signaling or pilot tones.

15. The apparatus of claim **10**, wherein the plurality of subcarriers are contiguous subcarriers or interleaved subcarriers.

16. The apparatus of claim **10**, wherein encoding comprises multiplying a vector or matrix of data symbols with a vector or matrix comprising the first set of complex-valued codes.

17. The apparatus of claim **10**, wherein applying comprises modulating the encoded data symbols onto the plurality of subcarriers.

18. The apparatus of claim **10**, wherein the non-transitory computer-readable memory further includes instructions stored thereon and executable by the processor for adding a cyclic prefix to the spread-OFDM signal before transmitting the spread-OFDM signal.

19. A computer program product for operating a transmitter in a wireless communication network that employs a first set of complex-valued codes to encode data symbols to be transmitted, and employs a second set of complex-valued codes to recover transmitted data symbols from a received signal, the computer program product comprising a non-transitory computer readable storage device having computer readable program code stored therein, said program code containing instructions executable by one or more processors of a computer system for:

selecting a plurality of subcarriers to be transmitted;

encoding the data symbols with the first set of complex-valued codes to produce encoded data symbols;

applying the encoded data symbols to the plurality of subcarriers to produce a spread-Orthogonal Frequency Division Multiplexing (OFDM) signal; and

transmitting the spread-OFDM signal;

wherein the first set of complex-valued codes are complex conjugates of the second set of complex-valued codes.

20. The computer program product of claim **19**, wherein selecting is responsive to spectrum allocation or is configured to provide for orthogonal frequency division multiple access.

21. The computer program product of claim 19, wherein selecting comprises selecting frequency spacing of the plurality of subcarriers.

22. The computer program product of claim 19, wherein an inverse discrete Fourier transform (IDFT) produces the spread-OFDM signal, and selecting comprises providing a set of zero and non-zero values to input frequency bins of the IDFT.

23. The computer program product of claim 19, wherein selecting comprises selecting subcarriers for control signaling or pilot tones.

24. The computer program product of claim 19, wherein the plurality of subcarriers are contiguous subcarriers or interleaved subcarriers.

25. The computer program product of claim 19, wherein encoding comprises multiplying a vector or matrix of data symbols with a vector or matrix comprising the first set of complex-valued codes.

26. The computer program product of claim 19, wherein applying comprises modulating the encoded data symbols onto the plurality of subcarriers.

27. The computer program product of claim 19, wherein said program code further includes instructions executable by the one or more processors of the computer system for adding a cyclic prefix to the spread-OFDM signal before transmitting the spread-OFDM signal.

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(54) **WIRELESS COMMUNICATIONS USING FLEXIBLE CHANNEL BANDWIDTH**

(71) Applicant: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

(72) Inventor: **Steve Shattil**, Cheyenne, WY (US)

(73) Assignee: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

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None
See application file for complete search history.

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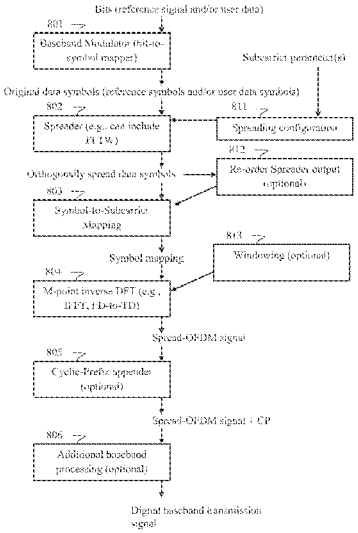
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Primary Examiner — Diane L Lo
(74) *Attorney, Agent, or Firm* — Steven J Shattil

(57) **ABSTRACT**

The disclosure relates in some aspects to providing a flexible channel bandwidth in a mobile radio communications network. For example, wherein a consecutive series of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers may be provisioned for uplink or downlink communications, a flexible frame structure may be provided by provisioning different subcarrier spacings for the consecutive series of OFDM subcarriers. The different subcarrier spacings may be used for transmitting and/or receiving OFDM signals.

24 Claims, 14 Drawing Sheets



Related U.S. Application Data

continuation of application No. 15/149,382, filed on May 9, 2016, now Pat. No. 9,628,231, which is a continuation-in-part of application No. 14/727,769, filed on Jun. 1, 2015, which is a continuation of application No. 14/276,309, filed on May 13, 2014, now Pat. No. 9,048,897, which is a continuation of application No. 12/545,572, filed on Aug. 21, 2009, now Pat. No. 8,750,264, which is a division of application No. 11/187,107, filed on Jul. 22, 2005, now Pat. No. 8,670,390.

(60) Provisional application No. 60/598,187, filed on Aug. 2, 2004.

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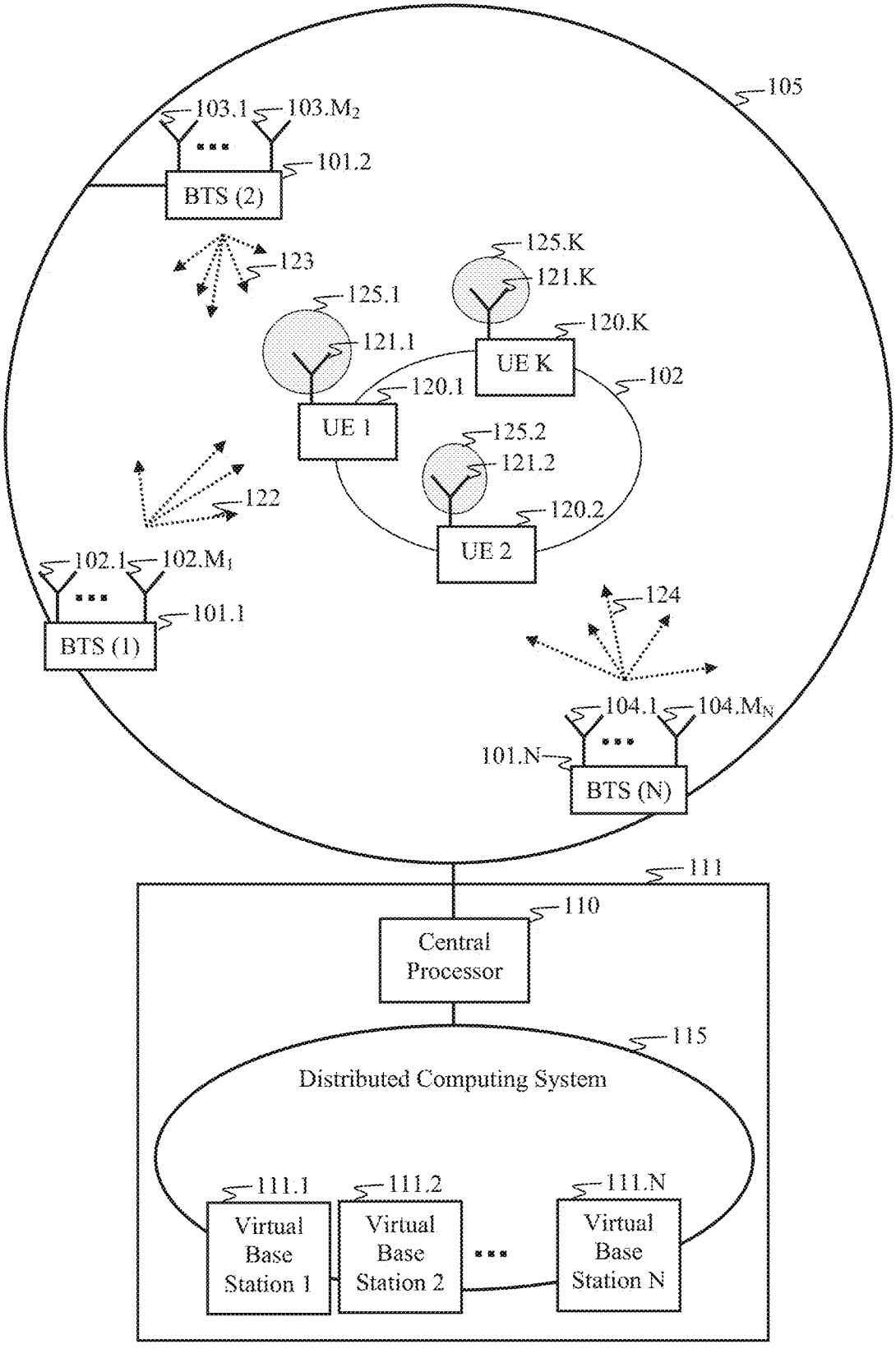

105
103.1
103.M2
101.2
BTS (2)
123
125.K
121.K
125.1
121.1
120.K
UE K
102
120.1
UE 1
125.2
121.2
122
120.2
UE 2
102.1
102.M1
101.1
BTS (1)
124
104.1
104.MN
101.N
BTS (N)
111
110
Central Processor
115
Distributed Computing System
111.1
111.2
111.N
Virtual Base Station 1
Virtual Base Station 2
Virtual Base Station N

Figure 1

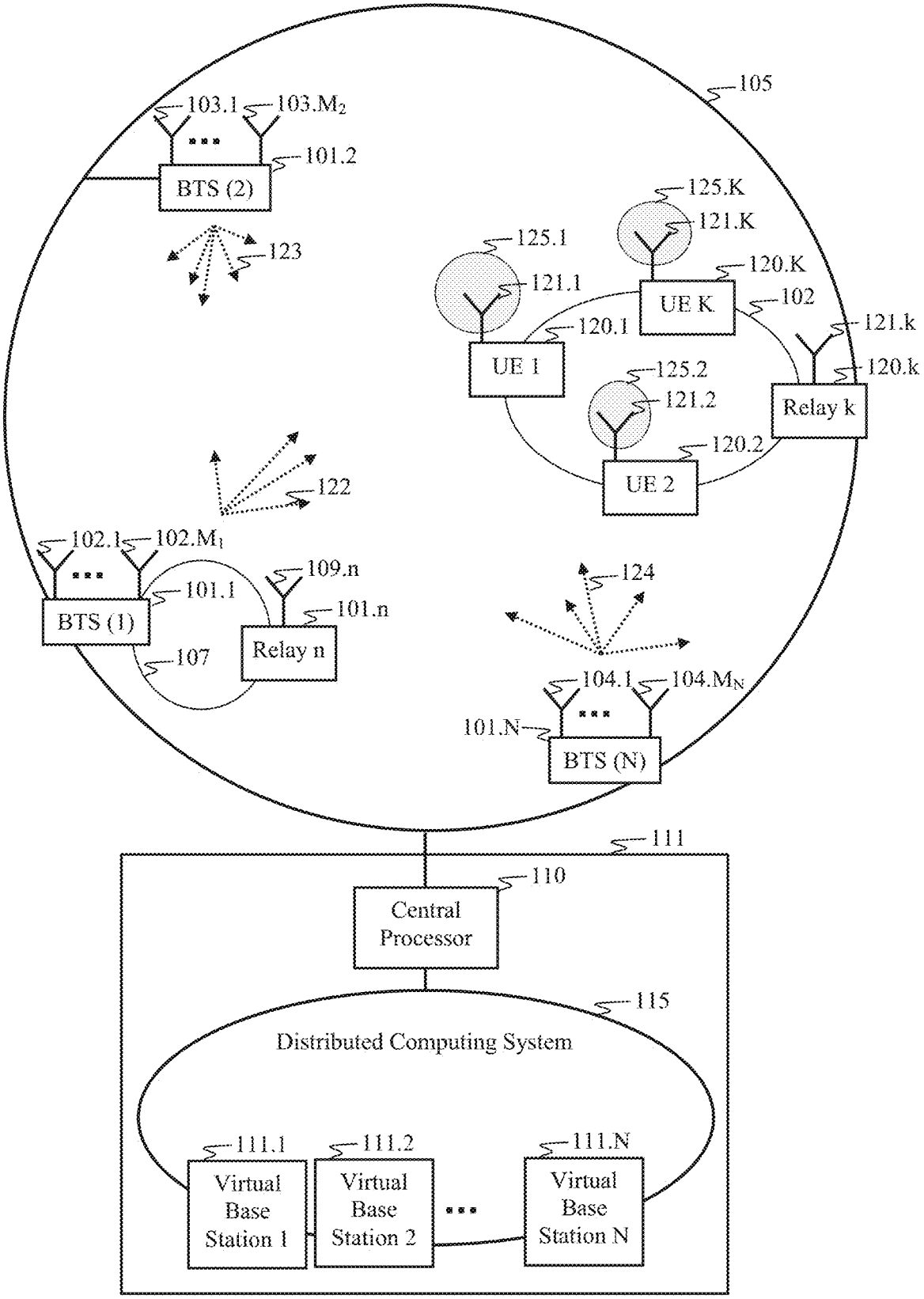

105
103.1
103.M2
101.2
BTS (2)
123
125.K
121.K
125.1
121.1
120.K
UE K
102
120.1
121.k
UE 1
125.2
120.k
121.2
Relay k
120.2
UE 2
122
102.1
102.M1
109.n
101.1
101.n
BTS (1)
Relay n
107
124
104.1
104.MN
101.N
BTS (N)
111
110
Central Processor
115
Distributed Computing System
111.1
111.2
111.N
Virtual Base Station 1
Virtual Base Station 2
Virtual Base Station N

Figure 2

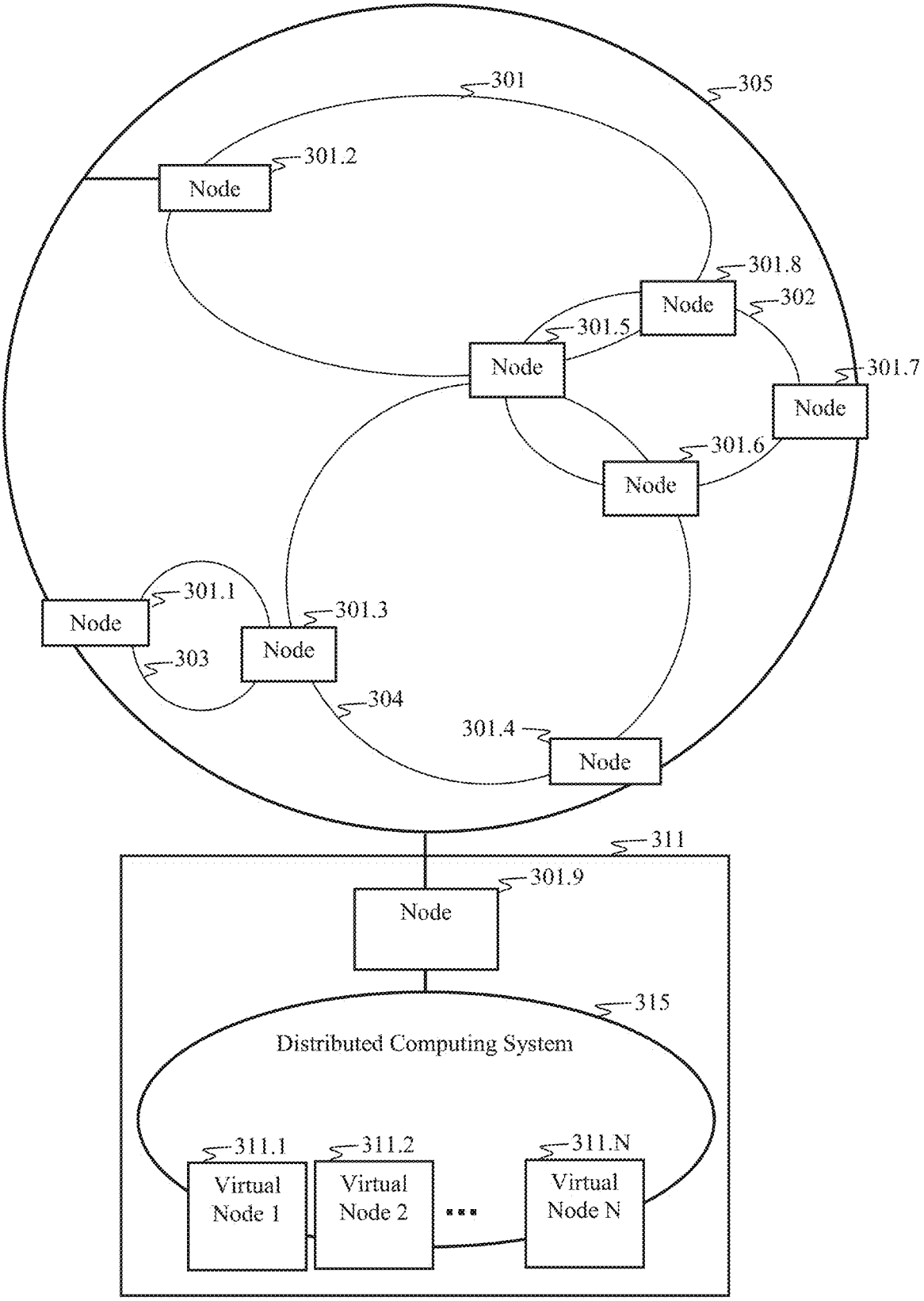

301
305
301.2
Node
301.8
Node
302
301.5
Node
301.7
Node
301.6
Node
301.1
Node
303
301.3
Node
304
301.4
Node
311
301.9
Node
315
Distributed Computing System
311.1
Virtual Node 1
311.2
Virtual Node 2
311.N
Virtual Node N

Figure 3

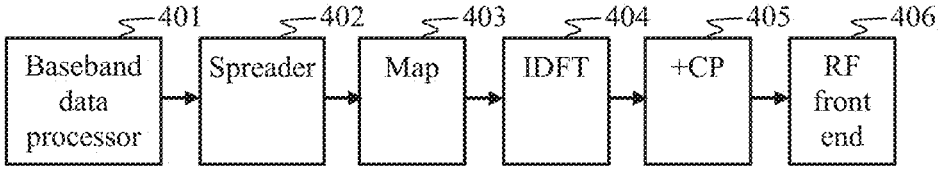


Figure 4A

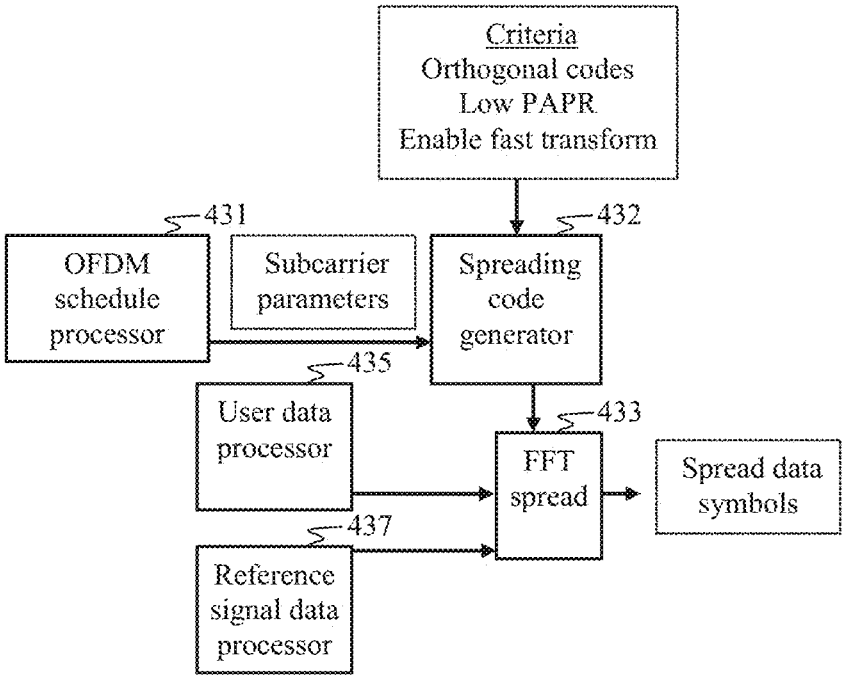


Figure 4B

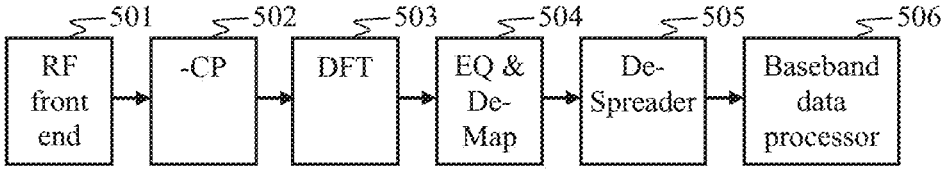


Figure 5A

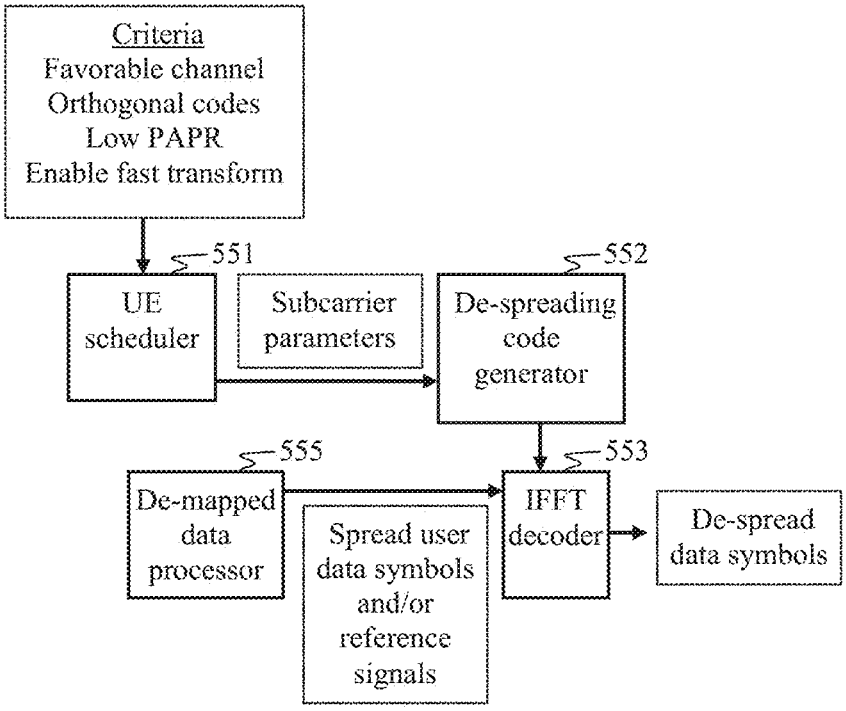


Figure 5B

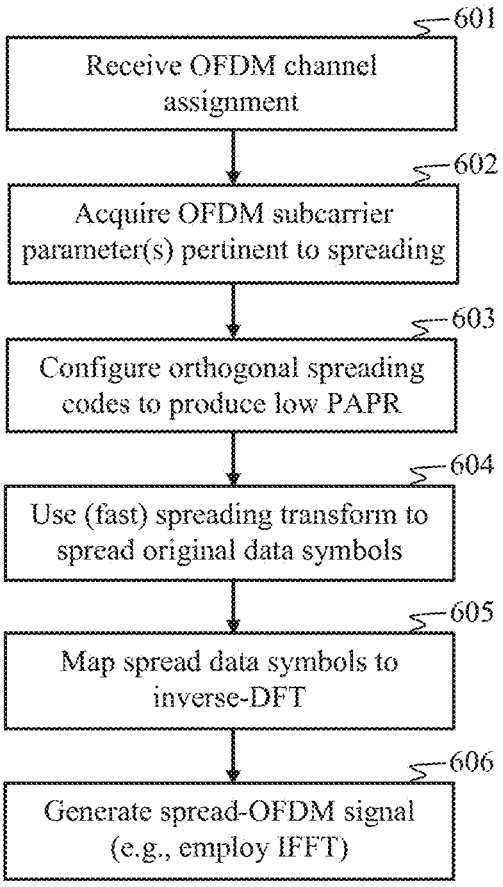


Figure 6A

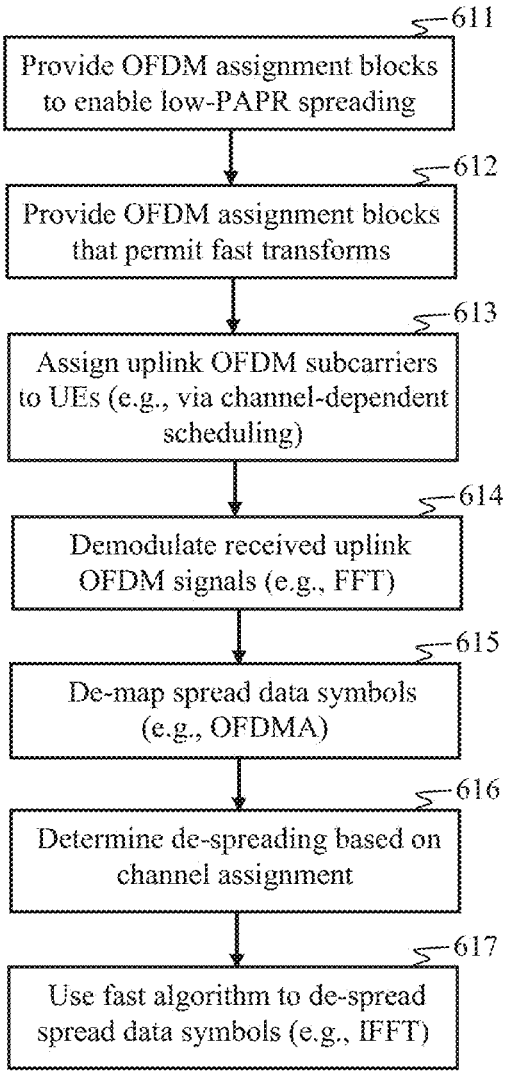


Figure 6B

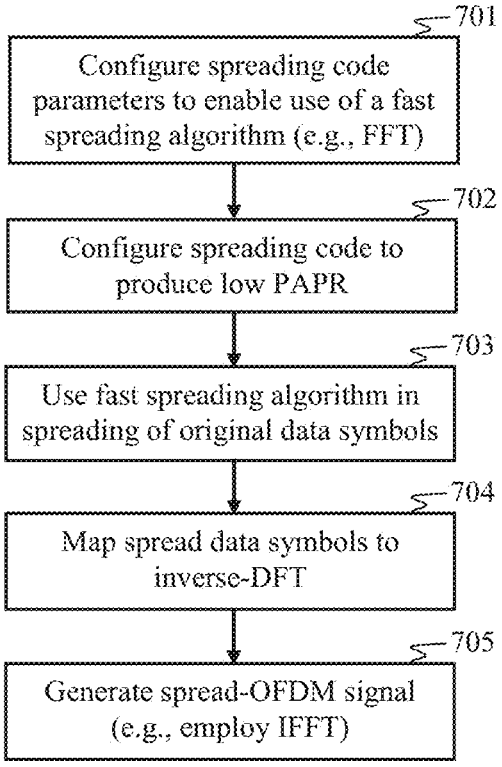


Figure 7A

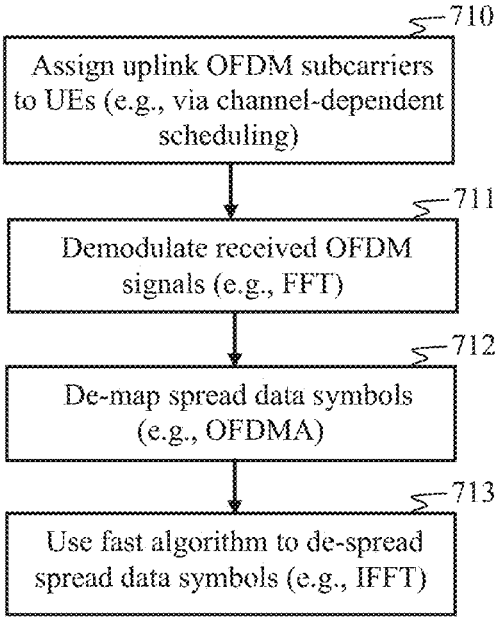


Figure 7B

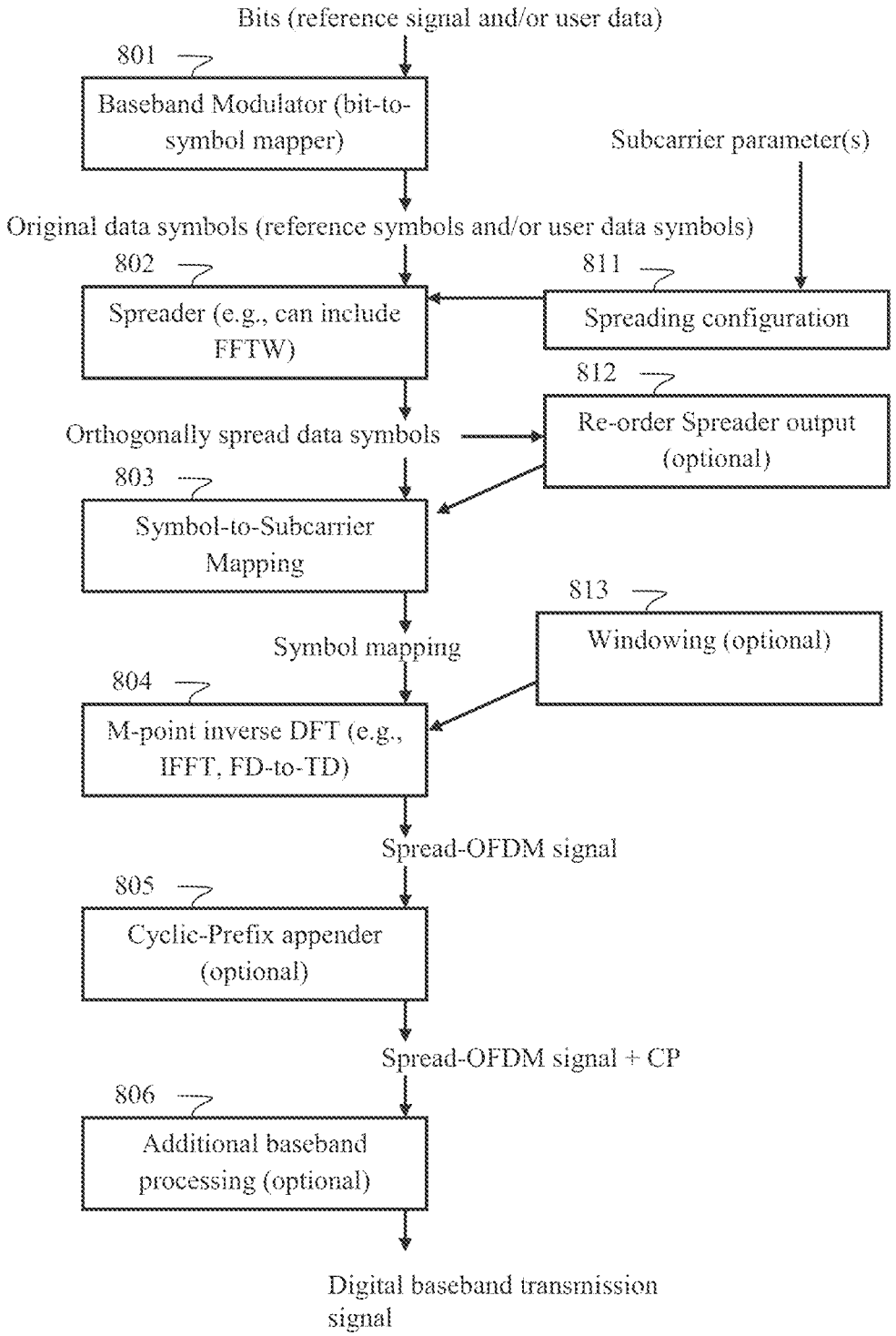

Bits (reference signal and/or user data)
801
Baseband Modulator (bit-to-symbol mapper)
Subcarrier parameter(s)
Original data symbols (reference symbols and/or user data symbols)
802
Spreader (e.g., can include FFTW)
811
Spreading configuration
812
Re-order Spreader output (optional)
Orthogonally spread data symbols
803
Symbol-to-Subcarrier Mapping
813
Windowing (optional)
Symbol mapping
804
M-point inverse DFT (e.g., IFFT, FD-to-TD)
Spread-OFDM signal
805
Cyclic-Prefix appender (optional)
Spread-OFDM signal + CP
806
Additional baseband processing (optional)
Digital baseband transmission signal

Figure 8A

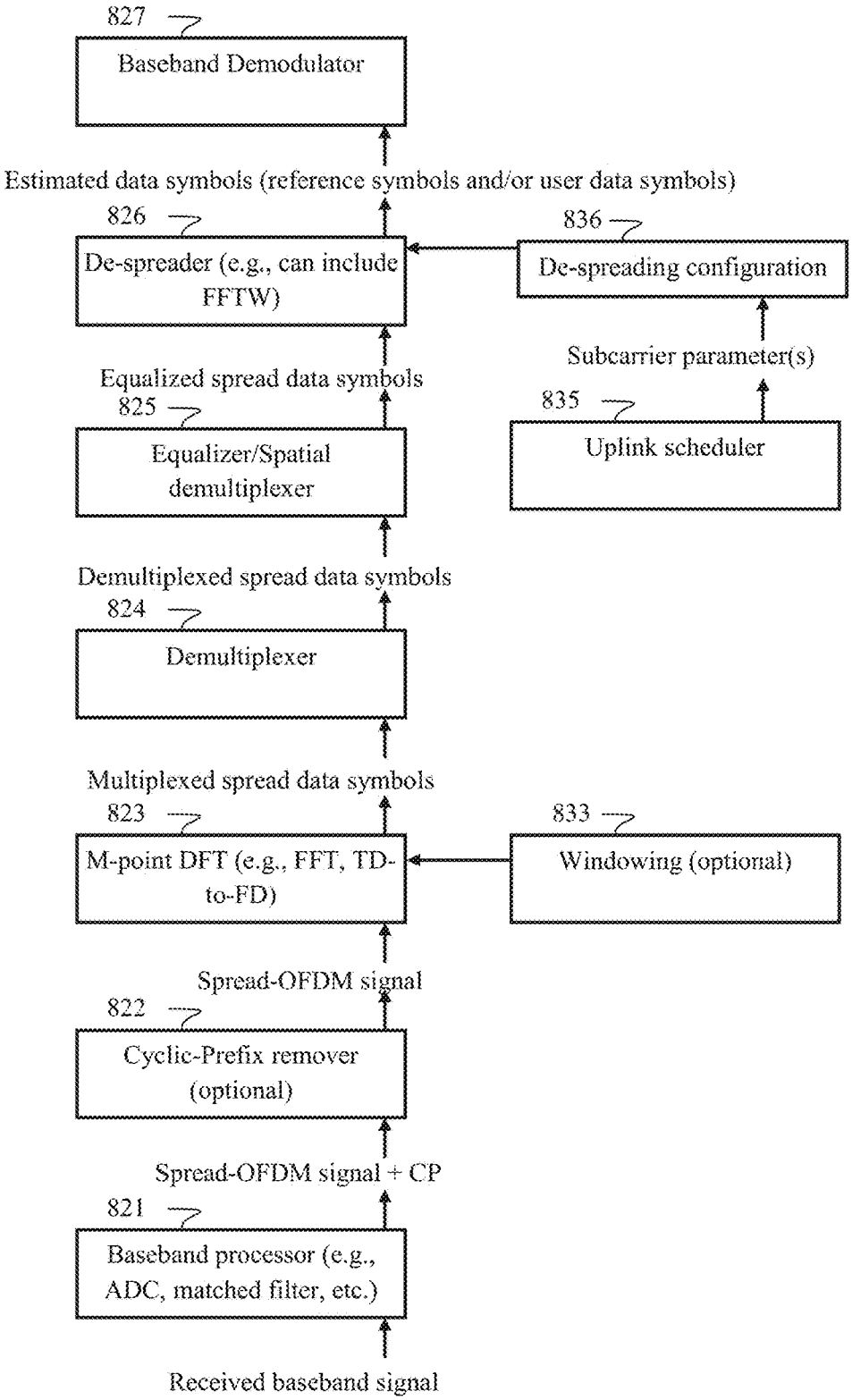

827
Baseband Demodulator
Estimated data symbols (reference symbols and/or user data symbols)
826
De-spreader (e.g., can include FFTW)
836
De-spreading configuration
Subcarrier parameter(s)
Equalized spread data symbols
825
Equalizer/Spatial demultiplexer
835
Uplink scheduler
Demultiplexed spread data symbols
824
Demultiplexer
Multiplexed spread data symbols
823
M-point DFT (e.g., FFT, TD-to-FD)
833
Windowing (optional)
Spread-OFDM signal
822
Cyclic-Prefix remover (optional)
Spread-OFDM signal + CP
821
Baseband processor (e.g., ADC, matched filter, etc.)
Received baseband signal

Figure 8B

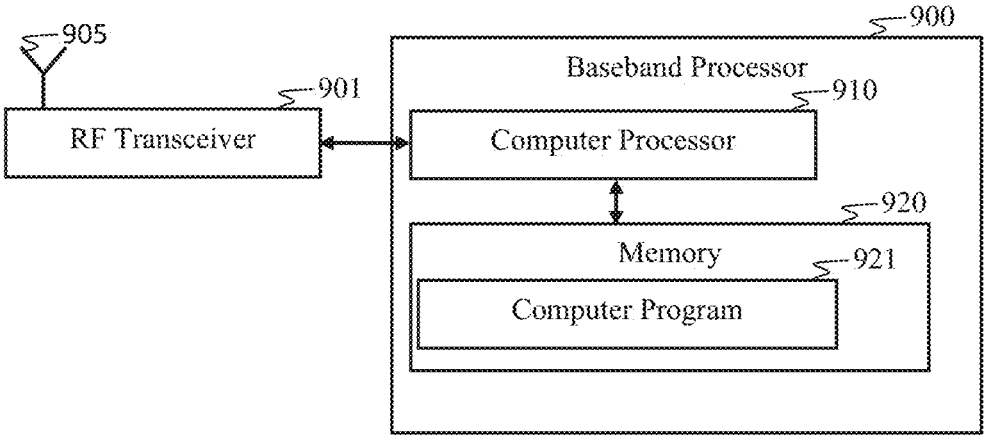

905
900
Baseband Processor
901
910
RF Transceiver
Computer Processor
920
Memory
921
Computer Program

Figure 9

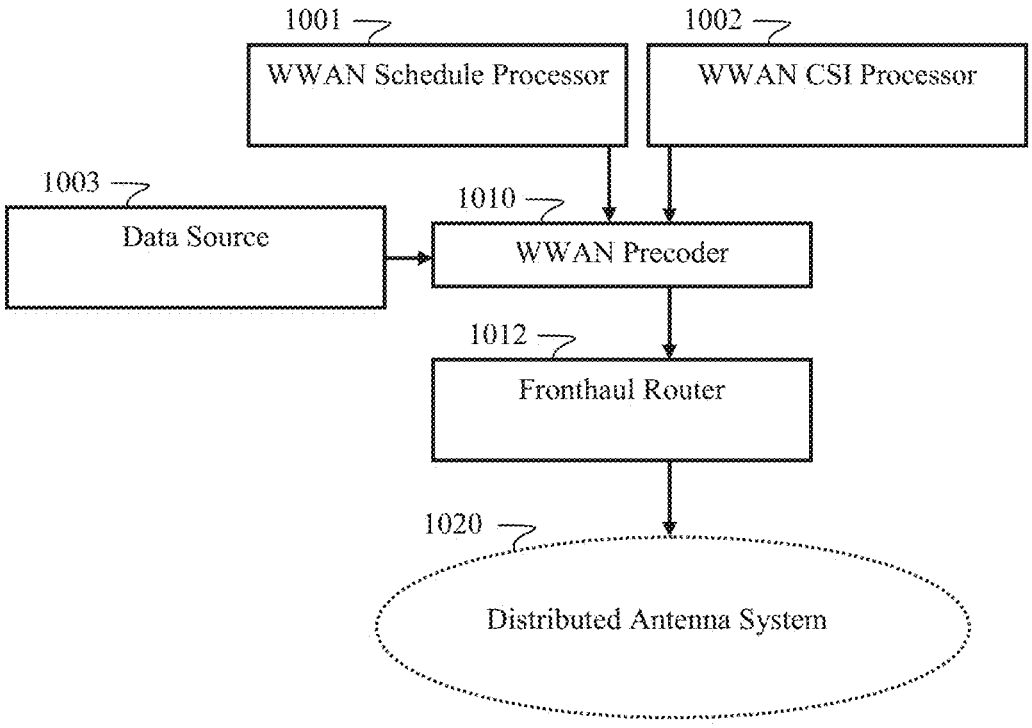

1001
WWAN Schedule Processor
1002
WWAN CSI Processor
1003
Data Source
1010
WWAN Precoder
1012
Fronthaul Router
1020
Distributed Antenna System

Figure 10A

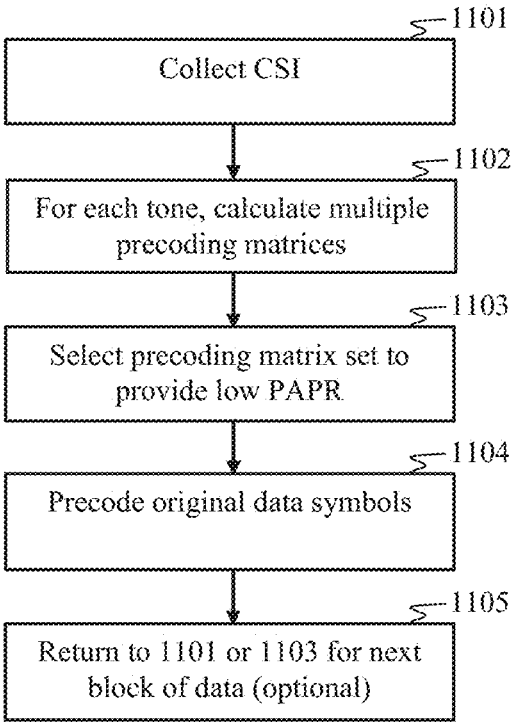


Figure 11

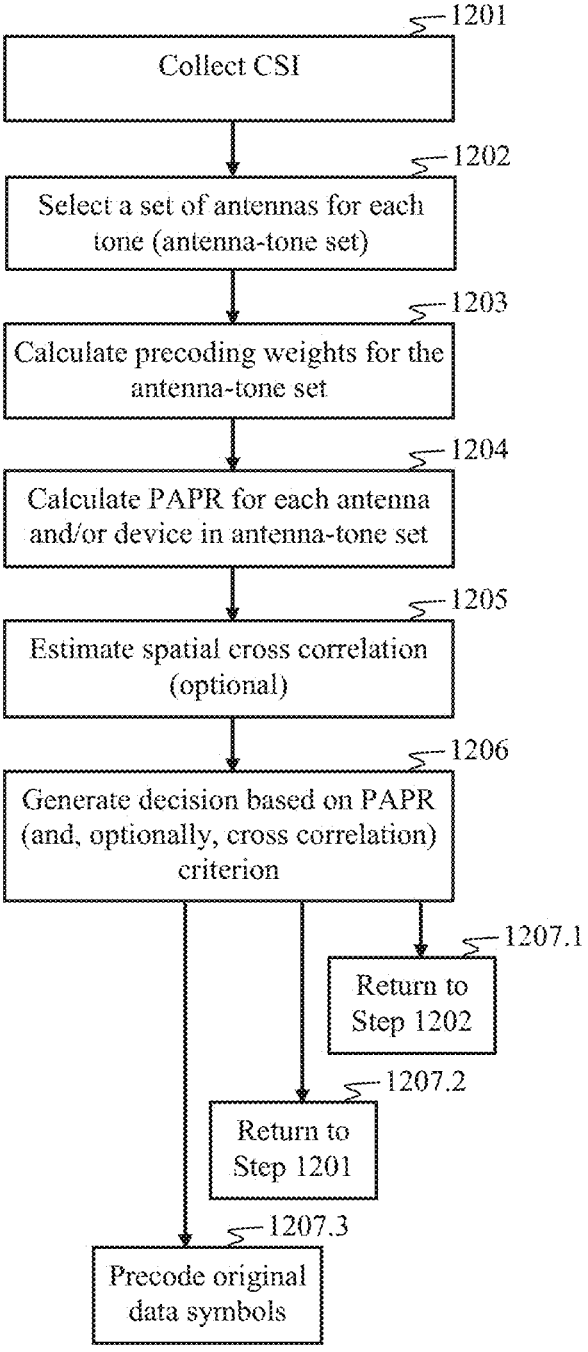


Figure 12

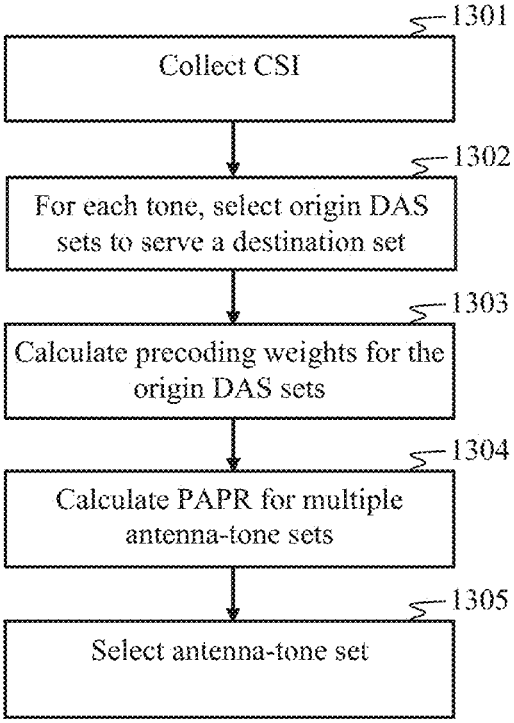

1301
Collect CSI
1302
For each tone, select origin DAS sets to serve a destination set
1303
Calculate precoding weights for the origin DAS sets
1304
Calculate PAPR for multiple antenna-tone sets
1305
Select antenna-tone set

Figure 13

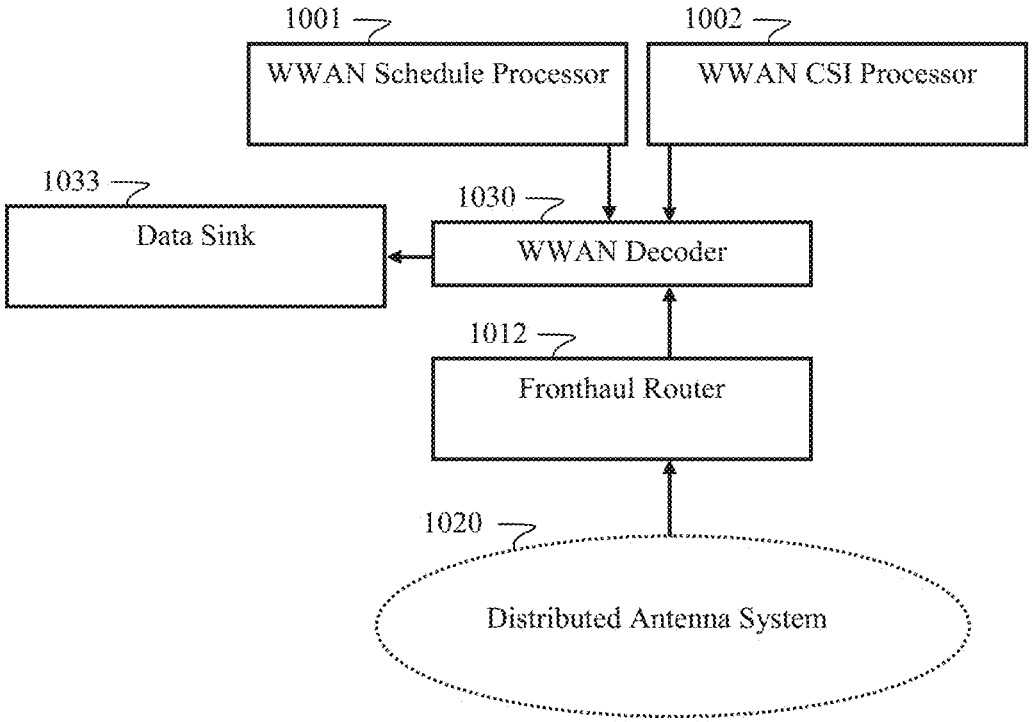

1001
WWAN Schedule Processor
1002
WWAN CSI Processor
1033
Data Sink
1030
WWAN Decoder
1012
Fronthaul Router
1020
Distributed Antenna System

Figure 10B

WIRELESS COMMUNICATIONS USING FLEXIBLE CHANNEL BANDWIDTH

RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 16/426,240, filed on May 30, 2019, which is a continuation of U.S. patent application Ser. No. 15/786,270, filed on Oct. 17, 2017, now U.S. Pat. No. 10,389,568, which is a continuation of U.S. patent application Ser. No. 15/489,664, filed on Apr. 17, 2017, now U.S. Pat. No. 9,800,448, which is a continuation of U.S. patent application Ser. No. 15/149,382, filed on May 9, 2016, now U.S. Pat. No. 9,628,231, which is a continuation-in-part of U.S. patent application Ser. No. 14/727,769, filed Jun. 1, 2015, which is a continuation of U.S. patent application Ser. No. 14/276,309, filed May 13, 2014, now U.S. Pat. No. 9,048,897, which is a continuation U.S. patent application Ser. No. 12/545,572, filed Aug. 21, 2009, now U.S. Pat. No. 8,670,390, which is a division of U.S. patent application Ser. No. 11/187,107, filed on Jul. 22, 2005, now U.S. Pat. No. 8,670,390, which claims priority to U.S. Provisional Patent Application No. 60/598,187, filed Aug. 2, 2004, all of which are hereby incorporated by reference in their entireties and all of which this application claims priority under at least 35 U.S.C. 120 and/or any other applicable provision in Title 35 of the United States Code.

BACKGROUND

I. Field

Aspects of the disclosure relate generally to wireless communication, and more specifically, but not exclusively, to transmitting and receiving multicarrier signals.

II. Background

The background description includes information that may be useful in understanding the present inventive subject matter. It is not an admission that any of the information provided herein is prior art or relevant to the presently claimed inventive subject matter, or that any publication, specifically or implicitly referenced, is prior art.

The most pressing need in mobile wireless wide area networks (WWANs), such as cellular networks, is to meet the increasing demand for data services. However, only a very small portion of the radio spectrum is suitable for WWAN communications. Above a few Gigahertz, path losses become too great for wide area communications in typical terrestrial environments. Only a fraction of the suitable spectrum is allocated for WWANs, and those allocations are divided among (ostensibly) competing cellular companies.

Various techniques have been proposed to enable more efficient use of the available spectrum, such as spectrum sharing, dynamic bandwidth exchange, and various "smart" radio schemes. Other techniques, such as joint scheduling and power control, can improve frequency reuse in cell configurations. Carrier aggregation simply allocates more radio channels to each client device without improving spectrum efficiency, providing a temporary increase in data services until those channels become congested.

While such techniques can provide more efficient use of the available WWAN spectrum, the laws of Physics still dictate a limit to the amount of information that can be carried with a given amount of WWAN spectrum and power.

Unfortunately, demand for data bandwidth continues to grow, irrespective of the limitations imposed by Physics.

SUMMARY

In accordance with some aspects of the disclosure, this most pressing need for ever-increasing data bandwidth within a finite amount of spectrum is solved.

By way of example, a Cooperative-MIMO network comprises a distributed antenna system coordinated with Cooperative-MIMO functionality to serve multiple client devices, such as User Equipments (UEs) in a mobile WWAN. This may be referred to as server-side Cooperative MIMO. The distributed antennas can comprise a fronthaul network configured to deliver precoded Cooperative MIMO baseband signals (such as from a central processor, a distributed computing system (e.g., Cloud computing system), a remote processor, or other processor(s)) to the antennas to provide for precoded MIMO transmissions into the WWAN channel. Precoding can be configured to produce a localized coherence zone at each of the multiple client devices, which can enable each client device to be served with the entire available WWAN spectrum without causing interference to other ones of the multiple client devices. The localized coherence zone can be referred to as a spatial subchannel or a subspace channel. In one aspect, Cooperative-MIMO precoding configures the distributed network of antennas and the natural scattering environment to focus transmissions that coherently combine at each of the client devices, thereby producing the localized coherence zones. Similarly, Cooperative-MIMO demultiplexing can separate same-band transmissions from the client devices. While server-side Cooperative MIMO can provide nearly ideal frequency reuse of the WWAN spectrum, the amount of data that can be transmitted to each client device is limited by the WWAN spectrum (and power).

Therefore, in accordance with some aspects of the disclosure, the aforementioned server-side Cooperative-MIMO system(s) can further comprise a client-side Cooperative-MIMO system. By way of example, nearby client devices may self-organize into Cooperative-MIMO clusters, or some other technique may be employed to group client devices to provide for Cooperative-MIMO processing. For example, a server-side or some other centralized coordination technique may be employed. A wireless fronthaul network communicatively couples together the client devices to provide a cluster. The wireless fronthaul network can employ short-range wireless links, such as extremely high-bandwidth (relative to WWAN link bandwidth), low-power transmissions. The fronthaul transmissions can employ millimeter-wave, infrared, and/or optical spectrum, which is usually impractical for use in mobile WWANs, but which supports much higher data bandwidth than a WWAN channel. In some aspects, the fronthaul links might enable 10,000 times (or more) spectrum than the total available WWAN spectrum.

In systems disclosed herein, the theoretical limit of the WWAN data bandwidth is no longer limited by the WWAN spectrum, but rather, it can increase up to the data bandwidth of the cluster's very wideband fronthaul network minus some processing overhead. For example, on the downlink, cooperative processing among client devices in a cluster can allow one client device to aggregate the data bandwidth of all the subspace channels (i.e., localized coherence zones) serving the cluster. This is advantageous since each client device, even when it is active, does not employ its available downlink channel one hundred percent of the time. Rather,

a client device typically transmits and receives data only a small fraction of the time it is being used. This is sometimes referred to as an activity factor. In accordance with aspects of the disclosure, as the cluster grows, each client device has more available instantaneous data bandwidth for the WWAN uplink and downlink. This is because multiple independent parallel spatial subchannels in the WWAN can be exploited to serve a single client device, thus expanding its data bandwidth far beyond the limited amount of spectrum in a single WWAN subspace channel.

Such aspects of the disclosure can provide the counter-intuitive result that as more client devices join a WWAN, the data bandwidth per client device increases instead of decreases, provided that there is a sufficient number of server-side antennas to accommodate the additional devices. In accordance with some aspects of the disclosure, client devices can be provisioned to operate as server-side antennas communicatively coupled to the server-side fronthaul network. This allows the network infrastructure to grow as client devices join the WWAN. A generalized concept of a relay node is introduced in which the relay node may be part of a server-side distributed antenna system, a client-side cluster, or both. A relay node can operate in multiple clusters and/or multipoint groups. The relay node can be a client device, a server-side device or component, or some other device, and it can be configured to adapt its function as it operates with different cooperating devices.

In accordance with some aspects of the disclosure, cooperative processing can be configured to reduce backhaul overhead, including the data bandwidth required for backhaul communications. For example, in some aspects, cooperative processing at the edge of the radio access network can reduce backhaul loads. However, in many aspects, the backhaul network's spectrum is far larger than the amount of spectrum allocated to the WWAN. Thus, in some implementations, a practical limitation to the WWAN data bandwidth might be related to the processing capability of the cooperating devices. This limitation can be advantageous in view of the alternative, because unlike the hard limitation imposed by Physics, processing power approximately doubles every eighteen months according to Moore's Law.

Some aspects of the disclosure provide for configuring distributed processing to enhance processing efficiency. For example, processing performed by cooperating client devices can be configured via various techniques and/or algorithms to improve processing efficiency. As used herein, processing efficiency can be achieved by employing signal processing algorithms that require a fewer number of total operations, require a fewer number of complex operations, require a fewer number of data exchanges with other processors, reduce latency, reduce power consumption, reduce processor idle time, and the like. Various processing techniques, such as pipelined processing architectures and the like, can be configured to improve processing efficiency. An end result of improved processing efficiency can include, among other things, a cluster being able to comprise a larger number of cooperating devices.

In some aspects of the disclosure, system configurations produce a high-rank channel matrix, which permits lower-complexity maximum ratio combining/transmission to be employed instead of zero forcing or other higher-complexity algorithms.

In accordance with some aspects of the disclosure, various signal-processing algorithms employed in a WWAN transceiver can be combined, thus enabling a more efficient implementation. In some aspects, complex spreading codes can be employed to spread data symbols (e.g., user data and/or reference signals) to enable certain benefits, such as crest-factor reduction, which can enable lower power consumption, less-expensive radio components, and/or other benefits.

While some aspects of the disclosure can employ techniques to reduce the peak-to-average power (PAPR) of an OFDM transmission at the inverse discrete Fourier transform (IDFT), such as by operating on the signal output at the IDFT (e.g., via clipping, signal cancellation, or selecting one of a set of candidate OFDM signals that has the lowest PAPR), certain advantages can be realized by spreading the data symbols before the IDFT operation in a manner that causes the IDFT output signal to have a low PAPR. In such aspects, the spreading codes can be configured in response to OFDM subcarrier assignment to the device (e.g., uplink subcarriers assigned to a client device) to produce a transmitted OFDM signal with low PAPR. Parameters of the assigned subcarriers, such as subcarrier frequency spacing and number of subcarriers, can be used to determine complex spreading codes that produce a low-PAPR signal at the IDFT output. Configuring the spreading codes to provide a spread-OFDM signal with low PAPR can comprise an appropriate mapping of spread symbols to OFDM subcarriers in a manner that produces the desired low-PAPR signal. This can include re-ordering the output of the spreader prior to its input to the IDFT. In some aspects, OFDM subcarriers are assigned to a client device by a server-side device, such as to provide for channel-dependent scheduling. Thus, the server-side device can also determine the complex spreading codes for the purpose of de-spreading signals received from the client device

In some aspects of the disclosure, characteristics of a data signal, such as its spectral information (i.e., frequency response) may be processed. In accordance with some aspects of the disclosure, this processing is responsive to OFDM subcarrier assignment to configure complex spreading of the data signal (and/or its spectral information) in a manner that, based on parameters of the assigned subcarriers (such as frequency spacing), produces a spread-OFDM signal with low PAPR. Without complex spreading configured in the aforementioned manner, the spectral information modulated onto an OFDM signal can produce a transmission with high PAPR. In some aspects of the disclosure, a transmitter receives an OFDM subcarrier assignment, and based on subcarrier parameters (such as frequency spacing, number of subcarriers, and/or other parameters) configures a transform operation that includes complex spreading codes which spread a data signal in a manner that, when modulated onto the OFDM subcarriers, produces a superposition signal (i.e., a transmitted OFDM signal) with a low PAPR.

By way of example, data spreading in the WWAN uplink channel can be performed by the individual client devices, wherein the spreading codes can be configured to employ fast algorithms for spreading and/or spreading-code generation. In some aspects, the data spreading can be configured to employ a similar fast algorithm used for a different signal processing operation, such as an IDFT used for modulating data onto an OFDM signal and/or a DFT used for demodulation. This can permit a given logical structure and/or physical processor architecture to perform similar signal processing algorithms (e.g., fast algorithms) for different radio transceiver operations (e.g., coding and modulation). In some aspects, a pipelined architecture can be employed, such as to make efficient use of one or more processors (e.g., a specialized hardware component or a general-purpose processor configured to perform the fast algorithm) to perform the different radio transceiver operations. In some

aspects, multiple processors residing on different devices (e.g., client devices, server devices, combinations thereof) can be configured to cooperatively process signals via fast algorithms, wherein the client-side fronthaul can function as a computer bus (such as between processors, memories, ports, and/or other network resources) between computing components distributed across multiple network nodes, including client devices. In such aspects, the networked processors can be pipelined to provide efficient processing of multiple radio transceiver operations.

By way of example, a fast algorithm can be a fast Fourier transform (FFT), such as a radix-2 FFT. Thus, a client device can be configured to perform a radix-2 FFT as part of a DFT-spreading of original data symbols, and the client device can be configured to perform a radix-2 FFT to modulate the spread data symbols onto OFDM subcarrier signals. In some aspects, the client device can configure processing hardware and/or software to employ the same radix-2 FFT (although possibly with different input parameters, transform size, etc.) for different, typically unrelated, radio transceiver operations, such as DFT-spreading and OFDM modulation, or DFT-spreading and OFDM demodulation, as well as others. It should be appreciated that such aspects may be performed as part of cooperative processing among multiple client devices, on the server side, with the aid of one or more relay devices, and/or some combination thereof.

In accordance with some aspects of the disclosure, spreading produces a different result than spectrum analysis. For example, spectrum analysis can provide for calculating frequency responses of a signal corresponding to tones. The term, "tones," is commonly used to mean orthogonal frequencies, such as in relation to the term, "discrete multitone modulation," which denotes OFDM-based communication systems that adapt the transmission to the channel conditions individually for each subcarrier. In OFDM, as in spectrum analysis, the tones are a set of frequency-multiplexed signals with the exact frequencies needed to make them orthogonal so they do not interfere with each other. In discrete systems, spectrum analysis expresses a discrete signal of N complex data symbols as a set of N/2 frequency responses. This is because frequencies between the Nyquist rate $f_{sam}/2$ and the sample rate f_{sam} alias to negative frequencies due to sampling above the Nyquist rate. These are the same tones as the corresponding positive frequencies. While the output of a DFT comprises N values, there are only N/2 tones, so the N/2 redundant frequency responses are typically discarded to provide spectral analysis, resulting in only half the values that DFT spreading would otherwise provide.

In some aspects of the disclosure, a radio transceiver can be configured to perform another type of signal-processing operation for different, typically unrelated, radio transceiver operations. By way of example, linear network coding can be configured to employ similar processing operations as in MIMO subspace precoding (i.e., multiplexing) and/or demultiplexing. Similarly, linear network decoding can employ similar operations as MIMO subspace multiplexing and/or demultiplexing. Thus, client-side and/or server-side processors can be configured to perform linear network coding that employs basically the same algorithms used to provide for spatial multiplexing and/or demultiplexing.

Aspects disclosed herein can be implemented as apparatus configurations comprising structural features that perform the functions, algorithms, and methods described herein. Flow charts and descriptions disclosed herein can embody instructions, such as in software residing on a non-transitory computer-readable medium, configured to operate a processor (or multiple processors). Flow charts and functional descriptions, including apparatus diagrams, can embody methods for operating a communication network(s), coordinating operations which support communications in a network(s), operating network components (such as client devices, server-side devices, relays, and/or supporting devices), and assembling components of an apparatus configured to perform the functions disclosed herein.

Groupings of alternative elements or aspect of the disclosed subject matter disclosed herein are not to be construed as limitations. Each group member can be referred to and claimed individually or in any combination with other members of the group or other elements found herein. One or more members of a group can be included in, or deleted from, a group for reasons of convenience and/or patentability. When any such inclusion or deletion occurs, the specification is herein deemed to contain the group as modified, thus fulfilling the written description of all Markush groups used in the appended claims.

All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided with respect to certain embodiments herein is intended merely to better illuminate the inventive subject matter and does not pose a limitation on the scope of the inventive subject matter otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the inventive subject matter.

Additional features and advantages of the invention will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The features and advantages of the invention may be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims. These and other features of the invention will become more fully apparent from the following description and appended claims, or may be learned by the practice of the invention as set forth herein.

The following patent applications and patents are hereby incorporated by reference in their entireties: U.S. Pat. Nos. 8,670,390, 10/145,854, 9,225,471, 9,270,421, 9,325,805, Ser. Nos. 14/789,949, 62/197,336, 14/967,633, 60/286,850, U.S. Pat. Nos. 8,929,550, 7,430,257, 6,331,837, and 7,076,168.

BRIEF DESCRIPTION OF DRAWINGS

Flow charts depicting disclosed methods comprise "processing blocks" or "steps" may represent computer software instructions or groups of instructions. Alternatively, the processing blocks or steps may represent steps performed by functionally equivalent circuits, such as a digital signal processor or an application specific integrated circuit (ASIC). The flow diagrams do not depict the syntax of any particular programming language. Rather, the flow diagrams illustrate the functional information one of ordinary skill in the art requires to fabricate circuits or to generate computer software to perform the processing required in accordance with the present disclosure. It should be noted that many routine program elements, such as initialization of loops and variables and the use of temporary variables are not shown. It will be appreciated by those of ordinary skill in the art that unless otherwise indicated herein, the particular sequence of steps described is illustrative only and can be varied. Unless

otherwise stated, the steps described below are unordered, meaning that the steps can be performed in any convenient or desirable order.

FIG. **1** is a block diagram of a communication system architecture in accordance with an exemplary aspect of the disclosure.

FIG. **2** illustrates a network configuration for super-array processing in accordance with some aspects of the disclosure.

FIG. **3** is a block diagram of a network topology, the type of which can be employed in accordance with aspects of the disclosure.

FIG. **4**A is a block diagram of a spread-OFDM transmitter in accordance with an aspect of the disclosure.

FIG. **4**B is a block diagram of a spread-OFDM spreader (such as spreader **402**) in accordance with some aspects of the disclosure.

FIG. **5**A is a block diagram of a receiver configured to receive and process spread-OFDM signals in accordance with aspects of the disclosure.

FIG. **5**B is a block diagram that depicts a portion of a receiver, such as a receiver that may be employed in a server-side WWAN terminal or system.

FIG. **6**A is a flow diagram that depicts a method performed in a radio transceiver, which can employ a fast algorithm to generate a spread data sequence from an original data sequence in accordance with some aspects of the disclosure.

FIG. **6**B is a flow diagram that depicts a method for processing received spread-OFDM signals, which can be employed in accordance with various aspects of the disclosure.

FIG. **7**A is a flow diagram that depicts a method for generating spread-OFDM signals in accordance with some aspects of the disclosure.

FIG. **7**B is a flow diagram that depicts a method of processing received spread-OFDM signals in accordance with some aspects of the disclosure.

FIG. **8**A is a block diagram that depicts modules corresponding to processing functions that can be implemented by a computer processor programmed to perform methods in accordance with aspects of the disclosure. The blocks can be interpreted as software modules, hardware components, or some combination thereof. The modules can represent steps in a method. In some aspects, the block diagram is indicative of structure and/or function of a client device (such as a UE) or a system of client devices.

FIG. **8**B is a block diagram that depicts modules corresponding to processing functions that can be implemented by a computer processor programmed to perform methods in accordance with aspects of the disclosure. The blocks can be interpreted as software modules, hardware components, or some combination thereof. The modules can represent steps in a method. In some aspects, the block diagram is indicative of structure and/or function of a server-side device (such as a base transceiver station (e.g., an eNodeB) or a central processor coupled to one or more base transceiver stations), or a system of server-side devices, such as a Coordinate Multipoint system.

FIG. **9** is a block diagram of a transceiver that can be configured to operate in accordance with aspects of the disclosure.

FIGS. **10**A and **10**B are block diagrams that illustrates transceiver configurations in accordance with aspects of the disclosure. The blocks can comprise processing elements that provide necessary computing facilities for the transceiver. By way of example only, processing elements can include special purpose hardware accelerators, such as co-processors for Fast Fourier Transform (FFT), encryption and decryption security processors, or programmable Central Processing Units (CPUs).

FIG. **11** is a flow diagram that depicts a precoding method in a distributed antenna system in accordance with some aspects of the disclosure.

FIG. **12** is a flow diagram that depicts a precoding method in a distributed antenna system in accordance with some aspects of the disclosure.

FIG. **13** is a flow diagram that depicts a precoding method in a distributed antenna system in accordance with some aspects of the disclosure.

DETAILED DESCRIPTION

Various aspects of the disclosure are described below. It should be apparent that the teachings herein may be embodied in a wide variety of forms and that any specific structure, function, or both being disclosed herein are merely representative. Based on the teachings herein one skilled in the art should appreciate that an aspect disclosed herein may be implemented independently of any other aspects and that two or more of these aspects may be combined in various ways. For example, an apparatus may be implemented or a method may be practiced using any number of the aspects set forth herein. In addition, such an apparatus may be implemented or such a method may be practiced using other structure, functionality, or structure and functionality in addition to or other than one or more of the aspects set forth herein.

In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the invention. It should be understood, however, that the particular aspects shown and described herein are not intended to limit the invention to any particular form, but rather, the invention is to cover all modifications, equivalents, and alternatives falling within the scope of the invention as defined by the claims.

FIG. **1** is a block diagram of a communication network in accordance with an exemplary aspect of the disclosure. A plurality N of geographically distributed base transceiver stations **101.1-101**.N (BTS(1), BTS(2), . . . , BTS(N)) are communicatively coupled to a super-array processing system **111** via a communication network **105**. Each base transceiver station **101.1-101**.N comprises an antenna system configured for communicating with one or more mobile units (e.g., User Equipment) **120.1-120**.K via a WWAN radio access network (RAN).

In one aspect, the first base transceiver station **101.1** comprises a first antenna array comprising a first plurality M_1 of antennas **102.1-102**.M_1, the second base transceiver station **101.2** comprises a second antenna array comprising a second plurality M_2 of antennas **102.1-102**.M_1, and the Nth base transceiver station **101**.N comprises an Nth antenna array comprising an Nth plurality M_N of antennas **104.1-104**.M_N. The base transceiver stations **101.1-101**.N are configured to provide RAN services to a plurality K of mobile units **120.1**, **120.2**, . . . , **120**.K, each having its own antenna system **121.1**, **121.2**, . . . , **121**.K, respectively. Each antenna system **121.1**, **121.2**, . . . , **121**.K may comprise one or more antennas.

The communication network **105** may comprise a fiber network, a cable (i.e., wired) network, a wireless network (including a free-space optical network), or any combination thereof. In some aspects, the network **105** is referred to as a "fronthaul" network. In some aspects, the network **105** can

comprise a backhaul network. In accordance with one aspect of the disclosure, a network that connects base transceiver stations to a processing system configured to perform joint processing (e.g., system **111**) can be referred to as a fronthaul, and a network (such as network **115**) which connects processing elements of the super-array processing system **111** can be referred to as a backhaul.

The terms "backhaul" and "fronthaul" can be used interchangeably in some aspects of the disclosure. A fronthaul is similar to a backhaul, which, at its simplest, links a radio access network to a wired (e.g., cable or optical fiber) network. A fronthaul can comprise a backhaul, or a portion of a backhaul. For example, a fronthaul can comprise a connection between one or more centralized controllers and remote stand-alone radio heads. A fronthaul can connect a central processor to multiple base transceiver stations. A fronthaul connects multiple base transceiver stations together when one or more of the base transceiver stations functions as a central processor. As used herein, a fronthaul may comprise a traditional backhaul network. For example, a fronthaul can comprise at least a portion of S1 and/or X2 interfaces. A fronthaul may be part of a base station network. In Pat. Appl. Ser. No. 60/286,850, it is disclosed that a fronthaul can comprise optical fiber, wired, and/or radio networks. In one aspect of the disclosure, point-to-point fiber links provide high bandwidth and low latency. In another aspect, radio (e.g., microwave) links can provide high bandwidth and low latency, and can be substantially less expensive to implement than fiber. Furthermore, wireless links enable mobile radios and/or other radio transceivers (e.g., remote radio equipment) to be networked together via a radio fronthaul, such as disclosed in patent application Ser. No. 10/131,163. Accordingly, a fronthaul can comprise any combination of wireless, wired, and optical fiber links that communicatively couple together a group of radio transceivers configured to perform cooperative MIMO. Here, a group of radio transceivers is also referred to as a "micro-cell" and a "pico-cell" in the '163 application, and as a "local group" and a "micro-network" in patent application Ser. No. 11/187,107, all of the patents and patent applications mentioned in this disclosure being incorporated by reference in their entireties.

In one aspect of the disclosure, the super-array processing system **111** comprises a distributed computing system configured to coordinate a plurality of physical processors (which may be centrally located or geographically distributed) such as to perform joint processing. In some aspects, the plurality of physical processors can be represented as processors **111.1-111**.N. In other aspects, virtual processors (such as virtual base stations implemented as software-defined radios (SDRs)) can be represented as processors **111.1-111**.N.

By way of example, but without limitation, physical processors in a distributed computing environment can be represented as processors **111.1-111**.N. As used herein, the term "processor" can refer to a computer processor, a computer, a server, a central processing unit (CPU), a core, a microprocessor, and/or other terminology that indicates electronic circuitry configurable for carrying out instructions of a computer program. In some aspects, a processor comprises geographically distributed computing elements (e.g., memories, processing cores, switches, ports, and/or other computing or network resources). A fronthaul and/or backhaul network communicatively coupling the geographically distributed computing elements can function as a computer bus.

The processors are communicatively coupled together via at least one network, such as a backhaul network **115**. The backhaul network **115** can comprise an optical fiber network, a wireline network (e.g., Ethernet or other cable links), a wireless network, or any combination thereof. In some aspects, the backhaul network **115** can comprise the RAN. In one aspect, each of N processors is programmed to function as one of a plurality N of virtual base stations **111.1-111**.N. In another aspect, each virtual base station **111.1-111**.N comprises multiple processing cores. In some aspects, each virtual base station **111.1-111**.N represents a hardware abstraction wherein details of how the hardware is implemented are concealed within the representation of each "processor" **111.1-111**.N as a single element. In such aspects, the physical implementation of each processor **111.1-111**.N can comprise physical computing elements that are geographically distributed and/or physical computing elements that are shared by multiple virtual base stations **111.1-111**.N.

By way of example, each virtual base stations **111.1-111**.N may comprise one or more of the processors and perform base station processing operations that would ordinarily be performed by one or more corresponding base stations **101.1-101**.N. Specifically, virtual base stations can be implemented via software that programs general-purpose processors. For example, an SDR platform virtualizes baseband processing equipment, such as modulators, demodulators, multiplexers, demultiplexers, coders, decoders, etc., by replacing such electronic devices with one or more virtual devices, wherein computing tasks perform the functions of each electronic device. In computing, virtualization refers to the act of creating a virtual (rather than actual) version of something, including (but not limited to) a virtual computer hardware platform, operating system (OS), storage device, or computer network resources.

In accordance with the art of distributed computing, a virtual base station's functions can be implemented across multiple ones of the plurality of processors. For example, workloads may be distributed across multiple processor cores. In some aspects, functions for more than one base station are performed by one of the processors.

As used herein, distributed computing refers to the use of distributed systems to solve computational problems. In distributed computing, a problem is divided into multiple tasks, and the tasks are solved by multiple computers which communicate with each other via message passing. A computer program that runs in a distributed system is referred to as a distributed program. An algorithm that is processed by multiple constituent components of a distributed system is referred to as a distributed algorithm. In a distributed computing system, there are several autonomous computational entities, each of which has its own local memory.

In accordance with aspects of the disclosure, the computational entities (which are typically referred to as computers, processors, cores, CPUs, nodes, etc.) can be geographically distributed and communicate with each other via message passing. In some aspects, message passing is performed on a fronthaul and/or backhaul network. The distributed computing system can consist of different types of computers and network links, and the system (e.g., network topology, network latency, number of computers, etc.) may change during the execution of a distributed program. In one aspect, a distributed computing system is configured to solve a computational problem. In another aspect, a distributed computing system is configured to coordinate and schedule the use of shared communication resources between network devices.

A distributed computing system can comprise a grid computing system (e.g., a collection of computer resources from multiple locations configured to reach a common goal, which may be referred to as a super virtual computer). In some aspects, a distributed computing system comprises a computer cluster which relies on centralized management that makes the nodes available as orchestrated shared servers. In some aspects, a distributed computing system comprises a peer-to-peer computing system wherein computing and/or networking comprises a distributed application architecture that partitions tasks and/or workloads between peers. Such distributed peer-to-peer computing systems are disclosed in the '107 application. In some aspects, peers are equally privileged, equipotent participants in the application. They are said to form a peer-to-peer network of nodes. Peers make a portion of their resources, such as processing power, disk storage, network bandwidth, etc., available to other network participants without the need for central coordination by servers or stable hosts. Peers can be either or both suppliers and consumers of resources.

In accordance with some aspects of the disclosure, the base transceiver stations **101**.1-**101**.N are "dumb terminals," wherein base station signal processing (for example, the baseband processing) is performed by the central processor **110** (which may include the distributed computing system **111**). Thus, in some aspects, the base transceiver stations **101**.1-**101**.N are simply radio remote units. For example, the base transceiver stations **101**.1-**101**.N might perform only basic signal-processing functions, such as RF processing (i.e., radio front-end processing), which can include frequency conversion and (optionally) ADC/DAC functions, while the central processor **110** (which may include the distributed computing system **111**) performs baseband processing, including channel analysis and generating base transceiver MIMO weights.

In one aspect, the central processor **110** coordinates or performs baseband signal processing corresponding to base station operations, whereas the base transceivers **101**.1-**101**.N provide only RF front end signal processing, including frequency conversion, and optionally, ADC/DAC. The central processor can perform waveform shaping, error detection, error correction, power control, channel selection, multiple access control, multiplexing, modulation, formatting, synchronization, coding, etc. for the plurality of base transceivers (i.e., access points) communicatively coupled to the central processor via the fronthaul network. In some aspects of the disclosure, the central processor **110** provides for base-station functionality, such as power control, code assignments, and synchronization. The central processor **110** may perform network load balancing (e.g., scheduling RAN resources), including providing for balancing transmission power, bandwidth, and/or processing requirements across the radio network. Centralizing the processing resources (i.e., pooling those resources) facilitates management of the system, and implementing the processing by employing multiple processors configured to work together (such as disclosed in the '163 application) enables a scalable system of multiple independent computing devices, wherein idle computing resources can be allocated and used more efficiently.

Some aspects allow base station processing resources (e.g., the processors in the distributed computing system **111**) and the remote RF units (e.g., the base transceiver stations **101**.1-**101**.N) to be deployed separately. For example, RAN coverage, capacity, and/or data bandwidth per UE can be improved by adding base transceiver stations, and then the SDR platform dynamically adapts to the new RAN base station configuration. Similarly, the SDR platform can adapt to the loss of one or more of the base transceiver stations **101**.1-**101**.N. The distributed computing system (e.g., cloud network) **111** can adapt to varying processing loads by allocating computing resources as needed. Furthermore, system upgrades, such as new transmission protocols, can be easily implemented via software upgrades to the SDR platform.

In some aspects, base-station functionality is controlled by individual base transceiver stations and/or UEs assigned to act as base stations. Array processing may be performed in a distributed sense wherein channel estimation, weight calculation, and optionally, other network processing functions (such as load balancing) are computed by a plurality of geographically separated processors. In some aspects, access points and/or subscriber units are configured to work together to perform computational processing. A central processor (such as central processor **110**) may optionally control data flow and processing assignments throughout the network.

As disclosed in the '850 application, the system depicted in FIG. **1** can provide system performance benefits by centralizing (e.g., pooling) much of the equipment (and/or signal processing) typically employed at the cell sites. Cost reduction is another motivation for centralizing the radio access network, as most of a cellular network's ownership costs comprise operating costs, including site rental, power, and support and maintenance expenses. Thus, instead of distributing baseband processing equipment at the edge of the network as in conventional cellular networks, centralizing the radio access network at the central processor **110** can greatly reduce capital expenditures to build out and upgrade the radio access network, as well as reduce operating expenditures.

As disclosed in the '163 application, providing for distributed computing at the central processor **110** provides network function virtualization to the RAN. Benefits that can be realized with some aspects of the disclosure include cost reduction from pooling and virtualizing baseband processing. This can eliminate the need to provision for peak capacity on a per-site basis, thus reducing processing requirements. Furthermore, instead of requiring dedicated base station hardware, some of the disclosed aspects provide for the use of commercial (e.g., general-purpose) servers running software.

As disclosed in the patents and applications incorporated by reference herein, other types of networks, including wireless networks, can connect the base transceiver stations **101**.1-**101**.N. One of the advantages of employing the optical fiber fronthaul **105** is that optical fiber can provide the high capacity and low latency required by many aspects of the invention. For example, when a large number of baseband processors are co-located at the central processor **110**, the amount of data bandwidth in the fronthaul and the synchronization requirements between base transceiver stations **101**.1-**101**.N can increase substantially when high RF bandwidth and MIMO are employed. Different aspects of the invention can provide for different functional splits between centralized and distributed functions.

Some aspects of the invention can reduce fronthaul requirements by implementing at least some of the Physical Layer processing at the base transceiver stations **101**.1-**101**.N while implementing other processing (e.g., higher layer processing, or the higher layer processing plus some of the Physical layer processing) at the central processor **110**. Thus, in some aspects of the invention, one or more of the base transceiver stations **101**.1-**101**.N depicted in the figures

may be replaced by UEs adapted to perform as routers, repeaters, and/or elements of an antenna array.

In one aspect of the disclosure, the base station network comprising base transceiver stations **101.1-101**.N is adapted to operate as an antenna array for MIMO subspace processing in the RAN. In such aspects, a portion of the network may be adapted to serve each particular UE. The SDRs (represented as the virtual base stations **111.1-111**.N) can be configured to perform the RAN baseband processing. Based on the active UEs in the RAN and the standard(s) they use for their wireless links, the SDRs can instantiate virtual base station processes in software, each process configured to perform the baseband processing that supports the standard(s) of its associated UE(s) while utilizing a set of the base transceiver stations within range of the UE(s).

In accordance with one aspect of the disclosure, baseband waveforms comprising RAN channel measurements and/or estimates (such as collected by either or both the UEs and the base transceiver stations) are processed by the SDRs (such as in a Spatial Multiplexing/Demultiplexing module (not shown)) using Cooperative-MIMO subspace processing to produce pre-coded waveforms. A routing module (not shown) sends the pre-coded waveforms over the fronthaul **105** to multiple ones of the base transceiver stations **101.1-101**.N, and optionally, to specific antennas **102.1-102**.M_1, **103.1-103**.M_2, . . . , **104.1-104**.M_N. The base transceiver stations **101.1-101**.N can be coordinated to concurrently transmit the pre-coded waveforms such that the transmitted waveforms propagate through the environment and constructively interfere with each other at the exact location of each UE **120.1-120**.K.

In one aspect, the super-array processing system **111** configures complex-weighted transmissions **122**, **123**, and **124** from the geographically distributed base transceiver station **101.1**, **101.2**, and **101**.N, respectively to exploit the rich scattering environment in a manner that focuses low-power scattered transmissions to produce a concentrated high-power, highly localized signal (e.g., coherence zones **125.1**, **125.2**, . . . , **125**.K) at each UE's **120.1-120**.K antenna system **121.1**, **121.2**, . . . , **121**.K, respectively. The coherent combining of the transmitted waveforms at the location of each UE **120.1-120**.K can result in the synthesis of the baseband waveform that had been output by the SDR instance associated with that particular UE **120.1-120**.K. Thus, all of the UEs **120.1-120**.K receive their own respective waveforms within their own synthesized coherence zone concurrently and in the same spectrum.

In accordance with one aspect of the invention, each UE's corresponding synthesized coherence zone comprises a volume that is approximately a carrier wavelength or less in width and centered at or near each antenna on the UE. This can enable frequency reuse between nearby—even co-located—UEs. As disclosed in the '107 application, Spatial Multiplexing/Demultiplexing can be configured to perform maximum ratio processing. Any of various algorithms for MIMO processing disclosed in the '107 application may be employed by methods and apparatus aspects disclosed herein. Some aspects can comprise zero forcing, such as to produce one or more interference nulls, such as to reduce interference from transmissions at a UE that is not an intended recipient of the transmission. By way of example, but without limitation, zero forcing may be performed when there are a small number of actual transmitters (e.g., base transceiver station antennas) and/or effective transmitter sources (e.g., scatterers in the propagation environment).

While the aforementioned techniques of server-side Cooperative MIMO in a multi-user MIMO system provide substantial bandwidth efficiency, which is a significant advance in wireless communications, the amount of data bandwidth available to each UE is still hard-limited based on the total radio bandwidth allocated to the WWAN. However, client-side Cooperative MIMO can elegantly circumvent the data bandwidth limitation of the aforementioned multi-user MIMO system.

By way of example, some aspects of the disclosure configure the UEs **120.1-120**.K to form a cluster in which the individual UEs **120.1-120**.K are communicatively coupled together via a client device fronthaul network **102**, which can comprise any of various types of local area wireless networks, including (but not limited to) wireless personal area networks, wireless local area networks, short-range UWB networks, wireless optical networks, and/or other types of wireless networks. In some aspects, since the bandwidth of the client device fronthaul network **102** is typically much greater than that of the WWAN, a UE **120.1-120**.K can share its access to the RAN (i.e., its WWAN spatial subchannel, or coherence zone) with other UEs **120.1-120**.K in the cluster, thus enabling each UE **120.1-120**.K to enjoy up to a K-fold increase in instantaneous data bandwidth.

In some aspects, otherwise inactive UEs can share their WWAN access with active UEs in the cluster. Since the activity factor of an active UE is typically a small fraction, an active UE can share its unused WWAN spatial subchannel with other UEs in the cluster. In addition to access to higher data bandwidth, there can be other incentives for a UE to cooperate in a cluster, including (but not limited to) lower power consumption (such as due to client-side antenna array gain), improved coverage and reliability, as well as other benefits and incentives.

In some aspects, a cluster of UEs can perform cooperative subspace demultiplexing. In some aspects, the cluster can perform cooperative subspace multiplexing by coordinating weighted (i.e., pre-coded) transmissions to produce localized coherence zones at other clusters and/or at the base transceiver stations **101.1-101**.N. In some aspects, the UEs **120.1-120**.K comprise a distributed computing platform configured to perform distributed processing (and optionally, other cloud-based services). Distributed processing may be performed for Cooperative-MIMO, other various SDR functions, and/or any of various network control and management functions.

FIG. **2** is a block diagram of a communication network in accordance with another exemplary aspect of the disclosure. Similar features depicted in FIG. **1** have the same reference numerals. In FIG. **2**, the concept of a relay node is introduced. By way of example, a relay n **101**.*n* comprises and antenna system **109**.*n* and is communicatively coupled to at least one base transceiver station (such as BTS (1)) via a fronthaul network, which may be fronthaul **105** or a separate fronthaul **107**. Similarly, a relay k **120**.*k* is depicted as being communicatively coupled to a cluster of UEs **120.1-120**.K via fronthaul **102**. The relay k **120**.*k* may be coupled to other network nodes via other fronthauls (such as fronthaul **105**).

In one aspect, a relay is a dedicated relay node, such as may be configured specifically to operate as part of the WWAN infrastructure. In another aspect, a relay is an abstraction which denotes any of various devices that is configurable to operate as a relay node, as a member of a UE cluster, and/or as a member of server-side (e.g., BTS) antenna system (e.g., in a base transceiver antenna cluster). In some aspects, a relay can be a UE. In some aspects, a relay can be a base transceiver station. For example, relay n **101**.*n* may be a UE configurable to cooperate with base transceiver

station **101.1**, such as to increase the rank of the antenna system's **102.1-102**.M_1 channel matrix. Relay k **120**.*k* can comprise a base transceiver station configurable to communicate with a UE cluster **120.1-120**.K via its fronthaul **102**, and/or increase the rank of the cluster's channel matrix. In some aspects, a relay can simultaneously operate in multiple clusters. For example, a relay could operate in multiple UE clusters. In some aspects, a relay can operate as both a UE and a base transceiver station (or as a component of a base transceiver station's antenna system).

As disclosed in the patents and patent applications incorporated by reference herein, and particularly with respect to aspects of Cooperative-MIMO systems and methods, network nodes can function as either or both clients and servers. Furthermore, when wireless network nodes cooperate in subspace processing, they can create network resources, such as subspace (i.e., spatial multiplexing) channels, performance gains, RAN coverage area, etc. Even when UEs cooperate as a client array (e.g., a UE cluster) in a Cooperative-MIMO implementation, each UE can improve the data bandwidth, quality of service, range, and power efficiency of the other UEs in the array, or cluster. Thus, in some aspects of a Cooperative-MIMO system, UEs can extend the network infrastructure, such as to increase per-client data bandwidth, the number of clients served, coverage area, and/or quality of service without requiring substantial capital outlays from network operator to upgrade the base station network.

In Cooperative-MIMO systems, mobile UEs can opportunistically join together via a peer-to-peer overlay network (e.g., fronthaul **102**) for client-side MIMO processing. In some aspects, UEs can join base transceiver arrays via an overlay network (e.g., fronthaul **107**) to assist in server-side MIMO processing. Due to random movement of UEs, aspects of the disclosure do not impose a particular structure on the overlay network. Because there is no structure globally imposed upon them, unstructured networks are easy to build and allow for localized optimizations to different regions of the overlay. Also, in such aspects, because the role of all peers in the network is the same, unstructured networks can be highly robust in the face of high rates of churn (i.e., when peers are frequently joining and leaving the network).

FIG. **3** is a block diagram of a network topology, the type of which can be employed in accordance with aspects of the disclosure. In this network topology, a plurality of nodes (e.g., nodes **301.1-301**.N) are communicatively coupled together via communication links (such as depicted by networks **301-305**), which form a network fabric. The depiction of "nodes" is a generalization, as the nodes **301.1-301**.N can comprise server-side devices, client-side devices, relay devices (or other intermediate devices), and/or combinations thereof.

A network fabric can comprise a switched fabric, which is a network topology in which nodes **301.1-301**.N connect via one or more network switches. Switches in a switched fabric can form a mesh network. While switched fabrics are typically associated with fibre channel switched fabrics, which use fibre channel switches, aspects of the disclosure include network fabrics with wireless links between at least some of the nodes. These wireless links can be radio channels, infrared, and/or free-space optical channels.

A network topology describes the arrangement of nodes and links of a communication network, and can comprise either or both a physical topology and a logical topology. The physical topology conveys the location of each node and characteristics of the links, and can include distances between nodes, node interconnections, transmission rates, signal types, and other physical-layer attributes. The logical topology conveys the data flows within a network, which can be independent of the physical design.

In some aspects, at least some of the nodes **301.1-301**.N in the network fabric can comprise aerial platforms, such as unmanned aerial vehicles (UAVs). By way of example, mobile radio communication services (such as a radio access network (RAN)) can be provided by using a network fabric comprising UAVs configured for network fronthaul and/or backhaul operations. The use of such mobile aerial platforms can be advantageous when there is a need to quickly deploy a radio network and/or dynamically adapt to changing user-demand topologies.

With the use of broadband data links between nodes in an aerial network fabric, such as can be implemented via short-range wideband radio, infrared, and/or free-space optical links, data rates over the network fabric can be commensurate with computer bus speeds. Not only can the aerial network fabric serve as the fronthaul and/or backhaul to enable the RAN's data transport, the aerial network fabric can serve as a computing bus that connects computing elements (and other resources) residing on different network nodes to support other applications.

In one aspect, each node **301.1-301**.N manages its contribution of shared resources for performing at least one other application while performing its RAN data transport duties. The other application(s) could include remote sensing or other various environment-monitoring operations, transcoding or other various media-processing operations, network security operations, content delivery management, client-device services (e.g., cloud storage, cloud computing, software-as-a-service, navigation, etc.), and/or RAN-supporting applications (e.g., Cooperative-MIMO, error detection/correction, coding/decoding, etc.).

Each application can comprise a combination of a routing topology, a storage topology, and a computation topology. In one aspect, one or more of the networks **301-305** corresponds to a topology for a particular application. By way of example, a storage topology can comprise storage devices distributed across multiple network nodes, and the storage topology can comprise a routing topology that is specific to accessing the storage devices for cloud storage on the multiple network nodes. The routing topology for cloud storage is typically different than the routing topology for RAN data transport. Thus, each node may comprise separate routing cores dedicated to different routing topologies. Similarly, each node may comprise separate storage devices, such as one set dedicated to RAN data transport and another set dedicated to a cloud storage application.

By way of example, a computation topology can comprise computing elements distributed across multiple network nodes. In one aspect, such as depicted in FIG. **3**, a system of resources **311** (such as a network of nodes) can be abstracted as a single node in a given topology. In some aspects, virtual nodes **311.1-311**.N (where N represents the number of virtual nodes) are an abstraction that conceals a corresponding underlying physical architecture, which can comprise multiple hardware components communicatively coupled together. The hardware components of a virtual node **311.1-311**.N might change during an application, such as to scale to demand for various resources (e.g., computational processing, memory, routing, etc.). Similarly, the network topology **315** might change for any of various reasons. In some aspects, the network **315** is a hidden (or concealed) network, such as a Tor network. In one aspect, a gatekeeper node (such as node **311.9**) indicates the availability of

certain services to the other nodes **301.1-301.8** or to specific applications while concealing from those nodes **301.1-301.8** or applications information as to how those services are acquired or arranged. In some aspects, certain services are only available to nodes within a subnetwork and are concealed from nodes outside the subnetwork. In some aspects, the network **315** comprises a virtual network overlay to a physical network. In some aspects, a virtual node **311.1-311**.N (and/or network) may comprise nodes **301.1-301.8** (and/or components thereof), groups of nodes **301.1-301.8**, other network resources, and/or subnetworks **301-305** (or portions thereof).

The computation topology for one application, such as RAN data transport, can be different from the computation topology used for another application. Furthermore, the computation topology can comprise a storage topology and a routing topology that are different for each application. Thus, a distributed application can employ a topology comprising dedicated apparatus-level components on different nodes **301.1-301.9**, but operating together to support the application's requirements. Each instantiation of the distributed application can comprise a unique set of the apparatus-level components, and thus may employ a corresponding unique topology.

In accordance with certain aspects, a distributed computing problem can be partitioned by a combination of processes, including (but not limited to) data partitioning and computation partitioning. A first network topology can be provisioned to perform a first one of the processes and a second network topology can be provisioned to perform a second one of the processes. By way of example, the first network topology is configured to perform processing associated with data partitioning, and the second network topology is configured to perform processing associated with computation partitioning. Computation processing can be further partitioned into tasks which may be provided with their own network topologies. It should be appreciated that network topologies can be tiered. For example, a topology corresponding to a data partition may comprise multiple subnetwork topologies corresponding to computation partitions, and a computation partition may include further partitions implemented by corresponding subnetworks. It should also be appreciated that subnetwork topologies can overlap, and a device or network configured to operate in one network topology may be configured to perform (simultaneously, or in alternative time intervals) processing corresponding to another network topology. As network topologies can comprise overlapping and/or tiered topologies, in some aspects, solutions provided by a set of subnetwork topologies can be processed by a processors in an encompassing network topology, and processors in the subnetworks can be directed to a next problem in a queue and/or redirected to solve different problems. In some aspects, network topologies can be adapted, such as to adapt to corresponding processing needs. In some aspects, the topologies change as problems are completed and/or processing for new problems is commenced.

Due to the deployment of multiple UAVs to provide fronthaul and/or backhaul support for the RAN, a system for managing navigation is typically employed, which can include various combinations of centralized and decentralized air traffic control. One promising technique uses swarm intelligence.

Swarm intelligence refers generally to the collective behavior of multi-component systems that coordinate using decentralized controls and self-organization. From an engineering point of view, swarm intelligence emphasizes the bottom-up design of autonomous distributed systems that can provide adaptive, robust, and scalable behaviors. While conventional distributed air traffic control techniques provide only navigation management (e.g., collision avoidance, maintaining safe aircraft spacing, optimal routing, etc.), aspects of the invention introduce network fabric processing criteria into the navigation decision-making process. Thus, navigation may be adapted to desired network topologies for various applications. Such adaptations to a UAV's navigation decision-making may take the form of self-organizing control signals, control signals from a UAV acting as a cluster leader or local master, and/or from a ground-based processing system providing for coordinated multipoint control.

By way of example, in a MIMO wireless communication system, the arrangement of scatterers in the transmission channel affects the system's capacity (e.g., L. Hanlen, M. Fu, "MIMO Wireless Systems: Capacity Limits for Sparse Scattering," 3rd AusCTW, Canberra, Australia, February 2002, which is incorporated by reference in its entirety). Thus, UAV navigation can be configured to employ techniques to arrange active scattering platforms in a manner that enhances system capacity. In some aspects, it is recognized that UAVs can act as passive scatterers of RAN transmissions. In such aspects, UAV navigation can be adapted to produce any of various scattering structures, such as mirrors, lenses, and waveguides. These scattering structures can comprise active scattering structures, passive scattering structures, or combinations thereof.

In some aspects, swarm intelligence is configurable with respect to additional criteria, such as the aforementioned Cooperative-MIMO processing, network topology control, scattering management, and the like. For example, local navigation decision-making may be adapted to produce complex scattering structures. In some aspects, local navigation decision-making can be adapted to produce or shape a network topology. In such aspects, the local rule base employed for navigation by each UAV can be adapted such that complex structures and/or topologies can be achieved with minimal or no centralized control. In other aspects, at least a small amount of centralized control, whether from a ground-based controller or an airborne cluster master, may provide for at least some navigation control. Such centralized control and management can be configured with other control and management activities. By way of example, such centralized control may be configured with timing management operations, such as disclosed in the other patents and patent applications which are incorporated by reference. Thus, aspects of the disclosure include devices, methods, and cooperating systems of devices configured for performing aerial fabric acrobatics.

In accordance with aspects of the disclosure, precoding aspects (including devices, device components, systems of devices, methods, and instructions for configuring a processor(s)) are disclosed herein for use in a variety of network configurations, including cellular networks (such as LTE networks), WPANs, WLANs, ad-hoc peer-to-peer networks, and multi-hop networks, to advanced network configurations, such as any of the variety of Cooperative-MIMO networks and airborne networks disclosed herein. It should be appreciated that aspects disclosed herein, including the precoding aspects, can be configured for any type of wireless network mentioned in any of the references incorporated herein.

FIG. **4**A is a block diagram of a spread-OFDM transmitter in accordance with an aspect of the disclosure. A baseband data processor **401** generates original data symbols from

user data, reference signals, or some combination thereof. A spreader **402** spreads the original data symbols into spread data symbols. A mapper **403** maps the spread data symbols to OFDM subcarriers, such as to input bins of an oversampled inverse discrete Fourier transform (IDFT) **404**, which is typically implemented as an oversampled fast transform (e.g., an FFT). The spread-OFDM signal output from the IDFT **404** is prepended with a cyclic prefix (in "+CP" circuit **405**) before amplification and up-conversion to RF in an RF front end **406**. Inter-symbol interference can be avoided if the cyclic prefix (or a guard interval) is longer than the delay spread of the impulse response of the channel.

In spread-OFDM, N subcarriers can be shared by every original data symbol in a block of up to N original data symbols if the spreading codes are configured to be orthogonal. The spreader **402** enables the N subcarriers to be shared by a block of up to N original data symbols. In one aspect, the function of the spreader **402** can be explained as follows: Each original data symbol of the block is replicated into N parallel copies. Each copy is then multiplied by a code chip from a corresponding spreading signature. A spreading signature can comprise a row or column of a spreading matrix, and may be referred to as a spreading code or a code space. The products are summed such that each sum (referred to as a spread data symbol) comprises one of N linear combinations of the original data symbols, wherein the coefficients are the code chips (e.g., a row or column of a corresponding spreading matrix), and the unknowns are the original data symbols. Each spread data symbol is modulated onto one of the N subcarriers, all of which are to be transmitted in parallel. The usual implementation of OFDM calls for the IDFT **404** to convert the parallel chips into serial form for transmission. In OFDM, the IDFT **404** is typically implemented via oversampling, so the input symbol block to the IDFT **404** is typically zero-padded, since zero padding in one domain (e.g., time or frequency) results in an increased sampling rate in the other domain (e.g., frequency or time). The cyclic prefix is appended to remove the interference between successive symbols and to accommodate the circulant convolution provided by the FFT.

In a receiver configured to receive spread-OFDM signals (such as the receiver block diagram depicted in FIG. **5**A), a received spread-OFDM transmission is filtered, converted to baseband, and digitized by an RF front end **501**, and then the cyclic prefix is removed (such as by a cyclic prefix removal circuit **502** or some equivalent). The receiver can comprise N matched filters, which can be implemented in the discrete baseband domain, such as by performing a DFT **503**. The output of the DFT **503** has the form of the transmitted signal multiplied by a diagonal channel matrix whose diagonal values are flat-fading coefficients, which allows for simple equalization **504**. The IDFT **404** and DFT **503** operations and the role of the cyclic prefix are implicitly absorbed through the diagonal structure of the channel response. Thus, aspects of the disclosure can provide for configuring the spreader **402** to provide various benefits, including (but not limited to) orthogonal codes, use of a fast-transform algorithm, and low PAPR.

In accordance with some aspects of the disclosure, a processor-based transceiver can include a non-transitory computer-readable memory with instructions stored thereon and configured to perform any of the algorithms disclosed herein. In reference to the spreader **402**, by way of example, each original data symbol in a block can be multiplied by a complex-valued spreading code, such as via a matrix multiplication operation. For example, a jth original data symbol d_j is multiplied by a jth column vector of an N×N spreading matrix S, where the jth column vector corresponds to the spreading code for symbol d_j, and N (which equals the number of subcarriers onto which the spread data is modulated) corresponds to the bandwidth expansion factor (e.g., spreading gain) to produce a jth spread data-symbol vector. The N different spread data vectors are summed to produce a vector of spread data symbols (of length N) before serial-to-parallel conversion and processing by the IDFT. It should be appreciated that if fewer than N original data symbols (e.g., n<N) are in a block, then N−n of the symbols in the block may be set to zero while still producing a length-N vector of spread data symbols.

FIG. **4**B is a block diagram of a spread-OFDM spreader (such as spreader **402**) in accordance with some aspects of the disclosure. An OFDM schedule processor **431** receives scheduling information which assigns a set of OFDM subcarriers to the corresponding transmitter. For example, if the transmitter is a UE, then the OFDM network assigns specific resource blocks (which includes a set of OFDM subcarriers) to be used by the UE for uplink transmissions. The OFDM schedule processor **431** obtains subcarrier parameters (e.g., number of subcarriers N, subcarrier spacing, and the like) which are conveyed to a spreading code generator **432**.

The spreading code generator **432** can be configured to process the subcarrier parameters and one or more criteria elements to select spreading codes. For example, the criteria can include code space orthogonality (i.e., orthogonal spreading codes), low PAPR, and enabling a fast transform operation for code generation and/or for encoding original data symbols. Other criteria may be employed. For example, a criterion which relates to pulse shaping (e.g., time-domain and/or frequency-domain shaping, or windowing) can further reduce PAPR by sacrificing some bandwidth efficiency. In one aspect, a mask (e.g., a spectral mask) may be applied to the subcarriers, such as by way of the coding or directly following the coding, in order to shape the spread-OFDM signal. This can achieve pulse shaping without directly processing the output of the IDFT **404**.

In one aspect, spreading is achieved via a fast transform operation (such as an FFT spreader **433**). The FFT spreader's **433** input parameters can be controlled by the spreading code generator in accordance with the criteria elements. In one aspect, FFT spreader **433** parameters, such as FFT size, input data block size, input data values, can be controlled by the spreading code generator **432**. In some aspects, the spreading code generator **432** can select how a fast transform is performed, such as by directly controlling the transform's operations or by indirectly controlling the transform via FFT size, and the like.

In one aspect, a user data processor **435** provides user data symbols to the spreader **433** for spreading. In another aspect, a reference signal data processor **437** provides reference signal data symbols to the spreader **433** for spreading. In some aspects, the user data processor **435** and the reference signal data processor **437** are configured to multiplex user data and reference signal data to produce the original data symbols, which are then spread by the spreader **433** to produce the spread data symbols.

Orthogonal Spreading

In accordance with an aspect of the disclosure, in a client device (such as a UE) configured to operate in an OFDM network, the spreading-code generator **432** is responsive to OFDM scheduling that assigns a particular set of uplink subcarriers to the client device, such as based on favorable channel conditions between the client device and one or more base transceiver stations. For example, channel-dependent scheduling of the uplink subcarriers to the client device

can be made to avoid interference, such as deep fades experienced by one or more subcarrier frequencies in a flat-fading environment, and/or interference caused by other transmitters. Responsive to the number of assigned uplink subcarriers, the spreading-code generator **432** selects a set of orthogonal complex spreading codes. Orthogonal functions (that is, signals or sequences) have zero cross-correlation. Zero correlation occurs if the product of two signals summed over a period of time (or sequence length) is zero. A set of signals or sequences in which all have zero cross-correlation with each other constitutes an orthogonal code space(s).

In one aspect, responsive to an assignment of N OFDM subcarriers, the spreading-code generator **432** selects an orthogonal N×N complex spreading matrix that comprises DFT coefficients. Some matrices comprising DFT coefficients are not orthogonal. While it is well known that some orthogonal functions can be generated or expanded using various algorithms, such as a seed algorithm or some other recursive technique, some of these algorithms do not provide codes with desirable features, such as orthogonality and low PAPR. For example, an N×N spreading matrix constructed by concatenating rows or columns of an N/2×N/2 DFT spreading matrix can yield fewer than N orthogonal spreading codes. Similar deficiencies result from concatenations and other combinations of different-size DFT matrices, permutations of DFT matrices, punctured DFT matrices, truncated DFT matrices, and the like. Thus, in some aspects, the spreading-code generator **432** advantageously provisions an N×N spreading matrix (or corresponding set of complex codes) to provide for N orthogonal spreading codes. This can be referred to as an orthogonal code space with dimension N.

In some aspects of the disclosure, the spreading-code generator **432** can orthogonally spread a block of up to N original data symbols with DFT-based complex spreading codes to produce a length-N vector of spread data symbols. In other aspects, the spreading-code generator **432** can employ complex spreading codes to spread N'>N original data symbols onto N subcarriers. While these complex spreading codes are not all orthogonal, the codes can be configured to have low cross correlation. Various techniques may be employed to select a code set having optimal features, such as low cross correlation, low PAPR, or a combination thereof. In some aspects, at least some of the spreading codes can be orthogonal to each other.

Low PAPR

In addition to providing for orthogonal spreading, the spreading code generator **432** can be responsive to OFDM scheduling to configure the complex spreading matrix to provide the spread-OFDM signal with a low PAPR. Unlike other PAPR-reduction techniques (such as clipping, peak cancellation, and others) which employ the IDFT **404** output (i.e., the spread-OFDM signal), the spreader **402** employs complex orthogonal spreading codes to spread original data symbols (which provides frequency diversity gain) while shaping the spread-OFDM signal to provide low PAPR.

Parameters of the assigned subcarriers, such as subcarrier frequency spacing and the number of subcarriers, can be used to determine complex orthogonal spreading codes that also produce a low-PAPR signal at the IDFT output. By way of example, the spreading-code generator can generate an orthogonal N×N spreading matrix wherein N is the number of subcarriers assigned to the transceiver, and the complex values of the spreading matrix can be generated based on the configuration of the assigned subcarriers, such as frequency spacing.

In one aspect, responsive to an assignment of a block of contiguous subcarrier frequencies, the spreading-code generator **432** can generate a complex spreading matrix with constant-modulus (e.g., constant magnitude) polyphase values derived from a DFT. In another aspect, if the subcarrier assignment comprises non-contiguous subcarriers with different frequency spacings, the complex spreading matrix that provides for low PAPR might comprise values with different magnitudes. Even in such aspects, the spreading-code generator **432** can generate a complex spreading matrix which achieves desired features corresponding to the criteria list, including low PAPR.

Fast Transforms

In accordance with some aspects of the disclosure, in a client device (such as a UE) configured to operate in an OFDM network, the spreading-code generator **432** is responsive to OFDM uplink scheduling to employ a complex spreading matrix that can be implemented via a fast transform algorithm. For example, based on a number of assigned OFDM subcarriers, an N×N complex spreading matrix can be selected in which the matrix-generation algorithm exploits the factorization of N. In some aspects, the number of assigned OFDM subcarriers equals N. In other aspects, a spreading matrix with dimension less than the number of assigned OFDM subcarriers might be selected, such as to facilitate spreading with a small sacrifice in data bandwidth, enable further PAPR reduction, or provide for other benefits. In some aspects, the scheduling is configured by the OFDM network such as to provide a number of assigned subcarriers that facilitates use of a fast transform algorithm by the spreading-code generator **432**.

The implementation of the DFT spreading as a fast algorithm (e.g., an FFT) can provide an efficient alternative to conventional Carrier Interferometry (CI) coding. In some aspects, an OFDM transceiver can employ the same FFT processor (e.g., such as FFT spreading module **433**, which can be an application-specific processor, a general purpose processor programmed to perform an FFT, or some other hardware configured to perform an FFT) and/or reuse a software program configured to perform spreading to perform other transceiver functions, such as OFDM modulation (e.g., IDFT **404**) and/or demodulation (e.g., DFT **503**). In such aspects, a common FFT hardware (e.g., module **433**, **404**, **503**, or **505**) or software module (e.g., program, object, function, or some other program construct) can be configured to adjust FFT processing parameters, such as relative to whether the FFT is being used for spread-OFDM coding, spread-OFDM decoding, OFDM modulation, or OFDM demodulation. FFT processing parameters can include one or more of oversampling factor, sampling rate, FFT length, zero-padding, truncating, modulo-length data wrapping, Radix-2 implementation, FFTW implementation, decimation in time, decimation in frequency, output ordering, input data format, rounding mode, saturate on integer overflow, sine table data type, product output data type, accumulator data type, output data type, output minimum, output maximum, and lock data type. Other FFT processing parameters can be employed.

A fast DFT algorithm, such as the Cooley-Tukey algorithm, can express a DFT of size $N=N_1N_2$ in terms of smaller DFTs of size N_1 and N_2 recursively to reduce the computation complexity to order of N log N for highly composite N (e.g., smooth numbers). The 2-smooth numbers are powers of 2 (i.e., a number of the form 2^n where n is an integer). Radix-2 implementation can comprise various algorithms, including (but not limited to) butterfly operation, double-

signal algorithm, half-length algorithm, decimation-in-time algorithm, and decimation-in-frequency algorithm.

Since the Cooley-Tukey algorithm breaks the DFT into smaller DFTs, it can be combined with other DFT algorithms. For example, Rader's algorithm, Bluestein's algorithm, Braun's algorithm, or other FFT algorithms can be used to handle large prime factors that cannot be decomposed by Cooley-Tukey, or the prime-factor algorithm can be exploited for greater efficiency in separating out relatively prime factors.

In many OFDM systems, the number N of subcarriers assigned to a transceiver is commonly a power of 2, which enables efficient OFDM modulation and demodulation. Thus, a radix-2 FFT of size N for DFT coding can also provides notable computational advantages. A processor for an OFDM transmitter configured to perform an IFFT, for example, can be easily configured to perform fast DFT spreading. Accordingly, some aspects of the disclosure employ a radix-2 DFT matrix to spread data symbols. This enables computationally efficient spreading, and like CI spreading, when the spread-DFT data is input to selected bins of an IFFT used in an OFDM transmitter, the resulting spread-DFT OFDM signal can have a low PAPR.

In accordance with some aspects of the invention, in an OFDM transmitter apparatus, a radix-2 DFT spreader (e.g., spreader **402**) and the subcarrier mapper **403** are configured in a manner such that the combination of DFT spreading and subcarrier allocation produces a transmitted OFDM signal with low PAPR. By way of example, the size N can equal the number of subcarriers allocated to the OFDM transmitter apparatus, and wherein the allocated subcarriers are uniformly spaced in frequency. The allocated subcarriers can comprise a block of contiguous subcarriers, such as may be assigned to the OFDM transmitter apparatus based on favorable channel conditions between the OFDM transmitter apparatus (e.g., a UE) and at least one server-side WWAN terminal (e.g., a base transceiver station). A determination of favorable channel conditions may be made by either or both the OFDM transmitter apparatus and the at least one server-side WWAN terminal (including a scheduler communicatively coupled to multiple WWAN terminals) and may be based on measurements and/or estimates of the channel at either or both the OFDM transmitter apparatus and the at least one re server-side WWAN terminal.

A processor for an OFDM receiver configured to perform an FFT, for example, might be configurable to perform the DFT spreading. In some aspects, the receiver processor does not normally operate while its associated transceiver device is in transmit mode, so the receiver's FFT is available to support transmit processing, such as to provide for the DFT spreading. In some aspects, the transmitter may employ the same processor to perform both DFT spreading and the IFFT. Such implementations can provide various benefits (e.g., reduce complexity, improve efficiency, reduce cost, reduce power consumption, etc.) by employing the same hardware to perform both spreading and OFDM modulation. With regard to software, such implementations disclosed herein can enable code reuse. In some aspects, pipelined FFT processing can be provided. By way of example, pipelined processing can be configured to provide multiple simultaneous FFT operations, such as DFT-spreading and subcarrier modulation (e.g., via IFFT). In some aspects, pipelined processing can be performed as part of cooperative processing between multiple processing cores (such as in a data center), or residing on different WWAN terminals (e.g., UEs and/or base transceiver stations) in a cooperating cluster.

In accordance with other aspects of the disclosure, an FFT processor configured for at least one transmitter operation can be configured for a receiver operation. In some aspects, a single FFT processor can be employed to enable multiple operations, including any combination of OFDM modulation, OFDM demodulation, DFT spreading, and DFT de-spreading.

In accordance with some aspects of the disclosure, the block diagram shown in FIG. **4**A comprises the transmitter part of a UE configured to transmit an uplink spread-OFDM signal with low PAPR, and the block diagram in FIG. **5**A comprises the receiver part of a server-side WWAN device (or system) configured to receive the UE's uplink spread-OFDM signal. In the server-side WWAN device (or system), an RF front-end system **501** filters, amplifies, down-converts, and digitizes the received spread-OFDM signal to produce a received baseband signal. The cyclic prefix is stripped (in "-CP" circuit **502**) and the OFDM signal is demodulated by the DFT **503**. Equalization and demapping **504** (which can include soft and/or hard decision processing) produces received spread-OFDM symbols. The de-spreader **505** can comprise an IFFT to efficiently de-spread DFT-spread symbols to produce estimates of the original data symbols. The baseband processor **506** performs additional down-stream baseband processing on the estimates, such as error detection, error correction, transcoding, formatting, and/or other post-processing operations.

FIG. **5**B is a block diagram that depicts a portion of a receiver, such as a receiver that may be employed in a server-side WWAN terminal or system. In one aspect, the de-spreader **505** comprises the system shown in FIG. **5**B. A de-spreading code generator **552** processes subcarrier parameters corresponding to the received spread-OFDM signal to control decoder **553**. Since the server side of the WWAN can schedule the uplink OFDM subcarriers used by each UE, the subcarrier parameters can be retrieved from a UE scheduler **551**.

In some aspects, the UE scheduler **551** assigns uplink subcarriers to a UE based on favorable channel conditions for that UE (which is referred to as channel-dependent scheduling). In addition to favorable channel conditions, a criteria list employed by the UE scheduler for assigning uplink subcarriers might include providing for orthogonal spreading codes, enabling spreading codes that produce a transmitted spread-OFDM signal with low PAPR, and/or enabling a fast transform to be used for spreading and de-spreading. While channel-dependent scheduling might identify a particular group of candidate subcarriers to be assigned to a UE uplink channel, the other criteria can specify the number N of subcarriers, the subcarrier spacing, as well as other signal parameters assigned by the scheduler **551**. For example, selecting N to be a power of 2 can enable certain fast transforms to be used in spreading and/or de-spreading. Selecting contiguous subcarriers or uniformly spaced subcarriers can facilitate (and possibly ensure) the UE's implementation of orthogonal spreading codes that provide low PAPR features.

In one aspect, a de-mapped data processor **555** can provide spread data symbols comprising spread user data symbols, spread reference signals, or both to the decoder **553**. The decoder **553** can employ a fast transform, such as an IFFT, to de-spread the spread data symbols and produce de-spread data symbols which are output for further processing. The de-mapped data processor **555** may be part of the equalizer and de-mapper **504** or it may be part of the de-spreader **505**.

DFT-Spreading Method:

In accordance with one aspect of the disclosure, as depicted in FIG. **6**A, a method performed in a radio transceiver is provided, which can employ a fast algorithm to generate a spread data sequence from an original data sequence. The algorithm which generates the spread data sequence is configured to provide a low PAPR to an OFDM signal modulated with the spread data sequence. Specifically, the spreading causes the transmitted OFDM signal (such as a signal output from IDFT **404**) to have a low PAPR compared to an un-spread OFDM signal (such as the resulting transmitted OFDM signal if spreading is not performed).

In some aspects, the method depicted in FIG. **6**A comprises functional steps implemented via software instructions operable to cause a processor (such as a general-purpose processor) to execute the steps in a process which produces a spread-OFDM signal. In some aspects, one or more of the functional steps are embodied in hardware, such as circuits.

By way of example, application-specific integrated circuits (ASICs), field-programmable gate arrays (FPGAs), and/or other circuits can be provided as embodying one or more of the functional steps disclosed throughout the specification and depicted in the drawings. In some aspects, multiple ones of the functional steps can be implemented by a common processor or circuit. For example, certain efficiencies might be achieved by configuring multiple functional steps to employ a common algorithm (such as an FFT and/or some other algorithm), thereby enabling a circuit, a processor, or some other hardware component to be used for different functions, and/or enabling software instructions to be shared for the different functions.

The radio transceiver, such as a UE, receives an OFDM channel assignment **601** from a scheduler in the WWAN. For example, OFDM channels in the WWAN might be assigned via channel-dependent scheduling. The OFDM channel assignment is processed to acquire OFDM subcarrier parameters pertinent to operation of the transceiver **602**. Based on the subcarrier parameters, orthogonal spreading codes are configured in a manner to cause a corresponding spread-OFDM signal to have low PAPR **603**. For example, the spread-OFDM signal is configured to have a lower PAPR than if spreading was not performed. Configuring the spreading codes in accordance with step **603** can comprise a combination of a) determining a spreading code length(s) based on the number of subcarriers assigned to the transceiver; b) determining spreading code values based on the spreading code length(s) and the configuration of subcarriers (e.g., subcarrier spacing) assigned to the transceiver; and c) arranging the spread data symbols (which can include re-ordering the output of a spreading function) in a particular order or arrangement such that each spread data symbol maps to a particular one of the assigned subcarriers to achieve at least one objective, such as to provide the spread-OFDM signal with a low PAPR.

In aspects of the disclosure, one or more spreading code parameters (such as code length) can optionally be configured to enable use of a fast spreading algorithm, such as an FFT, to perform spreading **604**. In other aspects, the spreading codes may be retrieved from a memory and employed in a matrix multiply or equivalent operation. For example, spreading codes might be generated for different subcarrier parameters (e.g., number of subcarriers, subcarrier spacing, and the like), possibly using a fast spreading algorithm, and stored in the memory. Then spreading codes corresponding to particular subcarrier parameter(s) can be retrieved from the memory to be used in spreading **604**.

Code parameters, such as code length and the code values, can be selected to allow a fast algorithm (such as the FFT) to be used for spreading-code generation and/or to spread original data symbols, such as via a fast transform. This can include selecting a block size of input original data symbols (and corresponding spreading matrix dimension) to facilitate use of a fast transform and/or achieve other processing efficiencies. In some aspects, zero values can be added to the block of original data symbols to provide a predetermined block size.

By way of example, but without limitation, a spreading code matrix can comprise complex spreading codes selected from a larger set of spreading codes, such as CI codes, which are complex spreading codes that exist for any code length. For example, restricting the code length (or matrix dimension) N to a length that is a power of 2 enables a specific set of spreading code values that permit a fast transform algorithm (such as a radix-2 decimation-in-time (DIT) FFT) to be employed as the spreading algorithm **604**. In other aspects, N can be selected to equal a product of small prime numbers which can include numbers other than 2.

Selecting the code length and the code values (such as specific code values corresponding to particular OFDM subcarriers assigned to the radio transceiver) can provide for configuring the spreading code **603** to produce a spread-OFDM signal (at the output of step **606**) with low PAPR. For example, in one aspect, an OFDM network might employ non-contiguous blocks of subcarriers (such as for opportunistic transmissions, cognitive radio applications, channel optimization, and/or for other purposes). Thus, the code values (and optionally, the code length) can be selected **603** to provide a low PAPR to the resulting transmitted OFDM signal. The code values and code length can also be selected to affect the orthogonality of the codes as part of step **603**, such as to provide orthogonal codes, sacrifice orthogonality for lower PAPR, sacrifice bandwidth efficiency for lower PAPR, or some combination thereof.

The spread data symbols are mapped to particular OFDM subcarriers **605**. In some aspects, mapping **605** comprises sequence reordering to map specific spread symbols to specific subcarriers, which can achieve certain advantages. For example, a preferred mapping of the spread data symbols to the OFDM subcarriers achieves the low PAPR, whereas an alternative mapping may not. Even when contiguous subcarriers and spread-DFT or CI codes are employed, the selection of the spreading codes **603** and the mapping **605** affects the PAPR. A proper mapping **605** of the spread data symbols to specific subcarriers achieves the low PAPR.

In one aspect, besides the trivial case of all ones, a spread-DFT code (which is a constant-modulus complex code) can be regarded as comprising a uniform phase increment in the complex plane from one code value to each successive value in the DFT code vector. In the trivial case, the phase increment is zero. Each spread data symbol comprises a sum of the products of each original data symbol with a code value from the original data symbol's corresponding spread-DFT code. This spreading can be implemented via a matrix multiply, such as between a spreading code matrix and a vector of original data symbols. The spreading can be implemented via a DFT, such as an FFT. However, the spread data symbols are markedly different from the frequency responses derived from a spectrum analyzer, which also uses a DFT.

Each spread data symbol comprises a linear combination of the original data symbols, wherein each coefficient in the linear combination comprises the code value corresponding

to the original data symbol's code and a common location in the code vector of that code. Stated another way, consider an nth original data symbol d_n spread by a corresponding n^{th} DFT spreading vector $c_n=[c_{n1}, c_{n2}, \ldots, c_{nm}, \ldots, c_{nN}]$. An mth spread data symbol in a spread data symbol vector x is the sum,

$$x_m = \sum_{n=1}^{N} c_{nm} s_n,$$

which indicates that the mth spread data symbol is the sum of each data symbol s_n multiplied by the mth code value in its corresponding code vector c_n. The mth code value c_{nm} represents the mth uniform phase increment in the complex plane for that code c_n. Thus, the mth spread data symbol can be associated with an mth set of uniform phase increments. Spreading yields N spread data symbols, whereas spectrum analysis (which uses a DFT) produces frequency responses corresponding to N/2 (orthogonal) tones due to the Nyquist limit.

In one aspect, the mapping **605** comprises arranging the spread data symbols in accordance with increasing uniform phase increments, and matching the spread data symbols according to this arrangement to a set of OFDM subcarriers having increasing uniform frequency increments. The mapping **605** of the spread data symbols having increasing uniform phase increments to the OFDM subcarriers with corresponding increasing frequency increments provides for producing a spread-OFDM signal with low PAPR. In serial implementations, arranging the spread data symbols can take the form of sequencing the symbols in ascending or descending order relative to their corresponding phase increments. In parallel implementations, arranging the spread data symbols can take the form of arranging the symbols relative to input bins of an IFFT for corresponding increasing OFDM subcarrier frequencies. Thus, in some aspects, the mapping **605** can comprise sequence reordering of a DFT output.

In some aspects, the mapping **605** order of symbols to IFFT bins may be fixed. Thus, configuring the spreading codes **603** and/or spreading **604** may be provisioned to configure the mapping **605** which ensures a low-PAPR spread-OFDM signal. For example, configuring the spreading codes **603** can comprise arranging the order of values in a spreading code matrix to produce a vector of spread symbol values arranged in a manner that the fixed mapping **605** results in a spread-OFDM signal with low PAPR, the order relating to a mathematical relationship with the subcarrier frequencies that achieves the low PAPR regardless of the arrangement of the original data symbols. In another aspect, the spreading **604** is configured to arrange the spread data symbols in a manner that the mapping **605** results in a spread-OFDM signal with low PAPR regardless of the order of the original data symbols.

In accordance with some aspects of the disclosure, such as in relationship to methods, software instructions, and devices which perform step **603**, the code length N can correspond to a number of OFDM subcarriers allocated to the radio transceiver. For example, the code length N might equal the number of OFDM subcarriers, which is commonly a power of 2. In some aspects, the code length N might be less than the number of assigned OFDM subcarriers. In other aspects, the code length N might be greater than the number of OFDM subcarriers, such as a multiple thereof. In some aspects, the code length N might equal the number of OFDM subcarriers assigned as user-data channels for the radio transceiver. In some aspects, the code length N might equal the number of OFDM subcarriers assigned as reference signals for the radio transceiver. In some aspects, unlike in conventional spread-OFDM, transmitted reference signals are spread. In some aspects, the reference data can be spread with the user data.

In one aspect, an N×N spreading code matrix is selected wherein N is a power of 2 and the code matrix values are selected from the set of basic CI code values to permit use of a radix-2 FFT for spreading a set of original data symbols. The CI coding may be provided via a DFT in order to provide for DFT spreading, which can be implemented by a fast transform, such as an FFT. The input to the radix-2 FFT can comprise a block of up to N original data symbols, and the fast spreading algorithm generates N spread data symbols.

At least one of an original data sequence length and a spread data sequence length is selected to enable use of a fast DFT transform. By way of example, the original data sequence length can equal the spread data sequence length, and this length can be selected to be a power of 2, which permits a radix-2 decimation-in-time (DIT) FFT to spread the original data sequence.

It should be appreciated that in alternative aspects, the spreading code matrix need not be a square matrix. In some aspects, the spreading codes can comprise alternative complex-valued code families, and the code values and code length can be selected to permit use of a fast spreading algorithm to spread the original data symbols and provide a resulting transmitted spread-OFDM signal with low PAPR.

Various types of fast spreading algorithms can be employed to spread the original data symbols to produce spread data symbols. In some aspects, the fast spreading algorithm comprises a DFT spreading operation.

The DFT spreading operation is defined by

$$x_k = \sum_{n=0}^{N-1} s_n e^{-i2\pi nk/N}$$

Where x_k represents the kth spread data symbol, s_n are the original data symbols, and N is the length. In this example, both the index k and the index n range from 0 to N−1.

The Radix-2 DIT FFT computes the DFTs of the even indexed inputs ($s_{2m}=s_0, s_2, \ldots, s_{N-2}$) and the odd indexed inputs ($s_{2m+1}=s_1, s_3, \ldots, s_N-1$), and then combines the results to produce the DFT-spread data sequence. For example, the Radix-2 DIT algorithm expresses the DFT-spreading of original data symbols s_n as a sum of spread even-numbered indices (n=2m) and spread odd-numbered indices (n=2m+1):

$$x_k = \sum_{m=0}^{N/2-1} s_{2m} e^{-i2\pi(2m)k/N} + \sum_{m=0}^{N/2-1} s_{2m+1} e^{-i2\pi(2m+1)k/N}$$

The common multiplier $e^{-i2\pi k/N}$ can be factored out of the second sum, so the spread data symbols can be represented as:

$$x_k = x_{even(k)} + e^{-i2\pi k/N} x_{odd(k)}$$

Where $x_{even(k)}$ is the even-indexed part, and $x_{odd(k)}$ is the odd-indexed part of x_k.

Due to the periodicity of the DFT, $x_{even(k+N/2)}=x_{even(k)}$ and $x_{odd(k+N/2)}=x_{odd(k)}$. Thus,

$$x_k = \begin{cases} x_{even(k)} + e^{-i2\pi k/N} x_{odd(k)} & \text{for } 0 \le k < N/2 \\ x_{even(k-N/2)} + e^{-i2\pi k/N} x_{odd(k-N/2)} & \text{for } N/2 \le k < N \end{cases}$$

Since the "twiddle" factor

$$e^{-i2\pi\left(k+\frac{N}{2}\right)/N} = -e^{-i2\pi k/N},$$

this reduces me number of these calculations by half. The spread sequence of length-N can be expressed recursively in terms of two spreading operations of size N/2 (0≤k<N/2)

$$x_k = x_{even(k)} + e^{-i2\pi k/N} x_{odd(k)}$$

$$x_k = x_{even(k)} - e^{-i2\pi k/N} x_{odd(k)}$$

This decimation operation can be performed down to the 2×2 DFT. The final outputs are obtained by a +/−combination of $x_{even(k)}$ and $e^{-i2\pi k/N}x_{odd(k)}$, which is simply a size-2 DFT.

It should be appreciated that other fast algorithms may be employed, including algorithms that exploit symmetry, remove redundant parts of a computation, and/or achieve other efficiencies, as well as other divide-and-conquer algorithms.

It should be appreciated that in practice, the actual performance of a fast algorithm depends on additional factors which affect computation speed, memory use, power consumption, and various processing overheads, such as communications between processors. In some aspects, in-place algorithms, bit reversal, data reordering, non-blocking pipelined configurations, and the like can be implemented in the fast algorithm. As such, operations of the fast algorithm can be configured to employ the required mapping that achieves the lowest possible PAPR for a given code set.

In some cases, performance metrics depend on the computing architecture employed. Thus, in accordance with some aspects of the disclosure, in addition to configuring the fast spreading algorithm **503** to improve performance on a given computing architecture, configuring the spreading code parameters to enable use of a fast spreading algorithm **501** can include selecting and/or adapting the spreading code parameters in a manner that improves the performance of the fast spreading algorithm.

In OFDM, active subcarriers are typically assigned with data symbols. For unassigned subcarriers, OFDM provides for zero-valued inputs for the IFFT (transmitter) and zero-valued outputs for the FFT (receiver). Often, conventional FFT/IFFT algorithms are not efficient due to the unwanted operations on zero values. Therefore, in some aspects of the disclosure, efficient FFT/IFFT algorithms can be employed to dynamically eliminate the multiplication and addition operations associated with deactivated subcarriers. For example, FFT pruning methods eliminate operations on input and output values which are not required. The basic concept involves determining the index of the butterflies to be chosen for computations and those to be discarded. Thus, FFT computation time can be significantly reduced by pruning the operations on zero values in the discarded butterflies. Most of these algorithms are suitable for applications with specific zero-input or zero-output pattern distributions. These types of efficient algorithms can be used in the FFT spreading and/or IFFT de-spreading operations, such as when zero-valued inputs and/or outputs are employed.

FIG. **6**B is a flow diagram that can be employed in accordance with various aspects of the disclosure, such as for processing received spread-OFDM signals. In one aspect, for example, the method depicted in FIG. **6**B is performed by a server-side device or system in a WWAN. A scheduler in the WWAN arranges OFDM assignment blocks in a manner that facilitates low-PAPR spreading **611**. Different block sizes may be allocated to accommodate different data rates. For example, if the blocks are configured such that resources assigned to a UE comprise contiguous (or otherwise equally spaced) OFDM subcarriers, then this can facilitate uplink spreading (by the UE) which achieves a low-PAPR spread-OFDM signal.

In some aspects, the scheduler arranges the OFDM assignment blocks in a manner that facilitates fast transforms to be employed for spreading (and, optionally, de-spreading) **612**. For example, the number of OFDM subcarriers in each block might be selected to equal a product of small prime numbers. In some aspects, the block sizes are configured to enable a Radix-2 DIT FFT for spreading (and optionally, a Radix-2 DIF IFFT for decoding).

As described herein and in patents and applications incorporated by reference, the uplink OFDM subcarriers can be assigned for use by the UEs **613**, such as via channel-dependent scheduling. The server-side device or system typically demodulates received uplink OFDM signals **614** by using a DFT, such as an FFT. Demodulation **614** can include equalization. In some aspects, the demodulated symbols, which are DFT-spread data symbols, are de-mapped **615**, such as via an OFDMA de-multiplexer, which separates the received uplink signals by UE. Thus, for each UE, a received uplink signal can be de-spread by determining the de-spreading codes based on the UE's channel assignment (which indicates the number of OFDM subcarriers and the subcarrier spacing) **616**, followed by employing a fast algorithm (e.g., an IFFT) configured to de-spread the spread data symbols **617**.

FIG. **7**A is a flow diagram that depicts a method for generating spread-OFDM signals in accordance with some aspects of the disclosure. Responsive to the subcarrier assignment and/or selection, the spreading code parameters can be configured to enable use of a fast spreading algorithm **701** and configured to produce a transmitted spread-OFDM signal with low PAPR **702**. The fast spreading algorithm, such as an FFT, is configured to spread the original data symbols with orthogonal spreading codes to produce the spread data symbols **703**, which are then mapped to an IFFT **704**. The IFFT modulates the spread data symbols onto the assigned (or selected) OFDM subcarriers to produce a spread-OFDM signal **705**. The spreading **703** and the IFFT **705** can each employ one or more of the FFT pruning methods, including modified FFT pruning, partial FFT pruning, split-radix FFT pruning, or traced FFT pruning. In some aspects, such as in hardware implementations of FFTs, a transform decomposition can be performed.

In accordance with some aspects of the disclosure, instead of separately calculating the spreading **703** and IFFT **705**, both transforms are combined into a single transform. In one aspect, this can be accomplished by using a unified butterfly so that the number of arithmetic operations, delays, and indexing are reduced. One approach can employ an algorithm based on a sparse matrices factorization method, such as via the Kronecker product technique. In another aspect, the spreading **703** and IFFT **705** are combined into a single

fast transform that comprises a fast orthonormal unitary transform. The aforementioned techniques for spreading and OFDM modulation can also be adapted for OFDM demodulation and de-spreading operations.

In accordance with some aspects of the disclosure, non-contiguous subcarriers can be employed, such as due to assignment of non-contiguous OFDM subcarriers to the radio transceiver or due to selection of a subset of subcarriers (e.g., reference signals or user data signals) to be provided with separate coding from the rest of the subcarriers. In such aspects, one or more of the steps in FIG. **7**A can be configured accordingly. In some cases, certain trade-offs can be made between PAPR, orthogonality, and/or bandwidth efficiency.

In one aspect of the disclosure, the spread data symbols are critically sampled (one sample per information symbol/subcarrier) and grouped in information signal blocks of length N. By way of example, but without limitation, the spread data symbols are generated at the critical sampling rate $f_s=1/T_s$ and modulated **705** onto the N orthogonal subcarriers during a time interval defined for one OFDM symbol with period Nils. In practice, the output of the IFFT **705** is a well-interpolated baseband signal. For example, oversampling in the time domain is usually achieved via frequency-domain interpolation, which is achieved by zero-padding the IFFT. If the oversampling rate is $f_{os}=Lf_s$, where L is the oversampling factor, the IDFT matrix has dimension (NL×NL). Although not shown, following block **705**, a cyclic prefix or guard interval is typically added to each OFDM symbol, followed by filtering, D/A conversion, frequency up-conversion, amplification, and possibly other radio front-end processing.

FIG. **7**B is a flow diagram that depicts a method of processing received spread-OFDM signals in accordance with some aspects of the disclosure. By way of example, the method depicted in FIG. **7**B can be performed by a server-side WWAN device or system to receive spread-OFDM uplink signals from at least one UE.

The WWAN assigns uplink OFDM subcarriers to UEs, such as via channel-dependent scheduling or some other scheduling scheme **710**. Uplink OFDM subcarriers can be scheduled dynamically, such as in response to specified bandwidth needs. Different blocks of subcarriers can be configured prior to assignment or on the fly, and in a manner that subcarrier parameters (such as the number of subcarriers and their spacing) are configured to enable orthogonal spreading codes (or at least spreading codes with low cross correlations), complex spreading codes with low PAPR, and/or coding/decoding that can utilize fast algorithms (such as FFTs).

In some aspects, a WWAN device has subcarrier parameter information available from the scheduling **710**. In other aspects, the WWAN device receives the subcarrier parameter information by some other means. In one aspect, the WWAN device reads the subcarrier parameter information transmitted in a control channel, which might include a broadcast channel containing scheduling information. In other aspects, the WWAN device reads and/or determines subcarrier parameter information from uplink UE transmissions. The subcarrier parameter information can then be used in subsequent steps or blocks, such as depicted in FIG. **7**B.

Received spread-OFDM signals are demodulated **711**. In some aspects, the subcarrier parameter information can be used to demultiplex received OFDMA signals, followed by demodulation **711** of the OFDM subcarriers corresponding to each UE. Although not shown, demodulation **711** can include RF front-end processing (such as amplification, filtering, down-conversion, ADC, etc.), cyclic prefix removal, equalization, and/or matched filtering. In some aspects, demodulation **711** can comprise spatial demultiplexing (such as MIMO subspace processing). Other types of demultiplexing may be performed. Demodulation **711** typically comprises performing an over-sampled FFT, although other types of demodulation may be employed. In some aspects, demodulated OFDM signals can be equalized, such as via frequency-domain equalization (not shown).

Estimated spread data symbols produced from demodulation **711** are de-mapped **712**. In one aspect, demodulation **711** comprises performing an FFT on all the received signals, and de-mapping **712** can comprise demultiplexing (e.g., separating the estimated spread data symbols with respect to corresponding UE). The subcarrier parameter information can be used to group the estimated spread data symbols according to their respective UEs. Demodulation **711** and/or de-mapping **712** can employ data re-ordering (e.g., symbol re-ordering and/or bit re-ordering) to facilitate de-spreading **713**.

De-spreading **713** can comprise utilizing a fast algorithm, such as an FFT, to de-spread the estimated spread data symbols. Input parameters to the de-spreading algorithm can be selected based on the subcarrier parameter information, such as to provide a correct de-spreading code length and/or appropriate de-spreading code values for de-spreading the estimated spread data symbols. Outputs from the de-spreading **713** comprise de-spread data symbols, which can be processed to generate estimates of the original data symbols. These estimates may be grouped by UE.

In one aspect, a spread-OFDM transceiver comprises a non-transitory computer-readable memory storing DFT-spread OFDM software instructions thereon and at least one processor configured to execute the DFT-spread OFDM software instructions to operate as a spread-OFDM transmitter. Such a transceiver is depicted in FIG. **9**.

In one aspect of the disclosure, FIG. **8**A depicts a set of modules, each comprising instructions stored on a non-transitory computer-readable memory and configured to instruct a general-purpose processor (such as a processor core, a server, a distributed computing system, etc.) to perform functions disclosed herein. In other aspects, one or more modules can comprise a specific-purpose processor, such as an application-specific integrated circuit or some other circuit.

A baseband modulator, which can be implemented as a software module **801**, transforms a binary input to a multi-level sequence of complex numbers in one of several possible modulation formats, including binary phase shift keying (BPSK), quaternary PSK (QPSK), 16-level quadrature amplitude modulation (16-QAM) and 64-QAM. The modulator **801** can adapt the modulation format, and thereby the transmission bit rate, to match current channel conditions of the transceiver. The output signal is referred to as original data symbols.

A spreader, which can be implemented as a software module **802** which provides spreading instructions to a processor, groups the original data symbols into blocks, each comprising N symbols. The spreader is configured to perform an N-point discrete Fourier transform (DFT) to produce a set of spread data symbols. In accordance with certain aspects of the disclosure, it is instructive to note that the DFT-spread output signal (i.e., the set of spread data symbols) differs from the customary frequency-domain representation of a spectral analysis that produces frequency responses according to tones (i.e., OFDM tones constitute

the transform's basis functions). For example, the DFT-spreading output signal comprises N spread data symbols, whereas the spectral analysis produces only N/2 frequency responses, as the bandwidth of the baseband frequency response signal is limited to the range of positive frequencies, 0 to half the sampling rate (=$f_{Nyquist}$).

We begin with the definition of frequency, which Merriam-Webster Dictionary defines as the number of repetitions of a periodic process in a unit of time; the number of complete alternations per second of an alternating current; and the number of complete oscillations per second of energy (as sound or electromagnetic radiation) in the form of waves. The definition of frequency offers no distinction between a negative frequency and a positive frequency. Rather, what differentiates a negative frequency from a positive frequency relates to direction, not tone.

The mathematical representation of negative frequency can be found in the expression of physical signals as a sum of complex exponential components. For example, the negative frequency can be seen in the representation of cosine and sine functions as the weighted sums of the corresponding exponential function:

$$\cos(\omega t)=\mathrm{Re}\{e^{i\omega t}\}=(e^{i\omega}+e^{-i\omega t})/2$$

$$\sin(\omega t)=\mathrm{Im}\{e^{i\omega t}\}=(e^{i\omega t}-e^{-i\omega t})/2i$$

In discrete systems, the frequency $f=\omega/2\pi$ of an analysis interval can range from 0 to f_{sam}, or equivalently, from $-f_{sam}/2$ to $+f_{sam}/2$, where f_{sam} is the sampling frequency (i.e., the number of samples per interval). In discrete-time systems, the frequency response is constrained by the Nyquist frequency, which is half the sampling rate f_{sam}.

In general, when a sinusoid of frequency f is sampled with frequency f_{sam}, the resulting number of cycles per sample is f/f_{sam} (known as normalized frequency), and the samples are indistinguishable from those of another sinusoid (called an alias) whose normalized frequency differs from f/f_{sam} by any integer (positive or negative). Replacing negative frequency sinusoids by their equivalent positive frequency representations, all the aliases of frequency f can be expressed as $f_{alias}(n)=|f-nf_{sam}|$ for any integer n, with $f_{alias}(0)$ being the true value.

Aliasing matters when analyzing a signal, such as performing spectrum analysis, which expresses the discrete signal of N complex data symbols as a set of N/2 frequency responses, sometimes referred to as tones. Tones are defined herein in the usual and customary sense with regard to the fields of OFDM and Fourier transforms as orthogonal frequencies, e.g., spectral components. The typical analysis technique employs the smallest of the $f_{alias}(n)$ frequencies. So it is important that $f_{alias}(0)$ be the unique minimum. A necessary and sufficient condition for this is $f_{sam}/2>|f|$, where $f_{sam}/2$ is the Nyquist frequency of a system with sampling rate f_{sam}. For example, with Fourier transform analysis in a digital spectrum analyzer, it is necessary to sample the input signal with a sampling frequency that is at least twice the bandwidth of the input signal due to the Nyquist limit. The Fourier transform will then produce a spectrum containing frequencies from 0 to $f_{sam}/2$. While only N/2 frequency responses are achievable, N-point spreading disclosed herein can produce N spread data symbols.

The following software code can be used to implement DFT spreader **802** in accordance with aspects of the disclosure. By way of example, the FFTW program (such as can be found at www.fftw.org, all the descriptions and documentation described therein and the contents of the links provided, being incorporated by reference in their entireties) can be employed to compute a DFT, such as a one-dimensional DFT of size N:

```
#include <fftw3.h>
. . .
{
  fftw_complex *in, *out;
  fftw_plan p;
  . . .
  in=(fftw_complex*)  fftw_malloc(sizeof(fftw_complex)*N);
  out=(fftw_complex*)  fftw_malloc(sizeof(fftw_complex)*N);
  p=fftw_plan_dft_1d(N, in, out, FFTW_FORWARD, FFTW_ESTIMATE);
  . . .
  fftw_execute(p); /* repeat as needed */
  . . .
  fftw_destroy_plan(p);
  fftw_free(in); fftw_free(out);
}
```

To use the FFTW program, this code example is linked with the fftw3 library. The example code first allocates the input and output arrays using the fftw_malloc function.

The data is an array of type fftw_complex, which is by default a double [2] composed of the real (in [i][0]) and imaginary (in [i][1]) parts of a complex number. The next step is to create a plan, which is an object that contains all the data that FFTW needs to compute the FFT. This function creates the plan:

```
fftw_plan fftw_plan_dft_1d(int N, fftw_complex *in,
  fftw_complex *out, int sign, unsigned flags);
```

The first argument, N, is the size of the transform that will be computed. While the size N can be any positive integer, sizes that are products of small factors can be transformed most efficiently, such as described herein. The next two arguments are pointers to the input and output arrays of the transform. These pointers can be equal, indicating an in-place transform. The fourth argument, sign, can be either FFTW_FORWARD (−1) or FFTW BACKWARD (+1) to indicate the direction of the transform. Technically, it is the sign of the exponent in the spreading codes. While aspects of the disclosure discuss forward transforms for spreading, other aspects can employ the backward (e.g., inverse) transform for spreading. For example, an IDFT can be implemented as an IFFT to provide for spreading or generating the spreading code(s). Thus, the term DFT as used herein is meant to include its corresponding backward (e.g., inverse) transform. The flags argument is usually either FFTW_MEASURE or FFTW_ESTIMATE. FFTW_MEASURE instructs FFTW to run and measure the execution time of several FFTs in order to find the best way to compute the transform of size N.

Once the plan has been created, it can be used multiple times for transforms on the specified input and output arrays by computing the transforms via

```
fftw_execute (plan):
void fftw_execute(const fftw_plan plan);
```

The DFT results are stored in-order in the output array (out), with the zero-frequency (DC) component in out [0]. If in!=out, the transform is out-of-place and the input array (in) is not modified. Otherwise, the input array is overwritten with the transform. To transform a different array of the same size, a new plan is created with fftw_plan_dft_1d, and FFTW automatically reuses the information from the previous plan, if possible. The plan can be deallocated by calling fftw_destroy_plan (plan).

FFTW uses the standard "in-order" output ordering, meaning that the nth output corresponds to the frequency n/N (or n/T, where T is the total sampling period). In terms of positive and negative frequencies, this means that the positive frequencies are stored in the first half of the output and the negative frequencies are stored in backwards order in the second half of the output (i.e., the frequency −n/Nis the same as the frequency (N−n)/N).

The output ordering of the FFT depends on the type of FFT employed, including whether the FFT is implemented in hardware or software. For example, an FFT block can output the frequency indices in linear or bit-reversed order. Linear ordering of the frequency indices requires a bit-reversal operation. Thus, in some aspects, it may be necessary for the FFT or the mapper to re-order the output, such as to provide a mapping to the OFDM subcarriers which yields the low PAPR.

In some aspects of the disclosure, spreader **802** may be implemented via the following steps. A DFT can be used to generate the spreading codes, which are then stored in memory. Based on OFDM subcarrier assignment, subcarrier parameter(s) is (are) input, and a corresponding set of codes is selected from the memory and used to spread the original data symbols, such as via a matrix multiplication operation. For example, the input vector (in) can be a kernel used by the FFTW program to generate the spreading matrix, which can then be stored in non-transitory memory, and selected thereafter (such as with respect to the number of subcarriers N, subcarrier spacing, and/or any other subcarrier parameter(s)) for use in a matrix multiplication operation with a matrix comprising the original data symbols.

In aspects disclosed herein, the input vector comprises the data symbols, wherein the vector length N can be selected to have small prime factors (which can provide certain processing performance advantages). The input data vector can be configured, such as via zero insertion and scaling, to affect the distribution and/or scaling of non-zero terms in the output vector.

In one aspect, a spreading configuration module **811** processes subcarrier parameters corresponding to resource blocks (e.g., OFDM subcarriers) assigned to the transmitter. The subcarrier parameters can be determined from scheduling information received in a control channel, such as a downlink broadcast channel in a WWAN used to communicate resource block assignments to the UEs for use in uplink transmissions. The spreading configuration module **811** might receive scheduling information or subcarrier parameters from a UE's RAN control module (not shown) configured to process network control information.

While aspects disclosed herein provide examples of uniformly spaced OFDM subcarriers, alternative spreading algorithms (which may employ a DFT) can be used to produce complex spreading codes adapted to other subcarrier topologies to provide for an advantageous combination of orthogonality (i.e., cross correlation) and low PAPR. Some of these spreading codes can be poly-magnitude as well as polyphase. In some aspects, better cross correlation can be sacrificed for improved PAPR. Bandwidth efficiency might be sacrificed to achieve better PAPR and/or orthogonality. Thus, in some aspects, various performance metrics (which can include PAPR, orthogonality, bandwidth efficiency, as well as others) can be employed in an optimization scheme in which the values of such metrics are weighted, and optimization comprises evaluating a weighted sum (or some other function) of the performance metrics.

The spreading configuration module **811** can configure (including dynamically adapting) the spreader **802** to produce the spread data symbols in accordance with the subcarrier parameter(s) and at least one spreading criterion. Spreading criteria can include objectives, such as providing a PAPR below a predetermined threshold, providing orthogonality (which can comprise an evaluation, such as whether spreading code cross correlations are below a threshold value), and enabling efficient spreading (such as via a fast transform algorithm, or other types of processing). Other spreading criteria may be employed.

By way of example, in IEEE 802.11a, the FFT size is typically 64 with a sample rate of 20 MHz. This yields a subcarrier spacing of 312.5 kHz. Of these 64 potential subcarriers, 12 of them are unused (sometimes referred to as "virtual carriers"). Of the remaining 52 subcarriers, 4 contain pilot tones, so only 48 subcarriers carry information at any given time. Instead of transmitting one original data symbol per 312.5 kHz subcarrier, the spreader **802** provides spread data symbols, each representing a linear combination of the original data symbols, which allows a portion of each original data symbol to be transmitted on all 48 or 52 subcarriers. While this IEEE 802.11a example is described, it should be appreciated that aspects of the disclosure described herein can be employed in other cases, which can include other systems.

In one aspect, the spreading configuration module **811** might configure the spreader **802** to employ a 52-point FFT to generate the spread data symbols corresponding to the reference signals plus user data signals. The resulting 52 spread data symbols are then mapped by the mapper **803** to the IFFT **804**. Since 52 has prime factors of 2, 2, 13 and 48 has prime factors of 2, 2, 2, 2, 3, the spreading configuration module **811** could configure the spreader **802** to employ a 48-point FFT to spread the user data signals and a 4-point FFT to spread the reference signals, which might provide more efficient spreading than the 52-point FFT spreading. However, employing separate spreading of the reference signals and user data signals could result in a higher PAPR. Thus, the spreader **802** might employ an algorithm that weighs the efficiency and PAPR criteria to select which spreading mode to employ. It should be appreciated that the algorithm employed by the spreader **802** can employ various additional criteria. In some cases, the additional criteria can affect the weights of the spreading criteria (e.g., efficiency and PAPR). For example, operating criteria, such as (but not limited to) the UE's transmitted signal power, modulation scheme, modulation constellation size, pre-coding, MIMO operation, etc., can affect how the spreading configuration module **811** configures the spreader **802** to spread the original data symbols. In some aspects, operating conditions, such as determined from channel state information, network traffic, network topology information, received signal strength, routing tables, and the like, can affect how the spreading configuration module **811** configures the spreader **802** to spread the original data symbols. In some aspects, the operating conditions may be measured to infer the UE's operating parameters (such as transmit power, modulation, pre-coding, etc.). In some aspects, higher PAPR might be tolerable when a small constellation size (e.g., BPSK modulation) and/or low transmit power is employed, so spreading can be configured to improve processing efficiency and/or orthogonality at the expense of allowing for a higher PAPR. When high transmission power and/or modulations that produce a high-PAPR signal are employed, there might be less PAPR budget for the spreader **802** to exploit. Thus, the spreading configuration module **811** might configure the spreader **802** to sacrifice processing efficiency and/or orthogonality in favor of lower PAPR.

In another aspect, with respect to the IEEE 802.11a example, the spreading configuration module **811** might configure the spreader **802** to employ a 64-point FFT to generate the 52 spread data symbols corresponding to the reference signals plus user data signals. For example, the spreader **802** might be configured to generate a pre-spread input of 64 pre-spread original data symbols to the 64-point FFT, wherein the pre-spreading causes the FFT output to comprise only 52 non-zero spread data symbols. The resulting 52 spread data symbols are then mapped by the mapper **803** to the IFFT **804**. It should be appreciated that aspects of spreading configuration can be used in other scenarios and in other systems to employ N-point transforms for generating fewer than N non-zero outputs, the outputs comprising spread data symbols that satisfy one or more criteria, which can include low PAPR and/or orthogonality.

In some aspects of the disclosure, instead of a fixed algorithm for computing the DFT, the spreading configuration module **811** can adapt the DFT algorithm in the spreader **802** relative to details of the underlying hardware in order to maximize performance. For example, while FFTW's planner determines the fastest way to compute the transform for the machine on which it resides, other factors that depend on the subcarrier parameters can affect the processing efficiency. Thus, the spreading configuration module **811** can interface with the planner (or perform functions of the planner) to adapt the DFT algorithm relative to specific features of the calculations that will be performed. Various features, such as DFT size, sparseness of the spreading matrix, and/or characteristics of the input data, can be employed along with information about the underlying hardware to configure the DFT algorithm. The planner produces a data structure called a plan that contains this information. Subsequently, the plan is executed to transform the array of input data as dictated by the plan.

In some aspects, pulse shaping can be performed by "windowing" the output of the spreader **802**. This can be performed as part of the spreading, or it may be performed by the mapper **803**, such as applied to inputs of the IFFT **804**. For example, a tapered window can taper the amplitudes of at least some of the spread data symbols such that the taper is applied to the edges of the allocated spectrum. Raised cosine and Gaussian filter shapes are often used, but other types of pulse shaping can be employed.

The spreader **802** and/or the mapper **803** can configure the spread data symbols by arranging their order relative to the IFFT **804** input. Output values of the FFT are appropriately mapped to OFDM subcarriers in a manner that produces a low-PAPR spread-OFDM signal (regardless of the order or values of the original data symbols). In one aspect, ordering provides for mapping spread data symbols (relative to ascending spreading-code index) to ascending subcarrier frequencies, such as wherein the zero-frequency (DC) value corresponds to the lowest subcarrier frequency, in order to provide low-PAPR spread-OFDM signal.

The mapper **803** maps each of the N DFT outputs to one of the M>N IFFT **804** bins. As in OFDMA, a typical value of M is 256 subcarriers and N=M/Q is an integer submultiple of M. Q is the bandwidth expansion factor of the symbol sequence. The result of the subcarrier mapping is a set of complex subcarrier amplitudes, where N of the amplitudes are non-zero. As in OFDMA, the M-point IDFT **804** transforms the subcarrier amplitudes to a complex time domain signal, which is the spread-OFDM signal.

The transmitter can comprise a cyclic prefix appender **805**, which inserts a cyclic prefix in order to provide a guard time to prevent inter-block interference (IBI) due to multipath propagation. In general, the cyclic prefix is a copy of the last part of the block, which is added at the start of each block. If the length of the cyclic prefix is longer than the maximum delay spread of the channel, or roughly, the length of the channel impulse response, then, there is no IBI. Since the cyclic prefix is a copy of the last part of the block, it converts a discrete time linear convolution into a discrete time circular convolution. Thus, transmitted data propagating through the channel can be modeled as a circular convolution between the channel impulse response and the transmitted data block, which, in the frequency domain, is a pointwise multiplication of the DFT frequency samples. Then, to remove the channel distortion, the DFT of the received signal can simply be divided by the DFT of the channel impulse response point-wise, or a more sophisticated frequency domain equalization technique can be implemented.

Additional baseband processing **806** can be performed. For example, pulse shaping can reduce out-of-band signal energy. In electronics and telecommunications, pulse shaping is the process of changing the waveform of transmitted pulses. Its purpose is to make the transmitted signal better suited to its communication channel, typically by limiting the effective bandwidth of the transmission. In RF communication, pulse shaping is essential for making the signal fit in its frequency band. At baseband, the time sequence of the spread-DFT signal is filtered by the pulse-shaping filter. The spectrum of the transmission is thus determined by the filter.

Digital-to-analog conversion (DAC), frequency up-conversion, and amplification are typically performed to produce a transmitted signal. In practical implementations, typical DACs use digital interpolation filtering before implementing the D-to-A conversion. By interpolating the data samples, the performance of the reconstruction filter is improved, as increasing the sampling frequency can be seen to directly reduce the analog filter requirements for alias suppression.

Interpolation in OFDM is typically performed by the IFFT **804**. Interpolators in OFDM are described in U.S. Pat. No. 6,597,745, which is incorporated by reference, wherein a transform-domain interpolation unit expands a length-N transform domain vector by inserting zeros in the length-N transform domain vector to produce a length-2N transform domain vector. This transform-domain up-sampling unit interpolates the transform domain vector.

Interpolators in spread-OFDM transmitters can be employed in various aspects of the disclosure. By way of example, interpolation is disclosed throughout U.S. Pat. No. 6,686,879 (such as illustrated in FIG. 19), which is incorporated by reference, wherein a data sequence is serial-to-parallel converted and then modulated onto multiple OFDM subcarriers, which are provided with phase offsets to synthesize a desired pulse shape for the resulting data-modulated pulse waveform. This process of transforming a serial data stream into a sequence of data-modulated pulses is implemented using an invertible transform function, such as an IFFT. Interpolation can also be provided via pulse shaping.

Aspects of the disclosure can include any of various types of interpolation. In order to perform frequency-domain interpolation, the input data is up-sampled before IFFT **804** processing. The up-sampling can be performed by zero-padding the middle samples of the input sequence. One disadvantage of frequency-domain interpolation is the increase in the IFFT size. For this reason, the oversampling rate is often kept relatively low.

As discussed above, in accordance with certain aspects of the disclosure, DFT-spreading **802** employs an N-point DFT to spread a sequence of data symbols s(n) to produce N spread symbols, x(n), which are to be modulated onto N OFDM subcarriers. To the contrary, in spectrum analysis, the transform of a discrete signal produces frequency responses corresponding to tones. The limitation of the transform's orthonormal basis to tones discards the negative-frequency components. Whether a pair of signals have negative and positive frequencies, or they have a relative phase offset (e.g., in-phase and quadrature phase), if they have the same frequency, then they are the same tone. The basic idea behind employing a DFT on a discrete signal to calculate frequency responses corresponding to tones is that the negative frequency components of the Fourier transform are superfluous due to Hermitian symmetry. These negative frequency components are discarded with no loss of information, leaving a complex-valued function. But in aspects of the disclosure, it is unnecessary to discard spread-DFT symbols produced by the DFT-spreading **802**.

To generate a spread-OFDM up-sampled-by-M analytic time signal (assuming N is even) from the spread symbols, x(n), a method, circuit, and/or processor, for example, according to one aspect of the disclosure can provide for performing the following steps.

1. Create an M·N-point spectral sequence $x_{int}(m)$ initially set to all zeros. In some aspects, the product M·N can be an integer power of two.
2. Assign $x_{int}(0)=x(0)$, and $x_{int}(N/2)=x(N/2)$.
3. Assign $x_{int}(m)=2x(m)$, for $1\leq m\leq=(N/2)-1$. For example, when performed by a UE, this step and the previous one can provide for mapping non-zero symbol values to the OFDM subcarriers assigned to the UE.
4. Compute an M·N-point IFFT of $x_{int}(m)$ to yield the desired M·N-length analytic (complex) $x_{c,int}(n)$ sequence.
5. Optionally, multiply $x_{c,int}(n)$ by M to compensate for the 1/M scaling factor.

In the domain of digital signal processing, the term interpolation refers to the process of converting a sampled digital signal to that of a higher sampling rate (i.e., up-sampling) using various digital filtering techniques (e.g., convolution with a frequency-limited impulse signal). In such applications, there is a specific requirement that the harmonic content of the original signal be preserved without creating aliased harmonic content of the original signal above the original Nyquist limit of the signal (i.e., above $f_s/2$, which is half of the original signal sample rate, 1/T). For example, Let X(f) be the Fourier transform of a function, x(t), whose samples at some sampling interval, T, equal the x[n] sequence. The passband bandwidth of the corresponding interpolation filter is defined by its cut-off frequency, 0.5/L, where L is the oversampling factor. In terms of actual frequency, the cutoff is ½·(1/T) Hz, which is the Nyquist frequency of the original x[n] sequence.

Bandwidth is the difference between the upper and lower frequencies in a continuous set of frequencies. The passband bandwidth is the difference between the upper and lower cut-off frequencies of, for example, a band-pass filter, a communication channel, or a signal spectrum. In the case of a low-pass filter or baseband signal, the bandwidth is equal to its upper cut-off frequency, $f_s/2$.

FIG. **8**B is a block diagram that depicts modules corresponding to processing functions that can be implemented by a computer processor programmed to perform methods in accordance with aspects of the disclosure. In accordance with an aspect of the disclosure, a server-side device or system receives spread-OFDM transmissions from one or more UEs in a WWAN. After processing by one or more RF front-ends (not shown), a server-side processor (or processors) can receive the down-converted baseband signal(s). A baseband processor(s) **821** can process the received baseband signal, typically providing ADC processing, matched filtering (e.g., pulse shape filtering), amplification, and/or possibly other baseband processing operations to produce a spread-OFDM signal(s), which possibly has a cyclic prefix. A cyclic prefix remover **822** can optionally remove any cyclic prefix. The spread-OFDM signal(s) is processed by an M-point DFT (or some equivalent time-domain to frequency-domain converter) **823** to produce spread data symbols, which may be estimates of the spread original data symbols that were transmitted on each OFDM subcarrier. In some aspects, the DFT **823** may be configured to perform frequency-domain windowing, such as via control of a windowing module **833**. A demultiplexer **824** may optionally be used to provide OFDMA demultiplexing if necessary. The spread data symbols are usually equalized by an equalizer **825** prior to despreading. However, equalization may not be necessary in certain aspects. In some aspects, the equalizer **825** may comprise a spatial demultiplexer. In some aspects, the spatial demultiplexer is configured to perform MIMO subspace demultiplexing, such as Cooperative-MIMO subspace demultiplexing.

A despreader **826** despreads the spread data symbols to produce estimates of the original (despread) data symbols. The despreader **826** can employ a fast transform algorithm, such as an IFFT, which can be implemented with the FFTW software. The despreader **826** is controlled by a despreading configuration module **836**, which can receive one or more subcarrier parameters corresponding to the OFDM subcarriers assigned to a particular UE(s). Subcarrier parameters, which can include number of subcarriers, subcarrier spacing, and the like, provide an indication of spreading parameters (and thus, despreading parameters), which the despreader **826** can use to despread received spread data symbols. In some aspects, subcarrier parameters are understood to comprise spreading (and/or despreading) parameters associated with OFDM resource blocks. In some aspects, such spreading (and/or despreading) parameters may be pre-associated with each resource block assignment and communicated via the scheduler **835** to the despreading configuration module **836**. In some aspects, the despreading configuration module **836** listens to a scheduling channel broadcast by an uplink scheduler **835** to determine the subcarrier parameters. In other aspects, the despreading configuration module **836** might determine the subcarrier parameters from the UE transmissions.

The despreader **826** can be configured to perform hard decisions, soft decisions, or mixed-decision processing to produce the estimated data symbols. A baseband demodulator **827** may optionally be provided to perform further baseband processing of the estimated data symbols.

As depicted in FIG. **9**, a transceiver configured in accordance with aspects disclosed herein can include a controller, such as at least one computer or data processor **910**, at least one non-transitory computer-readable memory medium embodied as a memory **920** that stores a program of computer instructions **921**, and at least one suitable radio frequency (RF) transmitter/receiver **901** for bidirectional wireless communications with at least one other transceiver via one or more antennas **905**. The exemplary aspects of the disclosure (including those depicted in the flow diagrams and block diagrams) may be implemented, at least in part, by computer software executable by the data processor **910**.

The transceiver shown in FIG. **9** can be a UE, a base transceiver station, a relay, or some other transceiver.

Aspects disclosed herein can include Cooperative-MIMO precoding, and can comprise configuring the spreading codes to provide for spreading across a combination of subcarriers and antennas (such as across multiple UEs). In such aspects, precoding can be configured to achieve a combination of cooperative spatial multiplexing across a plurality of UEs and a low PAPR for each UE's transmissions. In other aspects, precoding may comprise pre-equalizing the transmitted signal. In such aspects, for example, pre-equalization weights applied to transmitted OFDM subcarriers, such as may be implemented by incorporation into the spreading codes, can be derived from channel information. Various techniques, including multi-objective optimization and other multi-objective algorithms can be employed to generate spreading codes that optimize (or at least achieve a predetermined performance threshold relative to) certain objectives, such as low PAPR, low cross correlations, and/or other objectives.

A transceiver configured in accordance with aspects of the disclosure is depicted in the block diagrams of FIGS. **10**A and **10**B. The transceiver can comprise a client-side device or system, a server-side device or system, a relay device or system, and/or other WWAN transceivers. In some aspects, the blocks can comprise hardware components, such as circuits. The blocks can comprise processors, such as general-purpose processors programmed to perform functions in accordance with methods disclosed herein. The blocks are also indicative of functions that can be performed by a transceiver (which includes a network of transceivers) in accordance with aspect disclosed herein. In some aspects, the blocks can comprise separate devices communicatively coupled together via at least one network. In some aspects, at least some of the separate devices can be coupled together via a WLAN, which can include a radio and/or optical network.

In FIG. **10**A, the transceiver comprises a WWAN precoder **1010**, which is configured to calculate precoder weights for use in a distributed antenna system **1020**. The precoder **1010** receives information from a WWAN scheduler, such as a WWAN schedule processor **1001** and a WWAN CSI processor **1002**. A data source **1003** provides original data symbols to the WWAN precoder **1010**. The precoder **1010** is communicatively coupled to a fronthaul router **1012**, which is connected to the distributed antenna system **1020**.

In FIG. **10**B, the transceiver comprises a WWAN decoder **1030**, which is configured to calculate decoder weights for processing received signals, such as signals received from the distributed antenna system **1020**. The decoder **1010** receives information from the WWAN schedule processor **1001** and the WWAN CSI processor **1002**. A data sink **1033** processes decoded data symbols from the WWAN decoder **1030**. The decoder **1010** is communicatively coupled to the fronthaul router **1012**, which is connected to the distributed antenna system **1020**. In some aspects, the WWAN precoder **1010** and the WWAN decoder **1030** can be a single component or system.

In some aspects, blocks disclosed herein comprise processing elements that provide necessary computing facilities for the device or system. By way of example only, processing elements can include special purpose hardware, such as FFT, coding and/or decoding processors, or programmable CPUs. In aspects wherein one or more of the blocks are communicatively coupled together via a network, such as may be implemented in a distributed system, the blocks can comprise interfaces which contain appropriate traffic format conversion circuitry between the blocks and the interconnect network input and output. In some aspects, the system further includes internal resources with shared usage among various system blocks. By way of example only, these internal resources may comprise memory and a memory access controller.

In some aspects, the router **1012** includes Input-Output (I/O) device interface units that provide connection between the precoder **1010** and external devices of the distributed antenna system **1020** through one or more fronthaul interfaces. By way of example only, these devices may include Ethernet, wireless standard compliant networking, fiber networking, and/or an expansion interface for creating larger systems using multiple systems of the type shown in figure.

In one aspect, the transceiver is a server-side device or system, and the WWAN schedule processor **1001** is a scheduler, which assigns resource blocks (e.g., blocks of OFDM subcarriers) for uplink and downlink communications with one or more client-side devices (e.g., UEs). The WWAN precoder **1010** can use the scheduling information to determine a set of OFDM subcarriers for which precoding weights will be generated. The precoder **1010** can also use the scheduling information to help determine which antennas in the distributed antenna system **1020** to allocate for possible use in serving the client devices. For example, the scheduling information might contain geographical information about each corresponding client device. This can assist in allocating distributed computing resources operated by the WWAN precoder **1010**, for example, when multiple processing cores are employed. The WWAN precoder **1010** couples precoded-data signals or precoding weights and the original data signals to selected antennas of the distributed antenna system **1020** via the fronthaul router **1012**.

In another aspect, the transceiver is a client-side device or system, and the WWAN schedule processor **1001** receives WWAN scheduling information, such as is typically broadcast in the WWAN. However, the schedule processor can receive the WWAN scheduling information by other means. In one aspect, cooperating client devices may convey their corresponding scheduling information to the WWAN schedule processor **1001**, such as via the fronthaul network. The WWAN precoder **1010** can use the scheduling information to determine a set of OFDM subcarriers for which precoding weights will be generated. In some aspects, the WWAN precoder **1010** comprises a distributed computing system, such as may comprise multiple processing cores residing on different client-side devices. In some aspects, at least some of the processing cores of the WWAN Precoder **1010** might reside in a non-client device, such as a relay or a server-side device. The WWAN Precoder **1010** might be configured to use the scheduling information to allocate distributed computing resources (e.g., processing cores, memory, fronthaul resources, etc.), such as for precoding and/or other processing operations. The WWAN precoder **1010** can couple precoded-data signals or precoding weights and the original data signals to selected antennas of the distributed antenna system **1020** via the fronthaul router **1012**.

In one aspect, the transceiver is a server-side device or system, and the WWAN CSI processor **1002** provides downlink CSI to the WWAN precoder **1010**. For example, in a reciprocal channel, the CSI processor **1002** can infer downlink CSI from uplink CSI measurements. In some aspects, the client-side devices can measure CSI in the downlink and feedback their measurements to the server-side. The WWAN precoder **1010** then provides those CSI measurements to the WWAN precoder **1010**. The WWAN precoder **1010** can use

the CSI to select antennas in the distributed antenna system **1020** to serve each client device and then use the CSI to calculate the precoding weights. By way of example, the WWAN precoder **1010** might select a preliminary, or candidate, plurality of antennas to be used for precoding, and then refine the selection of antennas based on various criteria. One objective of the WWAN precoder **1010** might include determining a set of the antennas that enables low-PAPR pre-coded transmissions per antenna. The WWAN precoder **1010** is operable to configure the precoding in order to provide low-PAPR transmissions. The WWAN precoder **1010** may be configured to achieve additional criteria, including enabling use of a fast transform, providing for code orthogonality (e.g., code spaces with low cross correlations), limiting WLAN overhead, etc.

In accordance with some aspects of the disclosure, it should be appreciated that blocks depicted in the figures can comprise interconnects that are not shown. By way of example, the WWAN CSI processor **1002** can be communicatively coupled to at least the WWAN schedule processor **1001** (such as in FIGS. **10**A and **10**B). In some aspects, the WWAN schedule processor **1001** employs CSI and/or other channel information for scheduling, such as to provide for channel-dependent scheduling. Channel-dependent scheduling can comprise selecting OFDM resource blocks with estimated and/or measured channel conditions that are advantageous for specific client devices. In some aspects, channel-dependent scheduling can comprise scheduling resource blocks to client devices in a manner that is advantageous to the operation of the server-side system. For example, scheduling may provide for assigning the same or overlapping resources (e.g., resource blocks and/or other network resources, such as antennas, processers, fronthaul capacity, backhaul capacity, etc.) to a set of client devices, which may be clustered together or geographically separated, such as to enhance network efficiency and/or performance.

While CI coding eliminates the effect of data randomization on the PAPR of OFDM transmissions from a single user, channel-based precoding (such as MIMO precoding, pre-equalization, etc.) can introduce randomization into the transmittal signals' crest factors due to the natural randomness of the multipath channel, which translates into randomness in the precoding. Thus, some aspects of the disclosure are configured to exploit additional degrees of freedom available in a MIMO channel when the number of available transmit antennas exceeds the minimum required rank of the channel matrix to reduce the crest factors. For example, in one aspect, a set of active transmit antennas in the distributed antenna system can be selected from a larger set of candidate antennas in the distributed antenna system. In another aspect, the set of active transmitting antennas can comprise a larger number than the number of antennas receiving the precoded transmissions, the precoder **1010** exploiting the extra antennas to provide for reducing PAPR, reducing spatial cross correlation, improving diversity, and/or the like. This enables antenna selection to advantageously provide a set of antennas per OFDM tone that achieves low-PAPR transmissions per antenna and/or per device. A low-PAPR criterion might include an aggregate of PAPR across antennas and/or devices, PAPR corresponding to a subset of antennas and/or devices, an average PAPR, a mean PAPR, a peak PAPR, some other function of PAPR, or some function of PAPR weighted relative to some other criterion. In some aspects, the selection of antennas per tone can be performed for each set of original data symbols.

In one aspect, the transceiver is a client-side device or system, and the WWAN CSI processor **1002** provides uplink CSI to the WWAN precoder **1010**. For example, in a reciprocal channel, the CSI processor **1002** can infer uplink CSI from downlink CSI measurements. In some aspects, the server-side devices might measure CSI in the uplink and feedback their measurements to the clients. The WWAN precoder **1010** provides the uplink CSI to the WWAN precoder **1010**. The WWAN precoder **1010** can use the CSI to select antennas in the distributed antenna system **1020**, which can include other client devices configured to operate in a Cooperative MIMO network, and then use the CSI to calculate the precoding weights. By way of example, the WWAN precoder **1010** might select a preliminary, or candidate, plurality of antennas to be used for precoding, and then refine the selection of antennas based on various criteria. One objective of the WWAN precoder **1010** might include determining a set of the clients that enables low-PAPR pre-coded transmissions per client.

The data source **1003** provides a stream of original data symbols (which can comprise user data and/or reference signals) to the WWAN precoder **1010**. In one aspect, the WWAN precoder **1010** calculates precoding weights separately for the user data and the reference signals. In other aspects, the WWAN precoder **1010** provides precoding weights for a data set comprising both user data and reference signals. In one aspect, the WWAN precoder **1010** is configured to select a block of the original data symbols from the data source **1003** and generate the precoding weights specific to the selected block of data. In other aspects, the WWAN precoder **1010** can calculate the precoding weights without a data input and then precode blocks of data from the data source **1003**. In some aspects, the data source **1003** might reside in a client device and receive data from at least one other client device in a cluster of devices communicatively coupled together via the fronthaul network. Data from at least one other device can be input to the WWAN precoder **1010**, which performs at least one of determining the precoding weights and precoding the data.

In a server-side device or system, the fronthaul router **1012** can comprise a local network manager, such as a Coordinated Multipoint router, communicatively coupled to the distributed antenna system **1020** (e.g., base transceiver stations, relays, remote radio heads, etc.) via any combination of fiber optic and wireless links. In a client-side device, the fronthaul router **1012** can comprise a local network manager, such as a cluster master, communicatively coupled to the distributed antenna system **1020** (e.g., the other clients in the cluster, relays, etc.) via wireless links.

In some aspects, the system shown in the figures can comprise a distributed system wherein the blocks are communicatively coupled via a fronthaul interconnect and may also include an interconnect network scheduler (not shown) which can configure and service communication traffic between I/O devices, processing elements, and shared resources. The interconnect network scheduler can control and configure accesses through the fronthaul interconnect, optimize the overall system for metrics, such as performance and access latency using trade-off parameters (such as power consumption, overall system efficiency, and a fronthaul schedule program). In some aspects, the interconnect network scheduler can be implemented as a distributed mechanism, which may be inherently part of internal elements of the blocks, and may include routing units, integrated hardware with processing elements, shared resources, I/O devices, and/or software program(s) executed by processing elements.

In accordance with aspects disclosed with reference to FIG. **3**, different network topologies (such as can be employed for connecting blocks, the distributed antenna system, and/or other resources within the blocks in FIGS. **10**A and **10**B) can be representative of data traffic created or used during precoding and/or decoding and can further comprise subnetwork topologies corresponding to partitioned processes (e.g., via data partitioning and/or computation partitioning). FIG. **3** depicts a reconfigurable interconnect network topology and scheduler wherein the scheduler provides control, configuration, and optionally status collection capabilities to and from the network nodes. There can be one or several subnetworks, each consisting of point-to-point interconnects and/or broadcasts. Each communication link can be established via routing elements, which can direct traffic streams to and/or from various processing units, memories, other shared resources, and/or distributed antennas. The quantity, topology and parameters of the links and routing elements can determined at design time and/or dynamically configured.

Network topologies can be classified based on application operation mode and global characteristics, such as bandwidth, latency, and burst behavior. By way of example, different network topologies can be employed to process data corresponding to different OFDM subcarriers, different client devices being served, and/or different antennas in the distributed antenna system. In some aspects, computational partitioning can be performed. Different network topologies can correspond to different component problems. By way of example, a first network topology can be configured for processing CSI. A set of network topologies can be configured for determining precoding weights for each of a plurality of OFDM subcarriers. At least another network topology can be configured for configuring the precoding weights to provide a low-PAPR precoded transmission for one or more antennas and/or devices.

A fronthaul interconnect network schedule program can determine configuration of various nodes that meet concurrent communication traffic requirements of one or several application modes. Alternatively, each application operation mode may have its own schedule program. Configuration and operation of interconnect nodes can be statically determined or dynamically adapted based on the schedule program. The schedule program can organize input and output data for each node into distinct categories based on characteristics of interest, such as bandwidth, latency, ordering for more efficient resource utilization, quality of service, etc.

Mechanisms to employ multiple traffic schedules, including loading and storage of the new schedule programs can be provided. A router in the fronthaul interconnect may provide internal storage, selection, and forwarding of multiple traffic streams from multiple inbound links to multiple outbound links. A router may accommodate multiple traffic types based on a predetermined fabric schedule program.

In some aspects, multiple blocks or components may share a fronthaul interface. As determined by a fronthaul scheduler, a particular link may be used to carry traffic for multiple communicating units at a variety of transfer granularity sizes, service schedules, and/or durations. Multiple links may be selected to operate in tandem to provide required services for incoming or outgoing traffic.

For some topologies, it may be desirable to subdivide a stream into several streams across different links. This enhancement may facilitate potentially more efficient system operation, and each subdivision might be accommodated by a different schedule program. Alternatively, it may be beneficial to aggregate several data streams (possibly corresponding to different topologies) into one stream over a shared link.

FIG. **11** is a flow diagram that depicts a precoding method in a distributed antenna system in accordance with some aspects of the disclosure. CSI for a MIMO-OFDM channel is collected **1101** and is used for calculating multiple precoding matrices **1102** for each tone, each precoding matrix corresponding to a different antenna set. A set of precoding matrices, one for each tone, is selected **1103** according to a predetermined criterion based on PAPR. The selected set of precoding matrices is used to precode a block of the original data symbols **1104**. In some aspects, this process may be performed for each of a plurality of original data blocks. Step **1105** provides for returning to step **1101** or step **1102**. For example, in one aspect, steps **1103**-**1104** are repeated for a next block of original data symbols. In some aspects, steps **1101**-**1104** are repeated for the next block of original data symbols.

As disclosed above, the CSI may comprise measured channel conditions and/or statistical channel conditions. CSI may be inferred from channel measurements. For example, uplink CSI may be inferred from measured downlink CSI (and vise versa). Similarly, CSI corresponding to a particular tone may be interpolated from CSI corresponding to another tone. CSI may be directly measured from training signals (e.g., pilots) received by antennas in the distributed antenna system. In some aspects, CSI may be provided via data directed channel estimation. In some aspects, CSI is measured by devices communicatively coupled to the distributed antenna system via the WWAN and then fed back to the precoder(s) configured to perform the methods disclosed herein. By way of example, in an OFDM system, CSI can comprise flat-fading channel measurements and/or estimates (including statistics) corresponding to at least a subset of the antennas and for each tone.

Based on the CSI, a set of the antennas can be selected for each antenna on a device being served by the distributed antenna system via the WWAN. In some aspects, the device's antenna may be served by a first set of the antennas corresponding to a first tone and a second (different) set of antennas corresponding to a second tone. Some aspects disclosed herein provide for the distributed antenna system comprising a larger number of antennas than the aggregate number of antennas being served. This allows a subset of the antennas of the distributed antenna system to at least equal the aggregate number of antennas being served.

In one aspect, the distributed antenna system comprises a cluster of client devices, and the device(s) being served can comprise any of various antenna systems, including a server-side distributed antenna system, a server-side antenna array, one or more relay antennas, and/or one or more client-device antennas (e.g., a cluster of client devices, a client device antenna array, or some combination thereof). In some aspects, a cluster of devices may cooperate, such as in mesh networks, ad-hoc networks, multi-hop networks, cellular networks, and in other types of networks. In another aspect, the distributed antenna system can comprise a plurality of server-side antennas, including antennas residing on multiple base transceiver stations, and possibly antennas residing on other server-side devices and/or systems, including relays, remote radio heads, and the like. The device(s) being served can include any of the aforementioned client-side, server-side, and/or any intermediary devices.

In step **1102**, multiple combinations of serving antennas can be provided for each device (and/or antenna) being served, and there can be multiple combinations of serving

antennas per tone per device (and/or antenna) being served. The serving distributed antenna system can comprise a larger number of candidate antennas than the aggregate number of antennas being served, which allows each selected subset of the antennas of the distributed antenna system to at least equal the aggregate number of antennas being served. In some aspects, the number of active antennas in the distributed antenna system serving a cluster of served antennas is larger than the number of antennas in the cluster being served. This results in extra degrees of freedom which are ordinarily used for array processing purposes, such as to provide added antenna-array gain, diversity, redundancy, and the like. Aspects of the disclosure can exploit these extra degrees of freedom to reduce PAPR of the transmissions from each antenna and/or device. For example, the extra degrees of freedom can provide for adaptations to the precoding matrix which can achieve objectives, such as low PAPR, that are not directly related to array processing performance.

In some aspects, additional degrees of freedom can be achieved by employing extra spectrum, which may include extra tones, for transmission. By way of example, the IDFT can be configured to employ extra tones in order to reduce the PAPR of the transmitted OFDM signal. In one aspect, the extra tones might be transmitted in a manner that avoids interfering with the WWAN system. For example, the extra tones may comprise unscheduled resources in the WWAN. In another case, the extra tones may comprise WWAN control channels which are not transmitted during the uplink timeslot. In some aspects, the extra tones can correspond to a different communication system other than the WWAN. In these aspects, the extra tones can be weighted such as to reduce PAPR of the transmitted signals. In another aspect, the extra tones might comprise pilot tones, and data corresponding to weights applied to the pilots tones such as to reduce the PAPR may be communicated to the receive side such that the receive side can compensate for the weights in the received pilots. In such aspects, some data bandwidth is sacrificed to improve PAPR performance.

In some aspects disclosed herein, additional spectral bandwidth can be used to help reduce PAPR. However, the additional spectral bandwidth does not need to comprise tones. In some aspects, signals employed for reducing the PAPR can be pseudo-orthogonal or non-orthogonal relative to the spread-OFDM signal.

In one aspect of the disclosure, step **1102** comprises generating multiple precoding matrices for at least one tone such that each precoding matrix achieves a predetermined minimum cross correlation between subspace channels. By way of example, the degree of cross correlation can be determined based on spatial subchannel eigenvalues.

In step **1103**, a precoding matrix set can comprise one precoding matrix per tone. For each set, the PAPR for each antenna and/or device can be determined for the precoded transmission across the full set of tones. At least one PAPR criterion based on these PAPRs can be determined, and the precoding matrix set qualifying as "low PAPR" based on the at least one PAPR criterion can be selected.

It should be appreciated that in some aspects, step **1102** depends on the CSI but not on the data block being precoded, so it may be updated based on the channel conditions changing (such as may be determined by coherence time or some similar channel characterization). Step **1103** might depend on the data block being precoded, and may be repeated for each block of original data symbols to be precoded. In some aspects, step **1102** may be repeated for each block. For example, given a new block of original data symbols, a new set of precoding matrices may be selected. This can include adapting previous precoding matrices.

In some aspects, steps **1102** and **1103** can be combined in an iterative process wherein the precoding matrices are adapted and the PAPR criterion for the adapted set is evaluated, and the process is repeated until a predetermined criterion is satisfied, such as a maximum number of iterations, an elapsed amount of time, a predetermined PAPR threshold, or the like. In some aspects, step **1103** comprises selecting a precoding matrix set from multiple sets which correspond to a best PAPR. In some aspects, step **1102** can comprise adapting the matrices according to one or more adaptation schemes. By way of example, an adaptation scheme may comprise randomly adapting at least one precoding weight, adapting precoding weights in response to how a previous adaptation changed a metric (such as PAPR, cross correlation, etc.), and/or adapting at least one precoding weight according to a measured characteristic of the channel and/or original data symbols. In some aspects, certain configurations of CSI values and/or data can be used to determine how to adapt the precoding matrices. Such adaptations may be determined, based on a given configuration(s), to have a high probability of yielding a lower PAPR. Such determinations may be based on historical data, perhaps being associated with correlated behaviors and/or identified trends, and/or they may be determined analytically.

In some aspects, favorable cross correlation can be sacrificed for favorable PAPR, or vise versa. In some aspects, it should be appreciated that the low PAPR criteria may be weighted with respect to particular antennas and/or devices that are transmitting the precoded signals. For example, in one aspect, low PAPR can be more important for battery-powered transceivers. Thus, a precoding matrix set may be selected that allows for higher PAPR among devices that receive line power to enable lower PAPR among devices that are battery powered. In some aspects, the transmit power of each device may determine how important it is to be provided with a low-PAPR coded signal. For example, devices that are currently transmitting with low transmit power might tolerate a high-PAPR transmission better than devices transmitting at high power. In some aspects, the inherent PAPR of the modulation constellation being used by each device may determine the low-PAPR criterion. In some aspects, power consumption per device may be employed to determine the PAPR criterion. For example, it may be important to provide for uniform power consumption across the transmitting devices. In some aspects, the type of device for each transmitting device may be used to determine its weight in the low-PAPR criterion. In some aspects, an operating status of a device may be used to determine its weight.

For example, it may be more important for devices with low battery power to be provided with low-PAPR coded signals. It should be appreciated that other operating parameters and device characteristics may be employed to determine the low-PAPR criterion.

FIG. **12** is a flow diagram that depicts a precoding method in a distributed antenna system in accordance with some aspects of the disclosure. CSI for a MIMO-OFDM channel is collected **1201** and can be used for selecting a set of antennas for each tone **1202**. Precoding weights are calculated for each antenna-tone set (i.e., a set of antennas for each tone) **1203**. PAPR is calculated **1204** for each active antenna and/or device in the distributed antenna system. Spatial cross correlations of the weighted transmissions may optionally be calculated **1205**. A decision is based on the

PAPR (and optionally the cross correlations) **1206**, and the decision determines where control is transferred to in the flow diagram.

In one aspect, if the decision **1206** indicates that a PAPR criteria is not met with the current antenna-tone set, the method returns to step **1202** (indicated by decision result **1207.1**) in order to select a new antenna-tone set. In some aspects, step **1207.1** can comprise sending information (such as decision information, precoding weights, cross correlation information, and/or instructions for selecting the new antenna-tone set) to step **1202**.

In another aspect, the decision **1206** can cause control to return to step **1201** via step **1207.2**. For instance, decision **1206** can comprise a determination of whether the CSI needs to be updated. In some aspects, the CSI is collected **1201** based on a predetermined time interval, when measured reference signals indicate a sufficient change in the channel state, for each block of original data symbols, or via some other criteria or mechanism.

In another aspect, the decision **1206** can cause control to transfer to block **1207.3** wherein a set of precoding weights is selected to precode the original data symbols. For example, when a predetermined PAPR criterion is met, the original data symbols are precoded **1207.3** using the weights that satisfy the criterion. The weights may be selected from weights of a corresponding antenna-tone set that best satisfies the PAPR criterion after a predetermined number of iterations, or the weights may satisfy the PAPR criterion, at which point the iterations cease and control is transferred to block **1207.3**. In some aspects, additional criteria may be employed in the decision **1206** as described above, and when those criteria are satisfied, the original data symbols are precoded **1207.3**.

In one aspect, step **1202** comprises selecting a destination group of antennas. For example, a server-side system can select which client devices it will serve for a given set of distributed antennas. Optionally, this can be done for each OFDM tone or set of tones. In some aspects, the selected client devices comprise a cluster (which may be in close geographical proximity with each other), such as may be advantageous when the client devices are configured to perform client-side Cooperative MIMO. In other aspects, the selected clients may be geographically distributed, such as to ensure that reused frequency channels are uncorrelated. In some aspects, a similar decision on destination antennas is made by a cluster of client devices, such as a local group of UE's communicatively coupled together and configured to perform client-side Cooperative MIMO. The system (or cluster) can then select which antennas in its distributed antenna system to serve each destination antenna (or device), and this selection can be made for each tone or set of tones. For at least one tone, the selection can comprise a number of candidate distributed antennas that is greater than the channel-matrix rank necessary to provide a sufficient number of spatial subchannels to serve the destination antennas. For example, the number of transmitting antennas can be greater than the number of receiving antennas.

As described in the patents and applications incorporated by reference, the selection of spectral components (e.g., OFDM tones) and their association with particular wireless terminals can be performed to optimize WWAN system performance relative to the current WWAN channel. For example, the spectral components can be selected to minimize the effects of deep fades and/or interference. Spectral-component selection (e.g., scheduling) may be selected and/or adapted to optimize one or more WWAN link-performance metrics, including, but not limited to, SNR, BER, PER, and throughput. Spectral-component selection may be performed to achieve other objectives, such as to distribute processing loads across devices.

In accordance with certain aspects of the disclosure, scheduling can comprise one of two types of subcarrier mapping. Localized mapping comprises a contiguous block of subcarriers (e.g., a continuous frequency band), whereas distributed mapping comprises a non-contiguous (e.g., discontinuous, or frequency-interleaved) set of subcarriers. With localized subcarrier mapping, it is possible to exploit frequency selective gain via channel-dependent scheduling (e.g., assigning uplink frequencies to each UE based on favorable channel conditions).

A set of precoding matrices, one for each tone, can be calculated **1203** according to a predetermined criterion based on PAPR. In accordance with some aspects of the disclosure, a precoder configures the precoding matrix to provide a spread-OFDM transmission(s) with low PAPR. By way of example, low PAPR can be achieved by selecting appropriate spreading codes (such as may be based on number of OFDM tones and tone spacing) and properly configuring the order in which spread data symbols are mapped to particular tones. The spreading codes can be generating using a DFT that is configured with appropriate input parameters. Thus, the precoder can provide for frequency-domain synthesis to generate a spread-OFDM signal that comprises a set of contiguous and/or non-contiguous OFDM tones. In aspects wherein the precoder is configured to perform MIMO subspace precoding in addition to spread-OFDM coding, the precoder can be configured to produce low-PAPR transmissions, such as by employing the methods corresponding to FIGS. **11-13**. In some aspects, the precoder can adapt the transmit power of certain spatial subchannels in order to effect changes in the aggregate PAPR. By way of example, the precoder can scale the weights of a particular eigenvector to adjust power in the corresponding spatial direction.

The selected set of precoding matrices is used to precode a block of the original data symbols, and then the PAPR of each precoded transmission (such as transmitted by each transmitting antenna or device) can be calculated **1204**, such as by aggregating precoded signals across all the tones allocated to the antenna or device. In some aspects, the PAPR (and thus the precoding) may be specific to each block of original data symbols, so this process may be performed for each original data block.

As precoding is adapted to reduce the PAPR of the spread-OFDM signal(s), there can be a tradeoff between desirable PAPR and spatial correlation attributes. Estimating the spatial correlation **1205** can be performed, which in one sense can be regarded as a measure of code cross-correlation, which can be used to characterize orthogonality of the codes. Although many different techniques can be employed for determining the spatial correlation **1205**, it should be appreciated that spatial correlation depends on the eigenvalue distributions of the correlation matrices. Each eigenvector represents a spatial direction of the channel, and its corresponding eigenvalue describes the average channel/signal gain in this direction. For example, for the transmit-side spatial correlation matrix, it describes the average gain in a spatial transmit direction. In some aspects, both transmit-side and receive-side spatial correlation matrices are determined. In some aspects, step **1205** can comprise determining some value derived from or otherwise based on spatial correlation. For example, channel capacity, which depends on spatial correlation, might be determined instead.

FIG. **13** is a flow diagram that depicts a precoding method in a distributed antenna system in accordance with some aspects of the disclosure. CSI is collected **1301**, and then for each OFDM tone, a set of antennas in an origin distributed antenna system is selected to serve a set of destination antennas **1302**. Precoding weights are calculated for each origin set **1303**. PAPR is calculated for each antenna (and/or device) in the origin set **1304**. After one or more iterations, one of the origin sets is selected **1305** to be used for precoding.

In one aspect of the disclosure, a set of UEs comprises the distributed antenna system, and the method depicted in FIG. **13** provides for precoding uplink transmissions from the UEs to a set of eNodeBs. For each of a plurality N_{tones} of OFDM tones, step **1302** provides for selecting a number $N_{sets}(n_{tones})$ of f different UE sets to transmit pre-coded signals, where a particular number $N_{sets}(n_{tones})$ denotes a number of UE sets corresponding to an n_{tones}^{th} OFDM tone. For each of the N_{tones} tones, step **1303** calculates precoding weights for all the corresponding UE sets. If there are N_{sets} UE sets for each of the N_{tones} OFDM tones, then there might be up to a total of $N_{sets} \cdot N_{tones}$ precoding matrices. A combination of precoding matrices is provided by selecting one precoding matrix for each of the N_{tones} OFDM tones. Step **1304** provides for calculating the PAPR for each of multiple combinations of the precoding matrices. By way of example, a PAPR can be calculated from an IDFT of a set of spread original data symbols comprising the original data symbols spread by a corresponding precoding matrix.

Step **1305** can comprise any of various techniques for selecting an antenna-tone set. For example, if the corresponding combination of precoding matrices satisfies a threshold criterion, such as can be based on PAPR, then the antenna-tone set is selected and the combination of precoding matrices is used to encode the original data symbols. In other aspects, a "best" metric (such as may be based on PAPR) may be determined, such as from an exhaustive search or a combinatorial search. A combinatorial search is one that might exploit one or more pruning strategies to avoid testing all possible candidate combinations. Combinatorial searches can include branch and bound, greedy, local search methods, and a variety of heuristics that use partial knowledge about the structure of the solution space, which can achieve a "good" solution, if not the "best" solution.

The various blocks shown in the figures may be viewed as method steps, and/or as operations that result from operation of computer program code, and/or as a plurality of coupled logic circuit elements constructed to carry out the associated function(s).

In general, the various exemplary aspects may be implemented in hardware or special purpose circuits, software, logic or any combination thereof. For example, some aspects may be implemented in hardware, while other aspects may be implemented in firmware or software which may be executed by a controller, microprocessor or other computing device, although the invention is not limited thereto. While various aspects of the exemplary embodiments of this disclosure may be illustrated and described as block diagrams, flow charts, or using some other pictorial representation, it is well understood that these blocks, apparatus, systems, techniques or methods described herein may be implemented in, as non-limiting examples, hardware, software, firmware, special purpose circuits or logic, general purpose hardware or controller or other computing devices, or some combination thereof.

It should thus be appreciated that at least some aspects of the exemplary aspects of the disclosure may be practiced in various components such as integrated circuit chips and modules, and that the exemplary aspects of this disclosure may be realized in an apparatus that is embodied as an integrated circuit. The integrated circuit, or circuits, may comprise circuitry (as well as possibly firmware) for embodying at least one or more of a data processor or data processors, a digital signal processor or processors, baseband circuitry and radio frequency circuitry that are configurable so as to operate in accordance with the exemplary aspects of this disclosure.

Various modifications and adaptations to the foregoing exemplary aspects of this disclosure may become apparent to those skilled in the relevant arts in view of the foregoing description, when read in conjunction with the accompanying drawings. However, any and all modifications will still fall within the scope of the non-limiting and exemplary aspects of this disclosure.

The invention claimed is:

1. A method of communicating in a mobile radio communications network, comprising:

provisioning a consecutive series of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers for uplink or downlink communications;

provisioning a plurality of different selectable subcarrier spacings for the consecutive series of OFDM subcarriers;

performing discrete Fourier transform (DFT) coding on a plurality of data symbols to produce coded symbols;

performing an inverse-DFT on the coded symbols to produce a single-carrier frequency division multiple access signal that comprises a sum of the consecutive series of OFDM subcarriers; and

transmitting the single-carrier frequency division multiple access signal in the mobile radio communications network;

wherein provisioning the plurality of different selectable subcarrier spacings comprises providing the single-carrier frequency division multiple access signal with a particular one of a set of different symbol periods by selecting one of the plurality of different selectable subcarrier spacings.

2. The method of claim **1**, wherein at least one of the plurality of different selectable subcarrier spacings equals at least one other of the plurality of different selectable subcarrier spacings multiplied by a scaling factor that is a power of two.

3. The method of claim **1**, further comprising adding a cyclic prefix to the single-carrier frequency division multiple access signal prior to transmitting.

4. The method of claim **1**, wherein the plurality of different selectable subcarrier spacings are integer multiples of a first subcarrier spacing.

5. The method of claim **1**, wherein the provisioning the plurality of different selectable subcarrier spacings is configured for different deployment scenarios comprising different system requirements or different channel conditions.

6. The method of claim **1**, wherein each of the plurality of different subcarrier spacings provides a different number of symbols per frame.

7. The method of claim **1**, wherein the performing the inverse-DFT employs a discrete Fourier transform with a plurality of sampling rates that comprise harmonic frequencies.

8. The method of claim **1**, further comprising determining a delay spread in the mobile radio communication network;

and based on the delay spread, employing a first numerology or a second numerology; wherein the first numerology comprises a first one of the plurality of different selectable subcarrier spacings, and the second numerology comprises a second one of the plurality of different selectable subcarrier spacings.

9. An apparatus for communicating in a mobile radio communications network, comprising:

a non-transitory computer-readable memory storing one or more instructions; and

at least one processor in communication with the non-transitory computer-readable memory; wherein the one or more instructions, when executed by the at least one processor, cause the at least one processor to:

provision a consecutive series of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers for uplink or downlink communications;

provision a plurality of different selectable subcarrier spacings for the consecutive series of OFDM subcarriers;

perform discrete Fourier transform (DFT) coding on a plurality of data symbols to produce DFT coded symbols;

perform an inverse-DFT on the coded symbols to produce a single-carrier frequency division multiple access signal that comprises a sum of the consecutive series of OFDM subcarriers; and

transmit the single-carrier frequency division multiple access signal in the mobile radio communications network;

wherein the one or more instructions cause the at least one processor to provide the single-carrier frequency division multiple access signal with one of a set of different selectable symbol periods by selecting one of the plurality of different selectable subcarrier spacings.

10. The apparatus of claim **9**, wherein at least one of the plurality of different selectable subcarrier spacings equals at least one other of the plurality of different selectable subcarrier spacings multiplied by a scaling factor that is a power of two.

11. The apparatus of claim **9**, further comprising one or more instructions, when executed by the at least one processor, cause the at least one processor to add a cyclic prefix to the single-carrier frequency division multiple access signal.

12. The apparatus of claim **9**, wherein the plurality of different selectable subcarrier spacings are integer multiples of a first subcarrier spacing.

13. The apparatus of claim **9**, wherein each of the plurality of different selectable subcarrier spacings is configured for one of a plurality of different deployment scenarios, the plurality of different deployment scenarios comprising different system requirements or different channel conditions.

14. The apparatus of claim **9**, wherein each of the plurality of different selectable subcarrier spacings provides a different number of symbols per frame.

15. The apparatus of claim **9**, wherein the inverse-DFT a plurality of sampling rates that comprise harmonic frequencies.

16. The apparatus of claim **9**, wherein the one or more instructions that cause the at least one processor to provide the single-carrier frequency division multiple access signal with one of a set of different selectable symbol periods determine a delay spread in the mobile radio communication network; and based on the delay spread, select a first numerology or a second numerology; wherein the first numerology comprises a first one of the plurality of different selectable subcarrier spacings, and the second numerology comprises a second one of the plurality of different selectable subcarrier spacings.

17. An apparatus for communicating in a mobile radio communications network, comprising:

a transceiver-control circuitry configured for:

provisioning a consecutive series of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers for uplink or downlink communications;

provisioning a plurality of different selectable subcarrier spacings for the consecutive series of OFDM subcarriers; and

performing discrete Fourier transform (DFT) coding on a plurality of data symbols to produce DFT coded symbols; and

an OFDM transceiver communicatively coupled to the transceiver-control circuitry and configured for:

performing an inverse-DFT on the coded symbols to produce a single-carrier frequency division multiple access signal that comprises a sum of the consecutive series of OFDM subcarriers; and

transmitting the single-carrier frequency division multiple access signal in the mobile radio communications network;

wherein provisioning the plurality of different selectable subcarrier spacings comprises providing the single-carrier frequency division multiple access signal with a particular one of a set of different symbol periods by selecting one of the plurality of different selectable subcarrier spacings.

18. The apparatus of claim **17**, wherein at least one of the plurality of different selectable subcarrier spacings equals at least one other of the plurality of different selectable subcarrier spacings multiplied by a scaling factor that is a power of two.

19. The apparatus of claim **17**, wherein the OFDM transceiver is further configured to add a cyclic prefix to the single-carrier frequency division multiple access signal.

20. The apparatus of claim **17**, wherein the plurality of different selectable subcarrier spacings comprise integer multiples of a first subcarrier spacing.

21. The apparatus of claim **17**, wherein each of the plurality of different selectable subcarrier spacings is configured for one of a plurality of different deployment scenarios, the plurality of different deployment scenarios comprising different system requirements or different channel characteristics.

22. The apparatus of claim **17**, wherein each of the plurality of different selectable subcarrier spacings produces a different number of symbols per frame.

23. The apparatus of claim **17**, wherein the OFDM transceiver employs a discrete Fourier transform with a plurality of sampling rates that comprises harmonic frequencies.

24. The apparatus of claim **17**, wherein the transceiver-control circuitry is configured for determining a delay spread; and based on the delay spread, causing the transceiver to employ a first numerology or a second numerology; wherein the first numerology comprises a first one of the plurality of different selectable subcarrier spacings, and the second numerology comprises a second one of the plurality of different selectable subcarrier spacings.

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(54) **SPREADING AND PRECODING IN OFDM**

(71) Applicant: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

(72) Inventor: **Steve Shattil**, Cheyenne, WY (US)

(73) Assignee: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

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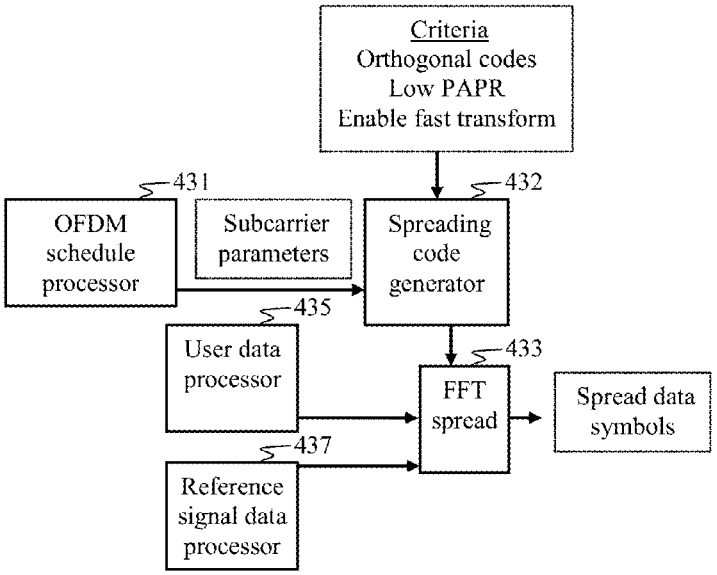
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(74) *Attorney, Agent, or Firm* — Steven J Shattil

(57) **ABSTRACT**

An OFDM transmitter spreads original data symbols with a complex-valued spreading matrix derived from a discrete Fourier transform. Spread data symbols are mapped to OFDM subcarriers. Spreading and mapping are configured to produce a transmitted spread-OFDM signal with a low peak-to-average power ratio (PAPR) and orthogonal code spaces. In MIMO systems, the complex-valued spreading matrix can comprise a MIMO precoding matrix, and the code spaces can comprise MIMO subspaces. In Cooperative-MIMO, a combination of low code-space cross correlation and low PAPR can be achieved.

36 Claims, 14 Drawing Sheets



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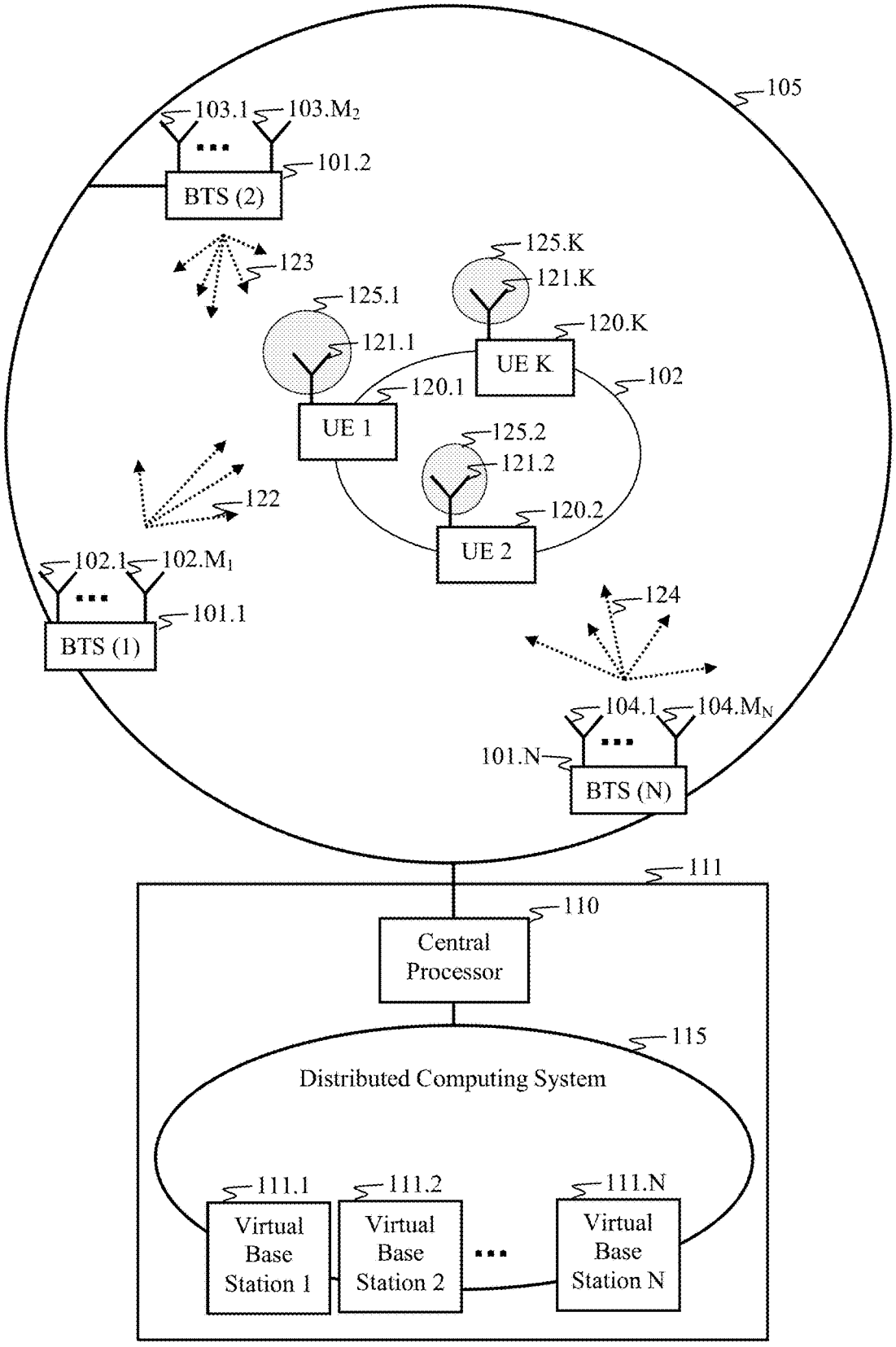

105
103.1
103.M2
101.2
BTS (2)
123
125.K
121.K
120.K
UE K
102
125.1
121.1
120.1
UE 1
125.2
121.2
120.2
UE 2
122
102.1
102.M1
101.1
BTS (1)
124
104.1
104.MN
101.N
BTS (N)
111
110
Central Processor
115
Distributed Computing System
111.1
111.2
111.N
Virtual Base Station 1
Virtual Base Station 2
Virtual Base Station N

Figure 1

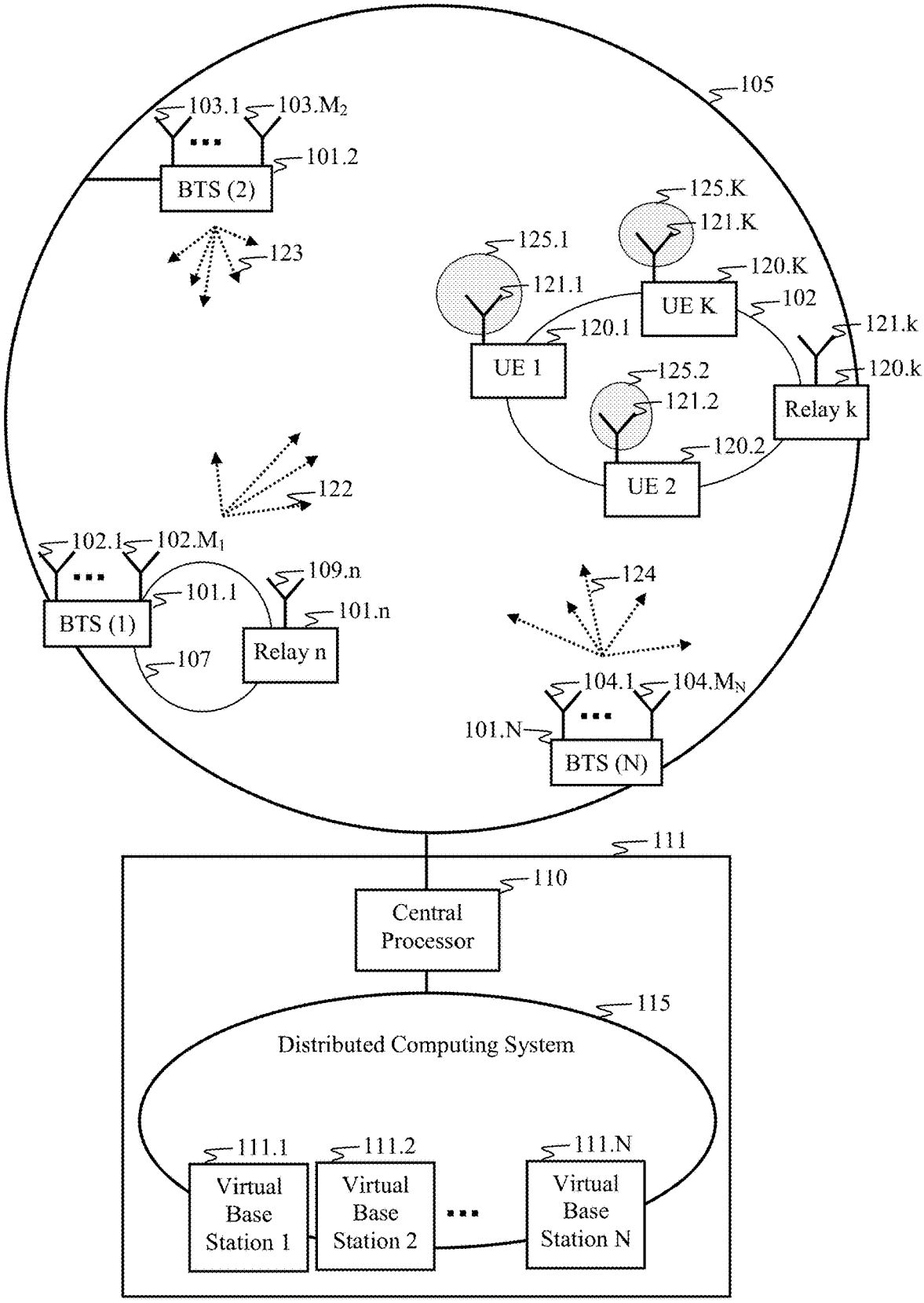

105
103.1
103.M2
101.2
BTS (2)
123
125.K
121.K
125.1
121.1
120.K
UE K
102
120.1
121.k
UE 1
120.k
125.2
121.2
Relay k
120.2
UE 2
122
102.1
102.M1
109.n
101.1
101.n
BTS (1)
Relay n
107
124
104.1
104.MN
101.N
BTS (N)
111
110
Central Processor
115
Distributed Computing System
111.1
111.2
111.N
Virtual Base Station 1
Virtual Base Station 2
Virtual Base Station N

Figure 2

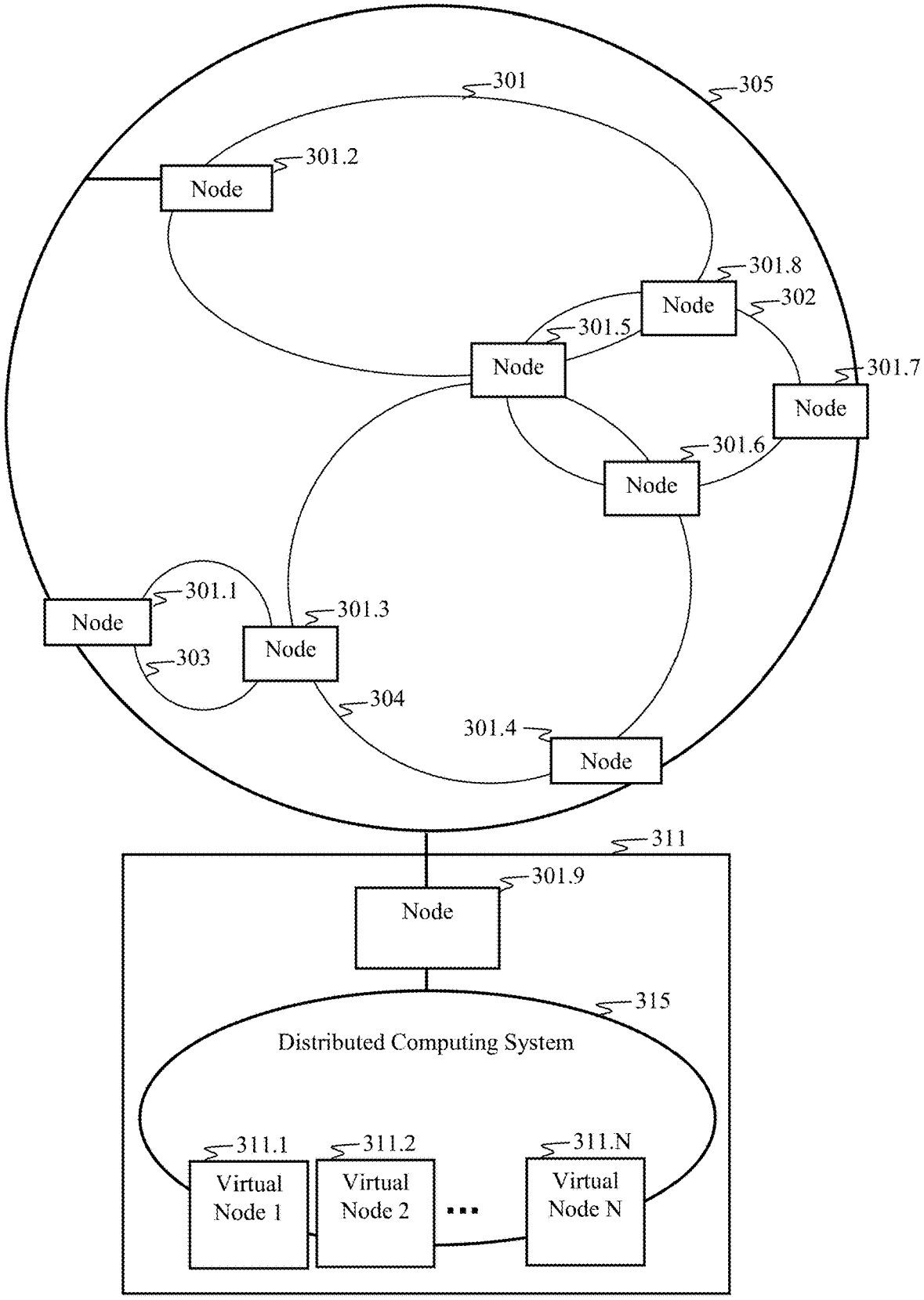

301
305
301.2
Node
301.8
Node
302
301.5
Node
301.7
Node
301.6
Node
301.1
Node
303
301.3
Node
304
301.4
Node
311
301.9
Node
315
Distributed Computing System
311.1
Virtual Node 1
311.2
Virtual Node 2
311.N
Virtual Node N

Figure 3

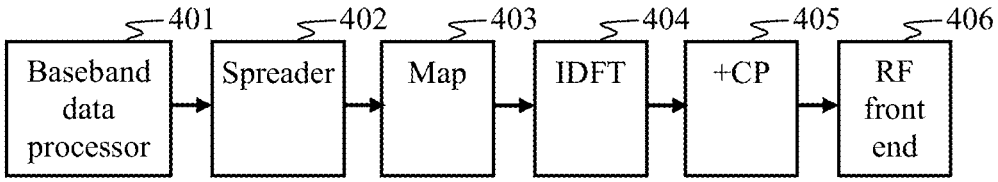


Figure 4A

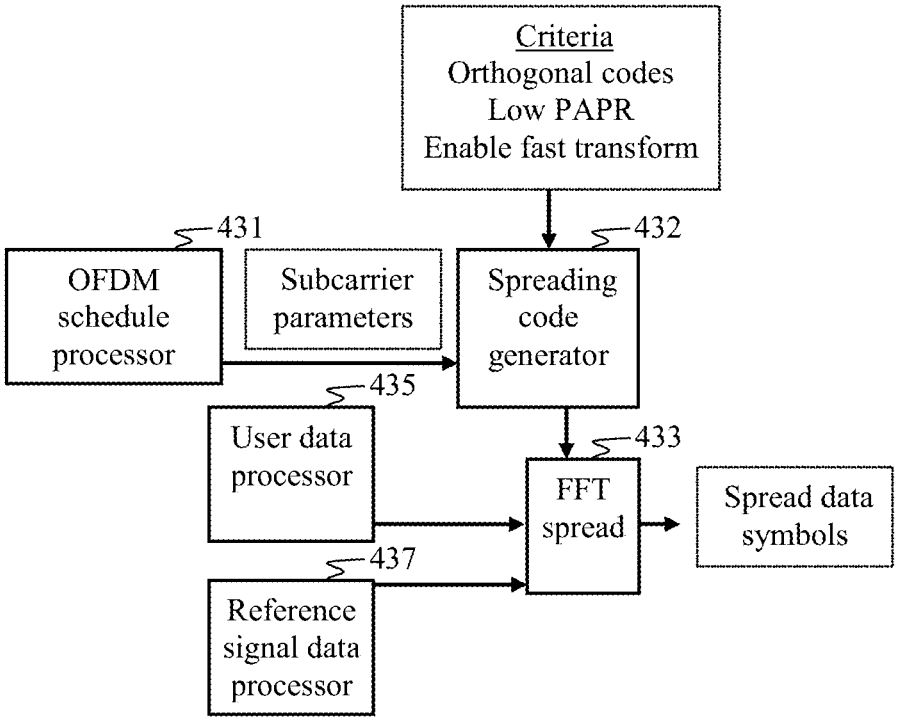


Figure 4B

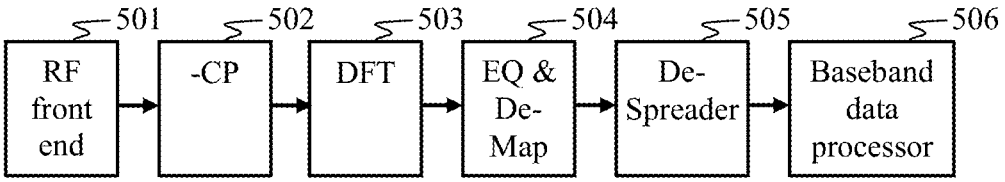


Figure 5A

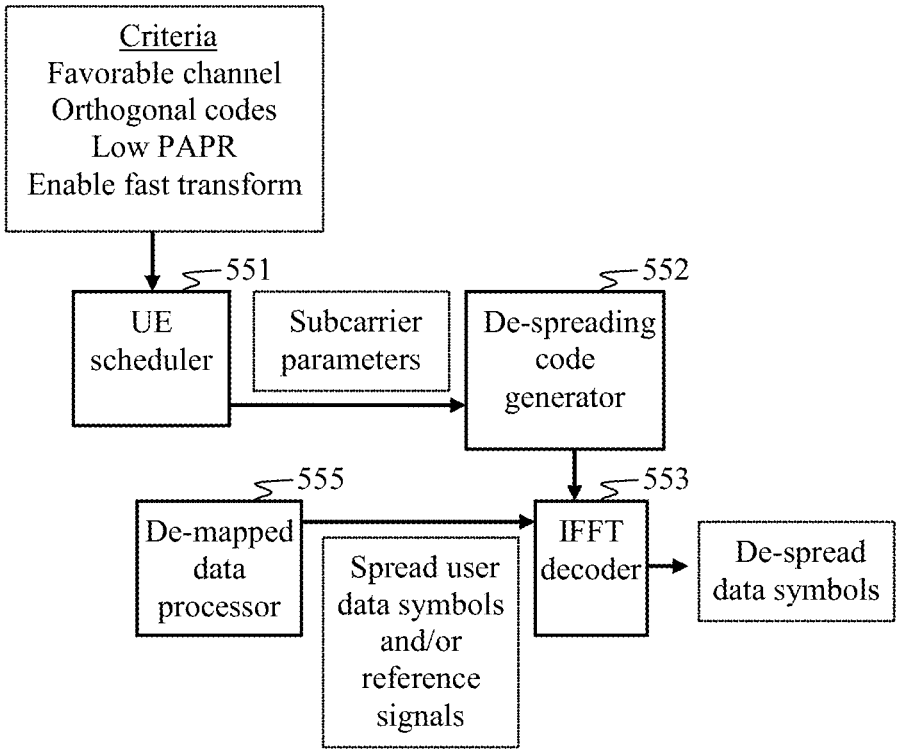


Figure 5B

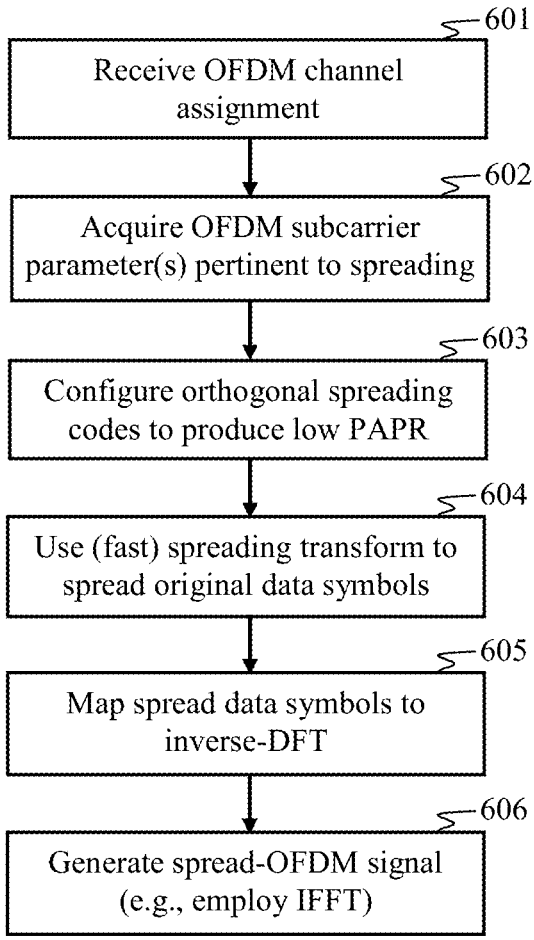


Figure 6A

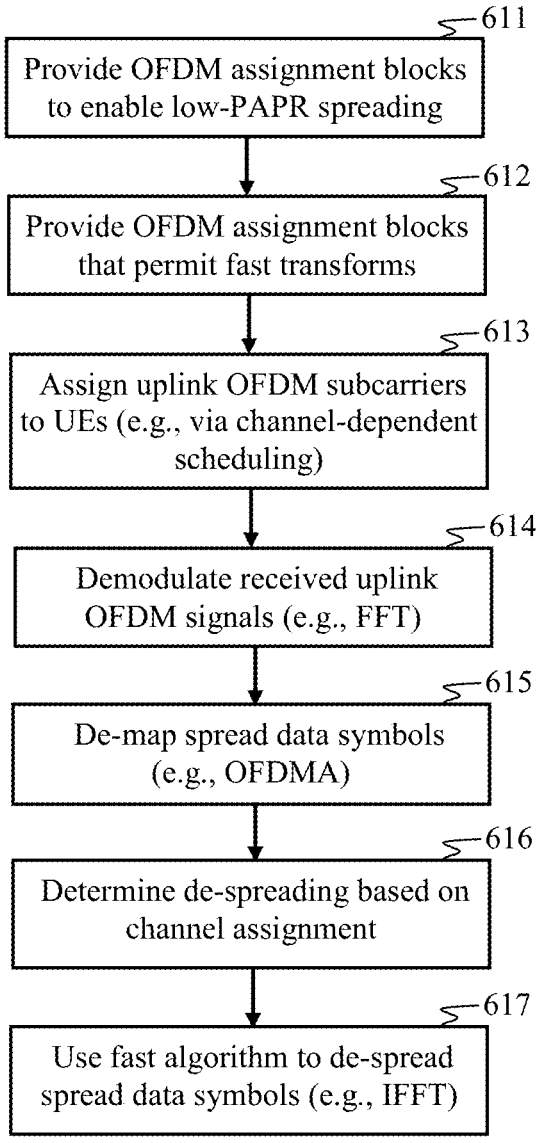


Figure 6B

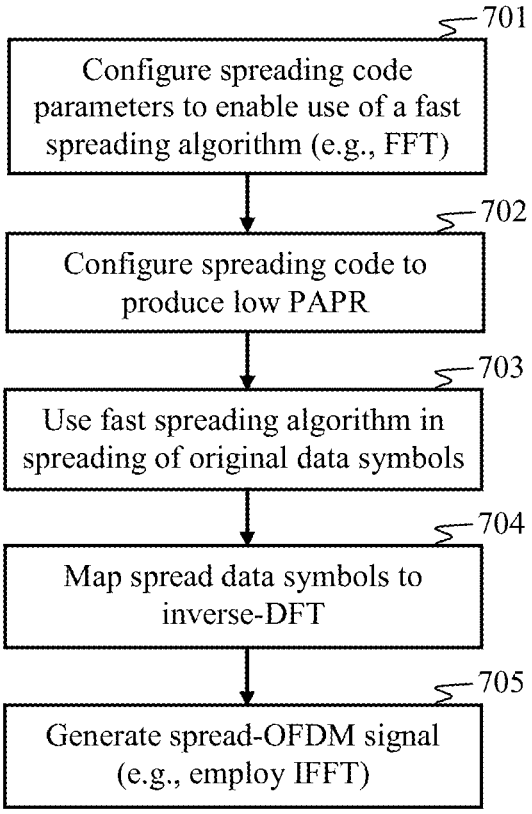


Figure 7A

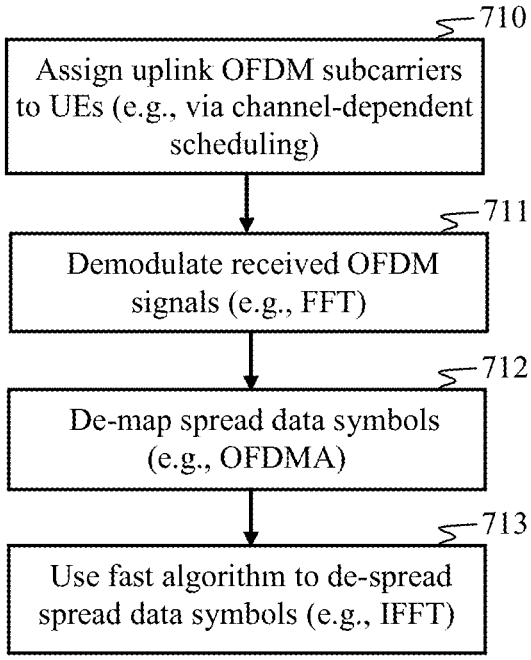


Figure 7B

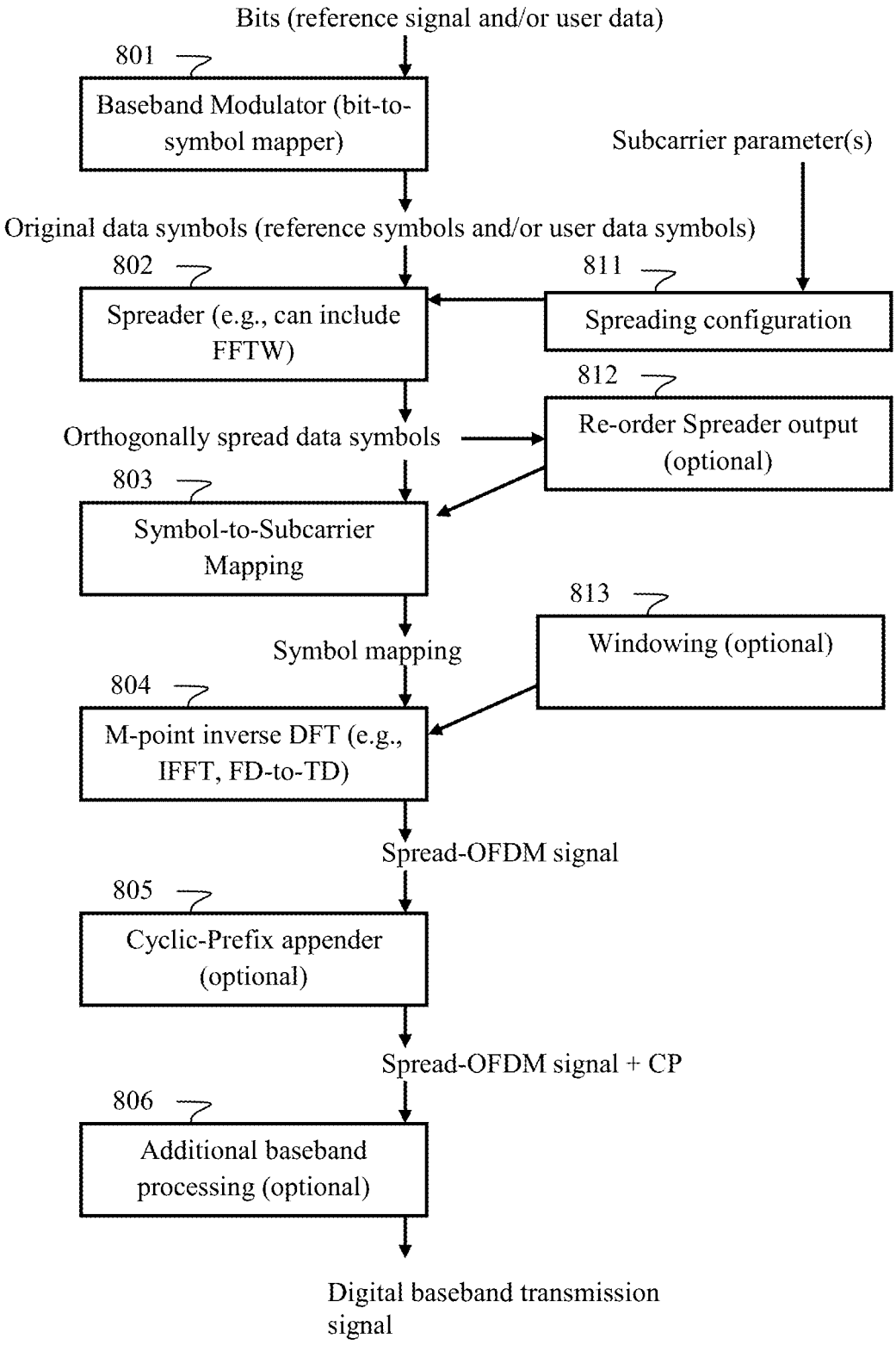

Bits (reference signal and/or user data)
801
Baseband Modulator (bit-to-symbol mapper)
Subcarrier parameter(s)
Original data symbols (reference symbols and/or user data symbols)
802
Spreader (e.g., can include FFTW)
811
Spreading configuration
812
Re-order Spreader output (optional)
Orthogonally spread data symbols
803
Symbol-to-Subcarrier Mapping
813
Windowing (optional)
Symbol mapping
804
M-point inverse DFT (e.g., IFFT, FD-to-TD)
Spread-OFDM signal
805
Cyclic-Prefix appender (optional)
Spread-OFDM signal + CP
806
Additional baseband processing (optional)
Digital baseband transmission signal

Figure 8A

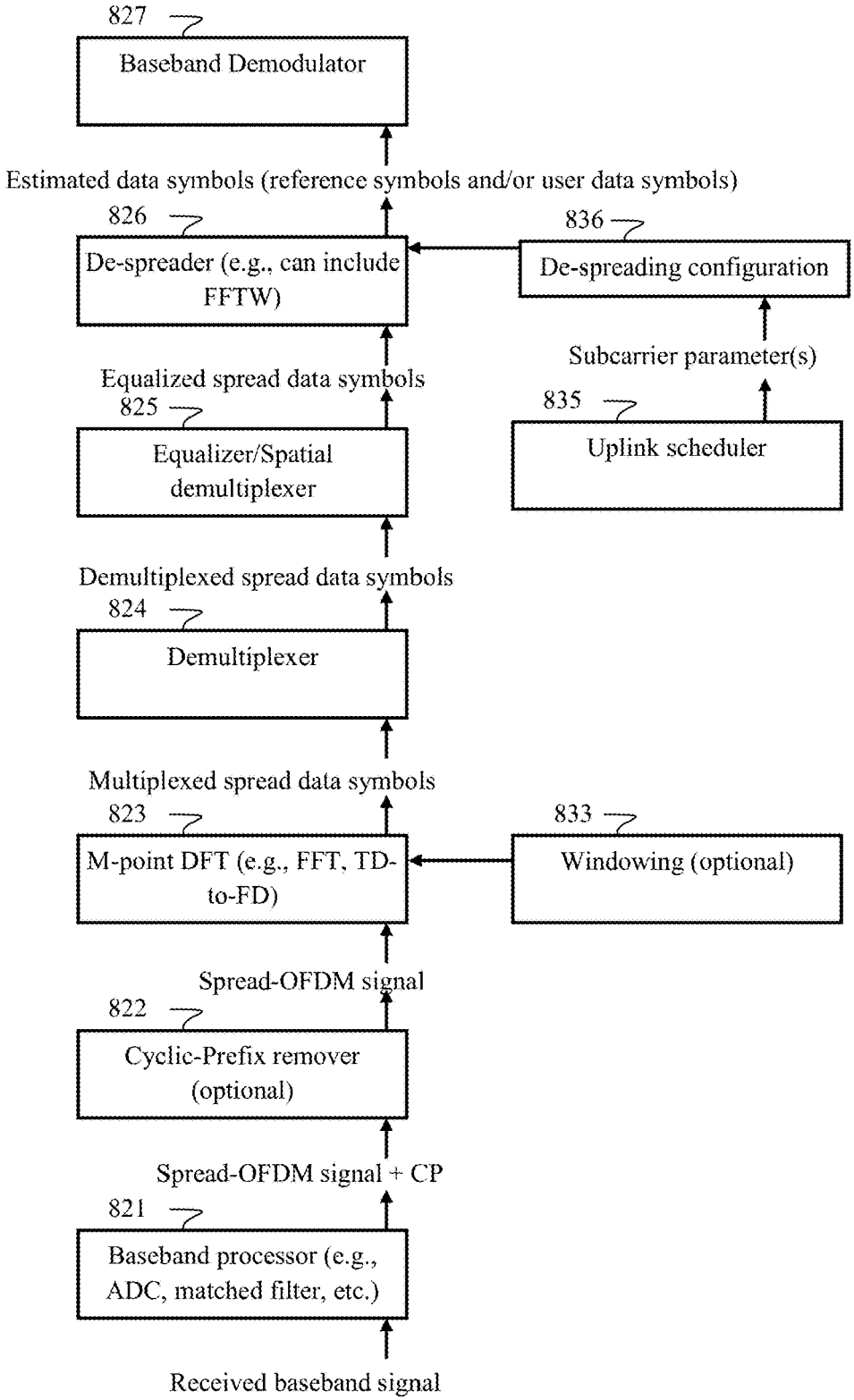

827
Baseband Demodulator
Estimated data symbols (reference symbols and/or user data symbols)
826
De-spreader (e.g., can include FFTW)
836
De-spreading configuration
Subcarrier parameter(s)
Equalized spread data symbols
825
Equalizer/Spatial demultiplexer
835
Uplink scheduler
Demultiplexed spread data symbols
824
Demultiplexer
Multiplexed spread data symbols
823
M-point DFT (e.g., FFT, TD-to-FD)
833
Windowing (optional)
Spread-OFDM signal
822
Cyclic-Prefix remover (optional)
Spread-OFDM signal + CP
821
Baseband processor (e.g., ADC, matched filter, etc.)
Received baseband signal

Figure 8B

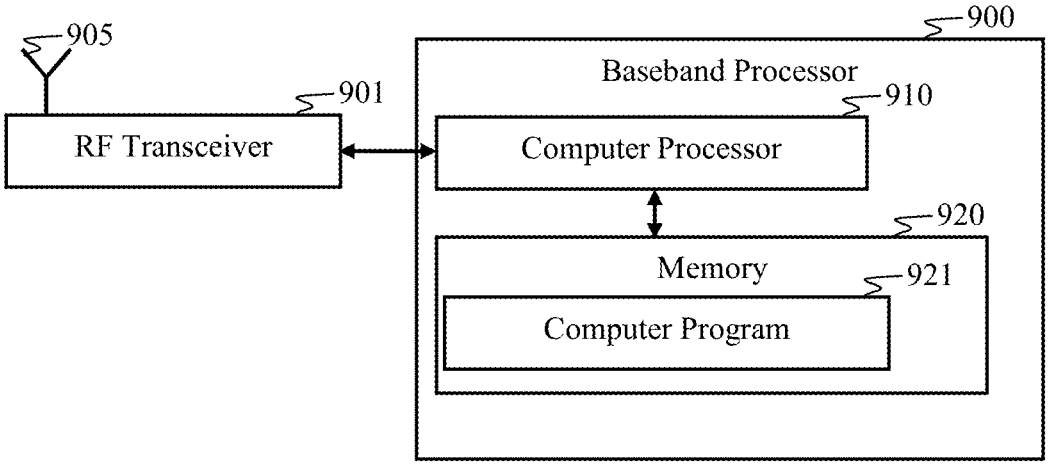

905
900
Baseband Processor
901
910
RF Transceiver
Computer Processor
920
Memory
921
Computer Program

Figure 9

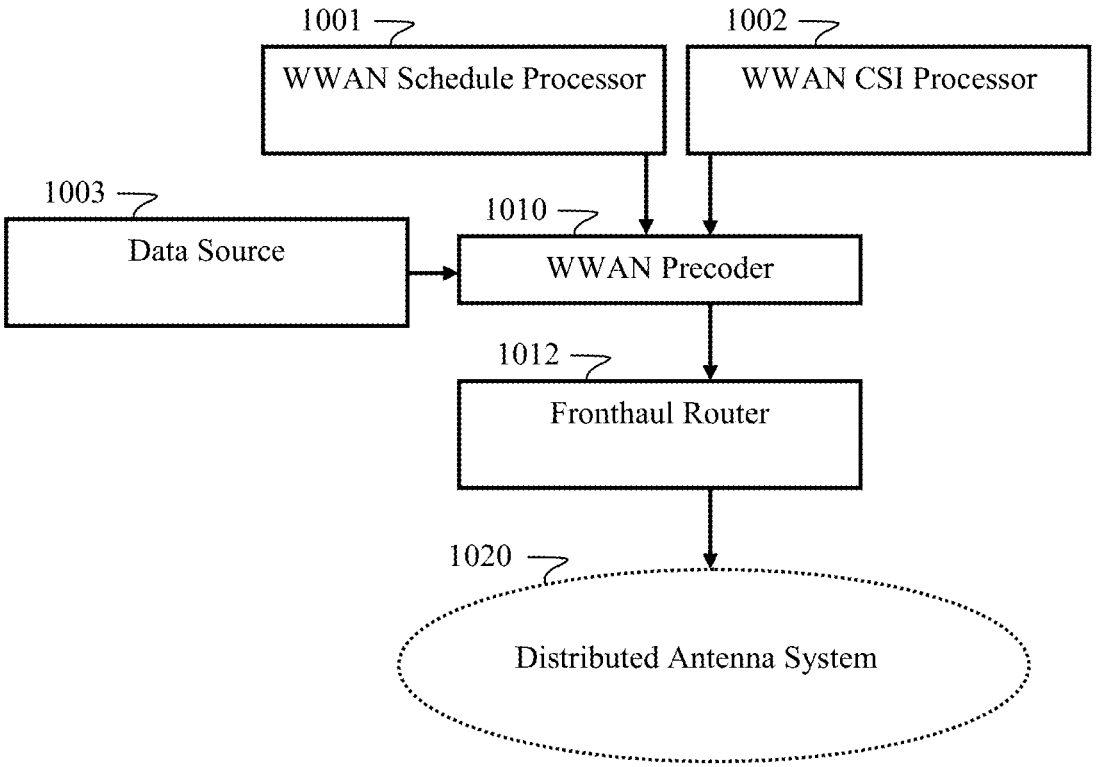

1001
WWAN Schedule Processor
1002
WWAN CSI Processor
1003
Data Source
1010
WWAN Precoder
1012
Fronthaul Router
1020
Distributed Antenna System

Figure 10A

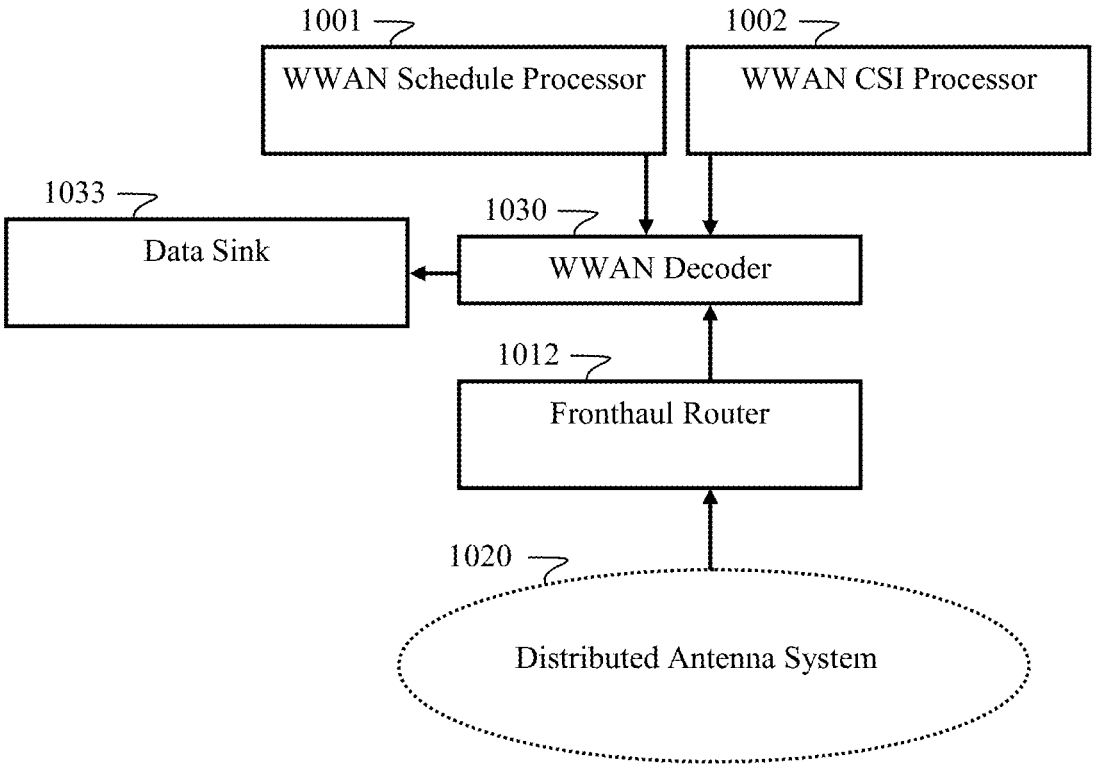

1001
WWAN Schedule Processor
1002
WWAN CSI Processor
1033
Data Sink
1030
WWAN Decoder
1012
Fronthaul Router
1020
Distributed Antenna System

Figure 10B

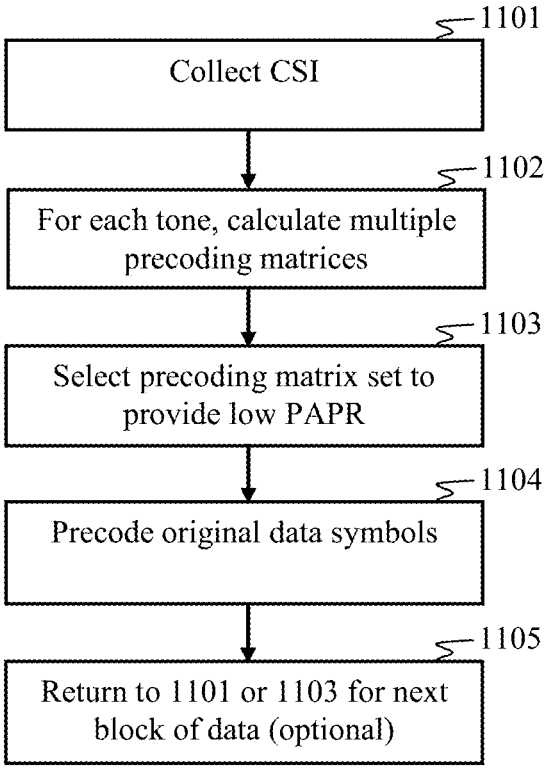


Figure 11

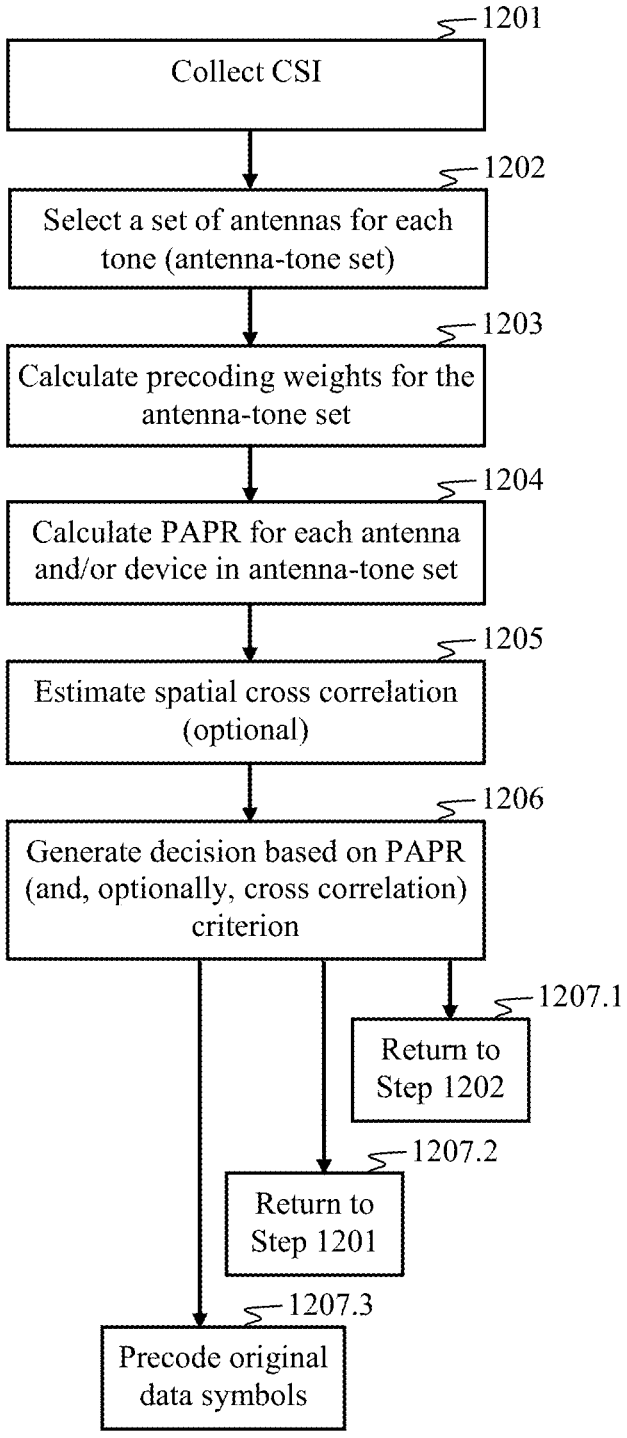


Figure 12

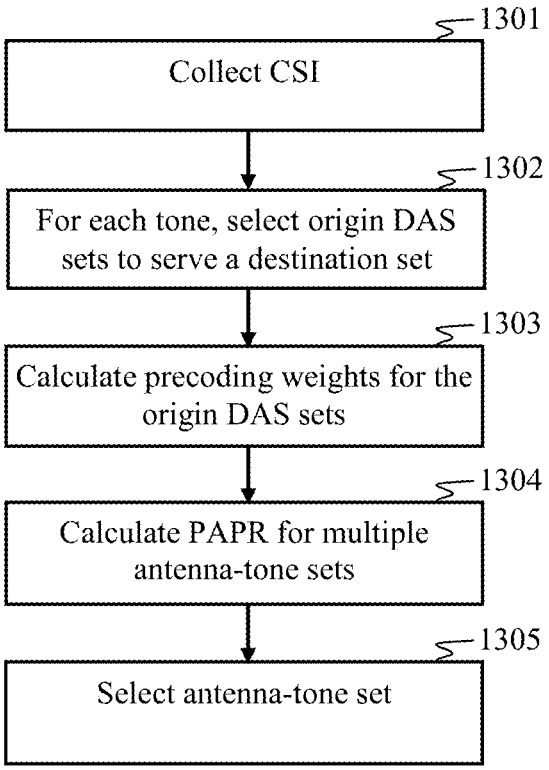

1301
Collect CSI
1302
For each tone, select origin DAS sets to serve a destination set
1303
Calculate precoding weights for the origin DAS sets
1304
Calculate PAPR for multiple antenna-tone sets
1305
Select antenna-tone set

Figure 13

SPREADING AND PRECODING IN OFDM

RELATED APPLICATIONS

This application is a Continuation-in-Part of U.S. patent application Ser. No. 14/727,769, entitled "Cooperative Wireless Networks," filed Jun. 1, 2015, which is a Continuation of U.S. patent application Ser. No. 14/276,309, entitled "Cooperative Wireless Networks," filed May 13, 2014, now U.S. Pat. No. 9,048,897, which is a Continuation of U.S. patent application Ser. No. 12/545,572, entitled "Cooperative Wireless Networks," filed Aug. 21, 2009, now U.S. Pat. No. 8,750,264, which is a Divisional of U.S. patent application Ser. No. 11/187,107, entitled "Cooperative Beam-Forming in Wireless Networks," filed on Jul. 22, 2005, now U.S. Pat. No. 8,670,390, which claims priority to Provisional Appl. No. 60/598,187, filed Aug. 2, 2004, all of which are incorporated by reference in their entireties.

BACKGROUND

I. Field

The present invention relates generally to wireless communication networks, and more specifically to precoding multicarrier waveforms.

II. Background

The background description includes information that may be useful in understanding the present inventive subject matter. It is not an admission that any of the information provided herein is prior art or relevant to the presently claimed inventive subject matter, or that any publication, specifically or implicitly referenced, is prior art.

The most pressing need in mobile wireless wide area networks (WWANs), such as cellular networks, is to meet the increasing demand for data services. However, only a very small portion of the radio spectrum is suitable for WWAN communications. Above a few Gigahertz, path losses become too great for wide area communications in typical terrestrial environments. Only a fraction of the suitable spectrum is allocated for WWANs, and those allocations are divided among (ostensibly) competing cellular companies.

Various techniques have been proposed to enable more efficient use of the available spectrum, such as spectrum sharing, dynamic bandwidth exchange, and various "smart" radio schemes. Other techniques, such as joint scheduling and power control, can improve frequency reuse in cell configurations. Carrier aggregation simply allocates more radio channels to each client device without improving spectrum efficiency, providing a temporary increase in data services until those channels become congested.

While such techniques can provide more efficient use of the available WWAN spectrum, the laws of Physics still dictate a limit to the amount of information that can be carried with a given amount of WWAN spectrum and power. Unfortunately, demand for data bandwidth continues to grow, irrespective of the limitations imposed by Physics.

SUMMARY

In accordance with some aspects of the disclosure, this most pressing need for ever-increasing data bandwidth within a finite amount of spectrum is solved.

By way of example, a Cooperative-MIMO network comprises a distributed antenna system coordinated with Cooperative-MIMO functionality to serve multiple client devices, such as User Equipments (UEs) in a mobile WWAN. This may be referred to as server-side Cooperative MIMO. The distributed antennas can comprise a fronthaul network configured to deliver precoded Cooperative MIMO baseband signals (such as from a central processor, a distributed computing system (e.g., Cloud computing system), a remote processor, or other processor(s)) to the antennas to provide for precoded MIMO transmissions into the WWAN channel. Precoding can be configured to produce a localized coherence zone at each of the multiple client devices, which can enable each client device to be served with the entire available WWAN spectrum without causing interference to other ones of the multiple client devices. The localized coherence zone can be referred to as a spatial subchannel or a subspace channel. In one aspect, Cooperative-MIMO precoding configures the distributed network of antennas and the natural scattering environment to focus transmissions that coherently combine at each of the client devices, thereby producing the localized coherence zones. Similarly, Cooperative-MIMO demultiplexing can separate same-band transmissions from the client devices. While server-side Cooperative MIMO can provide nearly ideal frequency reuse of the WWAN spectrum, the amount of data that can be transmitted to each client device is limited by the WWAN spectrum (and power).

Therefore, in accordance with some aspects of the disclosure, the aforementioned server-side Cooperative-MIMO system(s) can further comprise a client-side Cooperative-MIMO system. By way of example, nearby client devices may self-organize into Cooperative-MIMO clusters, or some other technique may be employed to group client devices to provide for Cooperative-MIMO processing. For example, a server-side or some other centralized coordination technique may be employed. A wireless fronthaul network communicatively couples together the client devices to provide a cluster. The wireless fronthaul network can employ short-range wireless links, such as extremely high-bandwidth (relative to WWAN link bandwidth), low-power transmissions. The fronthaul transmissions can employ millimeter-wave, infrared, and/or optical spectrum, which is usually impractical for use in mobile WWANs, but which supports much higher data bandwidth than a WWAN channel. In some aspects, the fronthaul links might enable 10,000 times (or more) spectrum than the total available WWAN spectrum.

In systems disclosed herein, the theoretical limit of the WWAN data bandwidth is no longer limited by the WWAN spectrum, but rather, it can increase up to the data bandwidth of the cluster's very wideband fronthaul network minus some processing overhead. For example, on the downlink, cooperative processing among client devices in a cluster can allow one client device to aggregate the data bandwidth of all the subspace channels (i.e., localized coherence zones) serving the cluster. This is advantageous since each client device, even when it is active, does not employ its available downlink channel one hundred percent of the time. Rather, a client device typically transmits and receives data only a small fraction of the time it is being used. This is sometimes referred to as an activity factor. In accordance with aspects of the disclosure, as the cluster grows, each client device has more available instantaneous data bandwidth for the WWAN uplink and downlink. This is because multiple independent parallel spatial subchannels in the WWAN can be exploited to serve a single client device, thus expanding its data

bandwidth far beyond the limited amount of spectrum in a single WWAN subspace channel.

Such aspects of the disclosure can provide the counter-intuitive result that as more client devices join a WWAN, the data bandwidth per client device increases instead of decreases, provided that there is a sufficient number of server-side antennas to accommodate the additional devices. In accordance with some aspects of the disclosure, client devices can be provisioned to operate as server-side antennas communicatively coupled to the server-side fronthaul network. This allows the network infrastructure to grow as client devices join the WWAN. A generalized concept of a relay node is introduced in which the relay node may be part of a server-side distributed antenna system, a client-side cluster, or both. A relay node can operate in multiple clusters and/or multipoint groups. The relay node can be a client device, a server-side device or component, or some other device, and it can be configured to adapt its function as it operates with different cooperating devices.

In accordance with some aspects of the disclosure, cooperative processing can be configured to reduce backhaul overhead, including the data bandwidth required for backhaul communications. For example, in some aspects, cooperative processing at the edge of the radio access network can reduce backhaul loads. However, in many aspects, the backhaul network's spectrum is far larger than the amount of spectrum allocated to the WWAN. Thus, in some implementations, a practical limitation to the WWAN data bandwidth might be related to the processing capability of the cooperating devices. This limitation can be advantageous in view of the alternative, because unlike the hard limitation imposed by Physics, processing power approximately doubles every eighteen months according to Moore's Law.

Some aspects of the disclosure provide for configuring distributed processing to enhance processing efficiency. For example, processing performed by cooperating client devices can be configured via various techniques and/or algorithms to improve processing efficiency. As used herein, processing efficiency can be achieved by employing signal processing algorithms that require a fewer number of total operations, require a fewer number of complex operations, require a fewer number of data exchanges with other processors, reduce latency, reduce power consumption, reduce processor idle time, and the like. Various processing techniques, such as pipelined processing architectures and the like, can be configured to improve processing efficiency. An end result of improved processing efficiency can include, among other things, a cluster being able to comprise a larger number of cooperating devices.

In some aspects of the disclosure, system configurations produce a high-rank channel matrix, which permits lower-complexity maximum ratio combining/transmission to be employed instead of zero forcing or other higher-complexity algorithms.

In accordance with some aspects of the disclosure, various signal-processing algorithms employed in a WWAN transceiver can be combined, thus enabling a more efficient implementation. In some aspects, complex spreading codes can be employed to spread data symbols (e.g., user data and/or reference signals) to enable certain benefits, such as crest-factor reduction, which can enable lower power consumption, less-expensive radio components, and/or other benefits.

While some aspects of the disclosure can employ techniques to reduce the peak-to-average power (PAPR) of an OFDM transmission at the inverse discrete Fourier transform (IDFT), such as by operating on the signal output at the IDFT (e.g., via clipping, signal cancellation, or selecting one of a set of candidate OFDM signals that has the lowest PAPR), certain advantages can be realized by spreading the data symbols before the IDFT operation in a manner that causes the IDFT output signal to have a low PAPR. In such aspects, the spreading codes can be configured in response to OFDM subcarrier assignment to the device (e.g., uplink subcarriers assigned to a client device) to produce a transmitted OFDM signal with low PAPR. Parameters of the assigned subcarriers, such as subcarrier frequency spacing and number of subcarriers, can be used to determine complex spreading codes that produce a low-PAPR signal at the IDFT output. Configuring the spreading codes to provide a spread-OFDM signal with low PAPR can comprise an appropriate mapping of spread symbols to OFDM subcarriers in a manner that produces the desired low-PAPR signal. This can include re-ordering the output of the spreader prior to its input to the IDFT. In some aspects, OFDM subcarriers are assigned to a client device by a server-side device, such as to provide for channel-dependent scheduling. Thus, the server-side device can also determine the complex spreading codes for the purpose of de-spreading signals received from the client device.

In some aspects of the disclosure, characteristics of a data signal, such as its spectral information (i.e., frequency response) may be processed. In accordance with some aspects of the disclosure, this processing is responsive to OFDM subcarrier assignment to configure complex spreading of the data signal (and/or its spectral information) in a manner that, based on parameters of the assigned subcarriers (such as frequency spacing), produces a spread-OFDM signal with low PAPR. Without complex spreading configured in the aforementioned manner, the spectral information modulated onto an OFDM signal can produce a transmission with high PAPR. In some aspects of the disclosure, a transmitter receives an OFDM subcarrier assignment, and based on subcarrier parameters (such as frequency spacing, number of subcarriers, and/or other parameters) configures a transform operation that includes complex spreading codes which spread a data signal in a manner that, when modulated onto the OFDM subcarriers, produces a superposition signal (i.e., a transmitted OFDM signal) with a low PAPR.

By way of example, data spreading in the WWAN uplink channel can be performed by the individual client devices, wherein the spreading codes can be configured to employ fast algorithms for spreading and/or spreading-code generation. In some aspects, the data spreading can be configured to employ a similar fast algorithm used for a different signal processing operation, such as an IDFT used for modulating data onto an OFDM signal and/or a DFT used for demodulation. This can permit a given logical structure and/or physical processor architecture to perform similar signal processing algorithms (e.g., fast algorithms) for different radio transceiver operations (e.g., coding and modulation). In some aspects, a pipelined architecture can be employed, such as to make efficient use of one or more processors (e.g., a specialized hardware component or a general-purpose processor configured to perform the fast algorithm) to perform the different radio transceiver operations. In some aspects, multiple processors residing on different devices (e.g., client devices, server devices, combinations thereof) can be configured to cooperatively process signals via fast algorithms, wherein the client-side fronthaul can function as a computer bus (such as between processors, memories, ports, and/or other network resources) between computing components distributed across multiple network nodes, including client devices. In such aspects, the networked

processors can be pipelined to provide efficient processing of multiple radio transceiver operations.

By way of example, a fast algorithm can be a fast Fourier transform (FFT), such as a radix-2 FFT. Thus, a client device can be configured to perform a radix-2 FFT as part of a DFT-spreading of original data symbols, and the client device can be configured to perform a radix-2 FFT to modulate the spread data symbols onto OFDM subcarrier signals. In some aspects, the client device can configure processing hardware and/or software to employ the same radix-2 FFT (although possibly with different input parameters, transform size, etc.) for different, typically unrelated, radio transceiver operations, such as DFT-spreading and OFDM modulation, or DFT-spreading and OFDM demodulation, as well as others. It should be appreciated that such aspects may be performed as part of cooperative processing among multiple client devices, on the server side, with the aid of one or more relay devices, and/or some combination thereof.

In accordance with some aspects of the disclosure, spreading produces a different result than spectrum analysis. For example, spectrum analysis can provide for calculating frequency responses of a signal corresponding to tones. The term, "tones," is commonly used to mean orthogonal frequencies, such as in relation to the term, "discrete multitone modulation," which denotes OFDM-based communication systems that adapt the transmission to the channel conditions individually for each subcarrier. In OFDM, as in spectrum analysis, the tones are a set of frequency-multiplexed signals with the exact frequencies needed to make them orthogonal so they do not interfere with each other. In discrete systems, spectrum analysis expresses a discrete signal of N complex data symbols as a set of N/2 frequency responses. This is because frequencies between the Nyquist rate $f_{sam}/2$ and the sample rate f_{sam} alias to negative frequencies due to sampling above the Nyquist rate. These are the same tones as the corresponding positive frequencies. While the output of a DFT comprises N values, there are only N/2 tones, so the N/2 redundant frequency responses are typically discarded to provide spectral analysis, resulting in only half the values that DFT spreading would otherwise provide.

In some aspects of the disclosure, a radio transceiver can be configured to perform another type of signal-processing operation for different, typically unrelated, radio transceiver operations. By way of example, linear network coding can be configured to employ similar processing operations as in MIMO subspace precoding (i.e., multiplexing) and/or demultiplexing. Similarly, linear network decoding can employ similar operations as MIMO subspace multiplexing and/or demultiplexing. Thus, client-side and/or server-side processors can be configured to perform linear network coding that employs basically the same algorithms used to provide for spatial multiplexing and/or demultiplexing.

Aspects disclosed herein can be implemented as apparatus configurations comprising structural features that perform the functions, algorithms, and methods described herein. Flow charts and descriptions disclosed herein can embody instructions, such as in software residing on a non-transitory computer-readable medium, configured to operate a processor (or multiple processors). Flow charts and functional descriptions, including apparatus diagrams, can embody methods for operating a communication network(s), coordinating operations which support communications in a network(s), operating network components (such as client devices, server-side devices, relays, and/or supporting devices), and assembling components of an apparatus configured to perform the functions disclosed herein.

Groupings of alternative elements or aspect of the disclosed subject matter disclosed herein are not to be construed as limitations. Each group member can be referred to and claimed individually or in any combination with other members of the group or other elements found herein. One or more members of a group can be included in, or deleted from, a group for reasons of convenience and/or patentability. When any such inclusion or deletion occurs, the specification is herein deemed to contain the group as modified, thus fulfilling the written description of all Markush groups used in the appended claims.

All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided with respect to certain embodiments herein is intended merely to better illuminate the inventive subject matter and does not pose a limitation on the scope of the inventive subject matter otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the inventive subject matter.

Additional features and advantages of the invention will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The features and advantages of the invention may be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims. These and other features of the invention will become more fully apparent from the following description and appended claims, or may be learned by the practice of the invention as set forth herein.

The following patent applications and patents are hereby incorporated by reference in their entireties: U.S. Pat. No. 8,670,390, patent application Ser. No. 10/145,854, U.S. Pat. Nos. 9,225,471, 9,270,421, 9,325,805, patent application Ser. No. 14/789,949, Pat. Appl. No. 62/197,336, patent application Ser. No. 14/967,633, patent application Ser. No. 10/360,346, patent application Ser. No. 10/414,663, Pat. Appl. No. 60/286,850, U.S. Pat. Nos. 8,929,550, 7,430,257, 6,331,837, and 7,076,168.

BRIEF DESCRIPTION OF DRAWINGS

Flow charts depicting disclosed methods comprise "processing blocks" or "steps" may represent computer software instructions or groups of instructions. Alternatively, the processing blocks or steps may represent steps performed by functionally equivalent circuits, such as a digital signal processor or an application specific integrated circuit (ASIC). The flow diagrams do not depict the syntax of any particular programming language. Rather, the flow diagrams illustrate the functional information one of ordinary skill in the art requires to fabricate circuits or to generate computer software to perform the processing required in accordance with the present disclosure. It should be noted that many routine program elements, such as initialization of loops and variables and the use of temporary variables are not shown. It will be appreciated by those of ordinary skill in the art that unless otherwise indicated herein, the particular sequence of steps described is illustrative only and can be varied. Unless otherwise stated, the steps described below are unordered, meaning that the steps can be performed in any convenient or desirable order.

FIG. **1** is a block diagram of a communication system architecture in accordance with an exemplary aspect of the disclosure.

FIG. **2** illustrates a network configuration for super-array processing in accordance with some aspects of the disclosure.

FIG. **3** is a block diagram of a network topology, the type of which can be employed in accordance with aspects of the disclosure.

FIG. **4**A is a block diagram of a spread-OFDM transmitter in accordance with an aspect of the disclosure.

FIG. **4**B is a block diagram of a spread-OFDM spreader (such as spreader **402**) in accordance with some aspects of the disclosure.

FIG. **5**A is a block diagram of a receiver configured to receive and process spread-OFDM signals in accordance with aspects of the disclosure.

FIG. **5**B is a block diagram that depicts a portion of a receiver, such as a receiver that may be employed in a server-side WWAN terminal or system.

FIG. **6**A is a flow diagram that depicts a method performed in a radio transceiver, which can employ a fast algorithm to generate a spread data sequence from an original data sequence in accordance with some aspects of the disclosure.

FIG. **6**B is a flow diagram that depicts a method for processing received spread-OFDM signals, which can be employed in accordance with various aspects of the disclosure.

FIG. **7**A is a flow diagram that depicts a method for generating spread-OFDM signals in accordance with some aspects of the disclosure.

FIG. **7**B is a flow diagram that depicts a method of processing received spread-OFDM signals in accordance with some aspects of the disclosure.

FIG. **8**A is a block diagram that depicts modules corresponding to processing functions that can be implemented by a computer processor programmed to perform methods in accordance with aspects of the disclosure. The blocks can be interpreted as software modules, hardware components, or some combination thereof. The modules can represent steps in a method. In some aspects, the block diagram is indicative of structure and/or function of a client device (such as a UE) or a system of client devices.

FIG. **8**B is a block diagram that depicts modules corresponding to processing functions that can be implemented by a computer processor programmed to perform methods in accordance with aspects of the disclosure. The blocks can be interpreted as software modules, hardware components, or some combination thereof. The modules can represent steps in a method. In some aspects, the block diagram is indicative of structure and/or function of a server-side device (such as a base transceiver station (e.g., an eNodeB) or a central processor coupled to one or more base transceiver stations), or a system of server-side devices, such as a Coordinate Multipoint system.

FIG. **9** is a block diagram of a transceiver that can be configured to operate in accordance with aspects of the disclosure.

FIGS. **10**A and **10**B are block diagrams that illustrates transceiver configurations in accordance with aspects of the disclosure. The blocks can comprise processing elements that provide necessary computing facilities for the transceiver. By way of example only, processing elements can include special purpose hardware accelerators, such as co-processors for Fast Fourier Transform (FFT), encryption and decryption security processors, or programmable Central Processing Units (CPUs).

FIG. **11** is a flow diagram that depicts a precoding method in a distributed antenna system in accordance with some aspects of the disclosure.

FIG. **12** is a flow diagram that depicts a precoding method in a distributed antenna system in accordance with some aspects of the disclosure.

FIG. **13** is a flow diagram that depicts a precoding method in a distributed antenna system in accordance with some aspects of the disclosure.

DETAILED DESCRIPTION

Various aspects of the disclosure are described below. It should be apparent that the teachings herein may be embodied in a wide variety of forms and that any specific structure, function, or both being disclosed herein are merely representative. Based on the teachings herein one skilled in the art should appreciate that an aspect disclosed herein may be implemented independently of any other aspects and that two or more of these aspects may be combined in various ways. For example, an apparatus may be implemented or a method may be practiced using any number of the aspects set forth herein. In addition, such an apparatus may be implemented or such a method may be practiced using other structure, functionality, or structure and functionality in addition to or other than one or more of the aspects set forth herein.

In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the invention. It should be understood, however, that the particular aspects shown and described herein are not intended to limit the invention to any particular form, but rather, the invention is to cover all modifications, equivalents, and alternatives falling within the scope of the invention as defined by the claims.

FIG. **1** is a block diagram of a communication network in accordance with an exemplary aspect of the disclosure. A plurality N of geographically distributed base transceiver stations **101.1-101**.N (BTS(1), BTS(2), . . . , BTS(N)) are communicatively coupled to a super-array processing system **111** via a communication network **105**. Each base transceiver station **101.1-101**.N comprises an antenna system configured for communicating with one or more mobile units (e.g., User Equipment) **120.1-120**.K via a WWAN radio access network (RAN).

In one aspect, the first base transceiver station **101.1** comprises a first antenna array comprising a first plurality M_1 of antennas **102.1-102**.M_1, the second base transceiver station **101.2** comprises a second antenna array comprising a second plurality M_2 of antennas **102.1-102**.M_1, and the Nth base transceiver station **101**.N comprises an M^h antenna array comprising an M^h plurality M_N of antennas **104.1-104**.M_N. The base transceiver stations **101.1-101**.N are configured to provide RAN services to a plurality K of mobile units **120.1**, **120.2**, . . . , **120**.K, each having its own antenna system **121.1**, **121.2**, . . . , **121**.K, respectively. Each antenna system **121.1**, **121.2**, . . . , **121**.K may comprise one or more antennas.

The communication network **105** may comprise a fiber network, a cable (i.e., wired) network, a wireless network (including a free-space optical network), or any combination thereof. In some aspects, the network **105** is referred to as a "fronthaul" network. In some aspects, the network **105** can comprise a backhaul network. In accordance with one aspect of the disclosure, a network that connects base transceiver stations to a processing system configured to perform joint processing (e.g., system **111**) can be referred to as a fron-

thaul, and a network (such as network **115**) which connects processing elements of the super-array processing system **111** can be referred to as a backhaul.

The terms "backhaul" and "fronthaul" can be used interchangeably in some aspects of the disclosure. A fronthaul is similar to a backhaul, which, at its simplest, links a radio access network to a wired (e.g., cable or optical fiber) network. A fronthaul can comprise a backhaul, or a portion of a backhaul. For example, a fronthaul can comprise a connection between one or more centralized controllers and remote stand-alone radio heads. A fronthaul can connect a central processor to multiple base transceiver stations. A fronthaul connects multiple base transceiver stations together when one or more of the base transceiver stations functions as a central processor. As used herein, a fronthaul may comprise a traditional backhaul network. For example, a fronthaul can comprise at least a portion of Si and/or X2 interfaces. A fronthaul may be part of a base station network. In Pat. Appl. Ser. No. 60/286,850, it is disclosed that a fronthaul can comprise optical fiber, wired, and/or radio networks. In one aspect of the disclosure, point-to-point fiber links provide high bandwidth and low latency. In another aspect, radio (e.g., microwave) links can provide high bandwidth and low latency, and can be substantially less expensive to implement than fiber. Furthermore, wireless links enable mobile radios and/or other radio transceivers (e.g., remote radio equipment) to be networked together via a radio fronthaul, such as disclosed in patent application Ser. No. 10/131,163. Accordingly, a fronthaul can comprise any combination of wireless, wired, and optical fiber links that communicatively couple together a group of radio transceivers configured to perform cooperative MIMO. Here, a group of radio transceivers is also referred to as a "micro-cell" and a "pico-cell" in the '163 application, and as a "local group" and a "micro-network" in patent application Ser. No. 11/187,107, all of the patents and patent applications mentioned in this disclosure being incorporated by reference in their entireties.

In one aspect of the disclosure, the super-array processing system **111** comprises a distributed computing system configured to coordinate a plurality of physical processors (which may be centrally located or geographically distributed) such as to perform joint processing. In some aspects, the plurality of physical processors can be represented as processors **111.1-111**.N. In other aspects, virtual processors (such as virtual base stations implemented as software-defined radios (SDRs)) can be represented as processors **111.1-111**.N.

By way of example, but without limitation, physical processors in a distributed computing environment can be represented as processors **111.1-111**.N. As used herein, the term "processor" can refer to a computer processor, a computer, a server, a central processing unit (CPU), a core, a microprocessor, and/or other terminology that indicates electronic circuitry configurable for carrying out instructions of a computer program. In some aspects, a processor comprises geographically distributed computing elements (e.g., memories, processing cores, switches, ports, and/or other computing or network resources). A fronthaul and/or backhaul network communicatively coupling the geographically distributed computing elements can function as a computer bus.

The processors are communicatively coupled together via at least one network, such as a backhaul network **115**. The backhaul network **115** can comprise an optical fiber network, a wireline network (e.g., Ethernet or other cable links), a wireless network, or any combination thereof. In some aspects, the backhaul network **115** can comprise the RAN. In one aspect, each of N processors is programmed to function as one of a plurality N of virtual base stations **111.1-111**.N. In another aspect, each virtual base station **111.1-111**.N comprises multiple processing cores. In some aspects, each virtual base station **111.1-111**.N represents a hardware abstraction wherein details of how the hardware is implemented are concealed within the representation of each "processor" **111.1-111**.N as a single element. In such aspects, the physical implementation of each processor **111.1-111**.N can comprise physical computing elements that are geographically distributed and/or physical computing elements that are shared by multiple virtual base stations **111.1-111**.N.

By way of example, each virtual base stations **111.1-111**.N may comprise one or more of the processors and perform base station processing operations that would ordinarily be performed by one or more corresponding base stations **101.1-101**.N. Specifically, virtual base stations can be implemented via software that programs general-purpose processors. For example, an SDR platform virtualizes baseband processing equipment, such as modulators, demodulators, multiplexers, demultiplexers, coders, decoders, etc., by replacing such electronic devices with one or more virtual devices, wherein computing tasks perform the functions of each electronic device. In computing, virtualization refers to the act of creating a virtual (rather than actual) version of something, including (but not limited to) a virtual computer hardware platform, operating system (OS), storage device, or computer network resources.

In accordance with the art of distributed computing, a virtual base station's functions can be implemented across multiple ones of the plurality of processors. For example, workloads may be distributed across multiple processor cores. In some aspects, functions for more than one base station are performed by one of the processors.

As used herein, distributed computing refers to the use of distributed systems to solve computational problems. In distributed computing, a problem is divided into multiple tasks, and the tasks are solved by multiple computers which communicate with each other via message passing. A computer program that runs in a distributed system is referred to as a distributed program. An algorithm that is processed by multiple constituent components of a distributed system is referred to as a distributed algorithm. In a distributed computing system, there are several autonomous computational entities, each of which has its own local memory.

In accordance with aspects of the disclosure, the computational entities (which are typically referred to as computers, processors, cores, CPUs, nodes, etc.) can be geographically distributed and communicate with each other via message passing. In some aspects, message passing is performed on a fronthaul and/or backhaul network. The distributed computing system can consist of different types of computers and network links, and the system (e.g., network topology, network latency, number of computers, etc.) may change during the execution of a distributed program. In one aspect, a distributed computing system is configured to solve a computational problem. In another aspect, a distributed computing system is configured to coordinate and schedule the use of shared communication resources between network devices.

A distributed computing system can comprise a grid computing system (e.g., a collection of computer resources from multiple locations configured to reach a common goal, which may be referred to as a super virtual computer). In some aspects, a distributed computing system comprises a

computer cluster which relies on centralized management that makes the nodes available as orchestrated shared servers. In some aspects, a distributed computing system comprises a peer-to-peer computing system wherein computing and/or networking comprises a distributed application architecture that partitions tasks and/or workloads between peers. Such distributed peer-to-peer computing systems are disclosed in the '107 application. In some aspects, peers are equally privileged, equipotent participants in the application. They are said to form a peer-to-peer network of nodes. Peers make a portion of their resources, such as processing power, disk storage, network bandwidth, etc., available to other network participants without the need for central coordination by servers or stable hosts. Peers can be either or both suppliers and consumers of resources.

In accordance with some aspects of the disclosure, the base transceiver stations **101.1-101**.N are "dumb terminals," wherein base station signal processing (for example, the baseband processing) is performed by the central processor **110** (which may include the distributed computing system **111**). Thus, in some aspects, the base transceiver stations **101.1-101**.N are simply radio remote units. For example, the base transceiver stations **101.1-101**.N might perform only basic signal-processing functions, such as RF processing (i.e., radio front-end processing), which can include frequency conversion and (optionally) ADC/DAC functions, while the central processor **110** (which may include the distributed computing system **111**) performs baseband processing, including channel analysis and generating base transceiver MIMO weights.

In one aspect, the central processor **110** coordinates or performs baseband signal processing corresponding to base station operations, whereas the base transceivers **101.1-101**.N provide only RF front end signal processing, including frequency conversion, and optionally, ADC/DAC. The central processor can perform waveform shaping, error detection, error correction, power control, channel selection, multiple access control, multiplexing, modulation, formatting, synchronization, coding, etc. for the plurality of base transceivers (i.e., access points) communicatively coupled to the central processor via the fronthaul network. In some aspects of the disclosure, the central processor **110** provides for base-station functionality, such as power control, code assignments, and synchronization. The central processor **110** may perform network load balancing (e.g., scheduling RAN resources), including providing for balancing transmission power, bandwidth, and/or processing requirements across the radio network. Centralizing the processing resources (i.e., pooling those resources) facilitates management of the system, and implementing the processing by employing multiple processors configured to work together (such as disclosed in the '163 application) enables a scalable system of multiple independent computing devices, wherein idle computing resources can be allocated and used more efficiently.

Some aspects allow base station processing resources (e.g., the processors in the distributed computing system **111**) and the remote RF units (e.g., the base transceiver stations **101.1-101**.N) to be deployed separately. For example, RAN coverage, capacity, and/or data bandwidth per UE can be improved by adding base transceiver stations, and then the SDR platform dynamically adapts to the new RAN base station configuration. Similarly, the SDR platform can adapt to the loss of one or more of the base transceiver stations **101.1-101**.N. The distributed computing system (e.g., cloud network) **111** can adapt to varying processing loads by allocating computing resources as needed. Furthermore, system upgrades, such as new transmission protocols, can be easily implemented via software upgrades to the SDR platform.

In some aspects, base-station functionality is controlled by individual base transceiver stations and/or UEs assigned to act as base stations. Array processing may be performed in a distributed sense wherein channel estimation, weight calculation, and optionally, other network processing functions (such as load balancing) are computed by a plurality of geographically separated processors. In some aspects, access points and/or subscriber units are configured to work together to perform computational processing. A central processor (such as central processor **110**) may optionally control data flow and processing assignments throughout the network.

As disclosed in the '850 application, the system depicted in FIG. **1** can provide system performance benefits by centralizing (e.g., pooling) much of the equipment (and/or signal processing) typically employed at the cell sites. Cost reduction is another motivation for centralizing the radio access network, as most of a cellular network's ownership costs comprise operating costs, including site rental, power, and support and maintenance expenses. Thus, instead of distributing baseband processing equipment at the edge of the network as in conventional cellular networks, centralizing the radio access network at the central processor **110** can greatly reduce capital expenditures to build out and upgrade the radio access network, as well as reduce operating expenditures.

As disclosed in the '163 application, providing for distributed computing at the central processor **110** provides network function virtualization to the RAN. Benefits that can be realized with some aspects of the disclosure include cost reduction from pooling and virtualizing baseband processing. This can eliminate the need to provision for peak capacity on a per-site basis, thus reducing processing requirements. Furthermore, instead of requiring dedicated base station hardware, some of the disclosed aspects provide for the use of commercial (e.g., general-purpose) servers running software.

As disclosed in the patents and applications incorporated by reference herein, other types of networks, including wireless networks, can connect the base transceiver stations **101.1-101**.N. One of the advantages of employing the optical fiber fronthaul **105** is that optical fiber can provide the high capacity and low latency required by many aspects of the invention. For example, when a large number of baseband processors are co-located at the central processor **110**, the amount of data bandwidth in the fronthaul and the synchronization requirements between base transceiver stations **101.1-101**.N can increase substantially when high RF bandwidth and MIMO are employed. Different aspects of the invention can provide for different functional splits between centralized and distributed functions.

Some aspects of the invention can reduce fronthaul requirements by implementing at least some of the Physical Layer processing at the base transceiver stations **101.1-101**.N while implementing other processing (e.g., higher layer processing, or the higher layer processing plus some of the Physical layer processing) at the central processor **110**. Thus, in some aspects of the invention, one or more of the base transceiver stations **101.1-101**.N depicted in the figures may be replaced by UEs adapted to perform as routers, repeaters, and/or elements of an antenna array.

In one aspect of the disclosure, the base station network comprising base transceiver stations **101.1-101**.N is adapted to operate as an antenna array for MIMO subspace process-

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ing in the RAN. In such aspects, a portion of the network may be adapted to serve each particular UE. The SDRs (represented as the virtual base stations **111.1-111**.N) can be configured to perform the RAN baseband processing. Based on the active UEs in the RAN and the standard(s) they use for their wireless links, the SDRs can instantiate virtual base station processes in software, each process configured to perform the baseband processing that supports the standard(s) of its associated UE(s) while utilizing a set of the base transceiver stations within range of the UE(s).

In accordance with one aspect of the disclosure, baseband waveforms comprising RAN channel measurements and/or estimates (such as collected by either or both the UEs and the base transceiver stations) are processed by the SDRs (such as in a Spatial Multiplexing/Demultiplexing module (not shown)) using Cooperative-MIMO subspace processing to produce pre-coded waveforms. A routing module (not shown) sends the pre-coded waveforms over the fronthaul **105** to multiple ones of the base transceiver stations **101.1-101**.N, and optionally, to specific antennas **102.1-102**.M_1, **103.1-103**.M_2, . . . , **104.1-104**.M_N. The base transceiver stations **101.1-101**.N can be coordinated to concurrently transmit the pre-coded waveforms such that the transmitted waveforms propagate through the environment and constructively interfere with each other at the exact location of each UE **120.1-120**.K.

In one aspect, the super-array processing system **111** configures complex-weighted transmissions **122**, **123**, and **124** from the geographically distributed base transceiver station **101.1**, **101.2**, and **101**.N, respectively to exploit the rich scattering environment in a manner that focuses low-power scattered transmissions to produce a concentrated high-power, highly localized signal (e.g., coherence zones **125.1**, **125.2**, . . . , **125**.K) at each UE's **120.1-120**.K antenna system **121.1**, **121.2**, . . . , **121**.K, respectively. The coherent combining of the transmitted waveforms at the location of each UE **120.1-120**.K can result in the synthesis of the baseband waveform that had been output by the SDR instance associated with that particular UE **120.1-120**.K. Thus, all of the UEs **120.1-120**.K receive their own respective waveforms within their own synthesized coherence zone concurrently and in the same spectrum.

In accordance with one aspect of the invention, each UE's corresponding synthesized coherence zone comprises a volume that is approximately a carrier wavelength or less in width and centered at or near each antenna on the UE. This can enable frequency reuse between nearby—even co-located—UEs. As disclosed in the '107 application, Spatial Multiplexing/Demultiplexing can be configured to perform maximum ratio processing. Any of various algorithms for MIMO processing disclosed in the '107 application may be employed by methods and apparatus aspects disclosed herein. Some aspects can comprise zero forcing, such as to produce one or more interference nulls, such as to reduce interference from transmissions at a UE that is not an intended recipient of the transmission. By way of example, but without limitation, zero forcing may be performed when there are a small number of actual transmitters (e.g., base transceiver station antennas) and/or effective transmitter sources (e.g., scatterers in the propagation environment).

While the aforementioned techniques of server-side Cooperative MIMO in a multi-user MIMO system provide substantial bandwidth efficiency, which is a significant advance in wireless communications, the amount of data bandwidth available to each UE is still hard-limited based on the total radio bandwidth allocated to the WWAN. However, client-side Cooperative MIMO can elegantly circumvent the data bandwidth limitation of the aforementioned multi-user MIMO system.

By way of example, some aspects of the disclosure configure the UEs **120.1-120**.K to form a cluster in which the individual UEs **120.1-120**.K are communicatively coupled together via a client device fronthaul network **102**, which can comprise any of various types of local area wireless networks, including (but not limited to) wireless personal area networks, wireless local area networks, short-range UWB networks, wireless optical networks, and/or other types of wireless networks. In some aspects, since the bandwidth of the client device fronthaul network **102** is typically much greater than that of the WWAN, a UE **120.1-120**.K can share its access to the RAN (i.e., its WWAN spatial subchannel, or coherence zone) with other UEs **120.1-120**.K in the cluster, thus enabling each UE **120.1-120**.K to enjoy up to a K-fold increase in instantaneous data bandwidth.

In some aspects, otherwise inactive UEs can share their WWAN access with active UEs in the cluster. Since the activity factor of an active UE is typically a small fraction, an active UE can share its unused WWAN spatial subchannel with other UEs in the cluster. In addition to access to higher data bandwidth, there can be other incentives for a UE to cooperate in a cluster, including (but not limited to) lower power consumption (such as due to client-side antenna array gain), improved coverage and reliability, as well as other benefits and incentives.

In some aspects, a cluster of UEs can perform cooperative subspace demultiplexing. In some aspects, the cluster can perform cooperative subspace multiplexing by coordinating weighted (i.e., pre-coded) transmissions to produce localized coherence zones at other clusters and/or at the base transceiver stations **101.1-101**.N. In some aspects, the UEs **120.1-120**.K comprise a distributed computing platform configured to perform distributed processing (and optionally, other cloud-based services). Distributed processing may be performed for Cooperative-MIMO, other various SDR functions, and/or any of various network control and management functions.

FIG. **2** is a block diagram of a communication network in accordance with another exemplary aspect of the disclosure. Similar features depicted in FIG. **1** have the same reference numerals. In FIG. **2**, the concept of a relay node is introduced. By way of example, a relay n **101**.*n* comprises and antenna system **109**.*n* and is communicatively coupled to at least one base transceiver station (such as BTS (1)) via a fronthaul network, which may be fronthaul **105** or a separate fronthaul **107**. Similarly, a relay k **120**.*k* is depicted as being communicatively coupled to a cluster of UEs **120.1-120**.K via fronthaul **102**. The relay k **120**.*k* may be coupled to other network nodes via other fronthauls (such as fronthaul **105**).

In one aspect, a relay is a dedicated relay node, such as may be configured specifically to operate as part of the WWAN infrastructure. In another aspect, a relay is an abstraction which denotes any of various devices that is configurable to operate as a relay node, as a member of a UE cluster, and/or as a member of server-side (e.g., BTS) antenna system (e.g., in a base transceiver antenna cluster). In some aspects, a relay can be a UE. In some aspects, a relay can be a base transceiver station. For example, relay n **101**.*n* may be a UE configurable to cooperate with base transceiver station **101.1**, such as to increase the rank of the antenna system's **102.1-102**.M_1 channel matrix. Relay k **120**.*k* can comprise a base transceiver station configurable to communicate with a UE cluster **120.1-120**.K via its fronthaul **102**,

and/or increase the rank of the cluster's channel matrix. In some aspects, a relay can simultaneously operate in multiple clusters. For example, a relay could operate in multiple UE clusters. In some aspects, a relay can operate as both a UE and a base transceiver station (or as a component of a base transceiver station's antenna system).

As disclosed in the patents and patent applications incorporated by reference herein, and particularly with respect to aspects of Cooperative-MIMO systems and methods, network nodes can function as either or both clients and servers. Furthermore, when wireless network nodes cooperate in subspace processing, they can create network resources, such as subspace (i.e., spatial multiplexing) channels, performance gains, RAN coverage area, etc. Even when UEs cooperate as a client array (e.g., a UE cluster) in a Cooperative-MIMO implementation, each UE can improve the data bandwidth, quality of service, range, and power efficiency of the other UEs in the array, or cluster. Thus, in some aspects of a Cooperative-MIMO system, UEs can extend the network infrastructure, such as to increase per-client data bandwidth, the number of clients served, coverage area, and/or quality of service without requiring substantial capital outlays from network operator to upgrade the base station network.

In Cooperative-MIMO systems, mobile UEs can opportunistically join together via a peer-to-peer overlay network (e.g., fronthaul **102**) for client-side MIMO processing. In some aspects, UEs can join base transceiver arrays via an overlay network (e.g., fronthaul **107**) to assist in server-side MIMO processing. Due to random movement of UEs, aspects of the disclosure do not impose a particular structure on the overlay network. Because there is no structure globally imposed upon them, unstructured networks are easy to build and allow for localized optimizations to different regions of the overlay. Also, in such aspects, because the role of all peers in the network is the same, unstructured networks can be highly robust in the face of high rates of churn (i.e., when peers are frequently joining and leaving the network).

FIG. **3** is a block diagram of a network topology, the type of which can be employed in accordance with aspects of the disclosure. In this network topology, a plurality of nodes (e.g., nodes **301**.**1**-**301**.N) are communicatively coupled together via communication links (such as depicted by networks **301**-**305**), which form a network fabric. The depiction of "nodes" is a generalization, as the nodes **301**.**1**-**301**.N can comprise server-side devices, client-side devices, relay devices (or other intermediate devices), and/or combinations thereof.

A network fabric can comprise a switched fabric, which is a network topology in which nodes **301**.**1**-**301**.N connect via one or more network switches. Switches in a switched fabric can form a mesh network. While switched fabrics are typically associated with fibre channel switched fabrics, which use fibre channel switches, aspects of the disclosure include network fabrics with wireless links between at least some of the nodes. These wireless links can be radio channels, infrared, and/or free-space optical channels.

A network topology describes the arrangement of nodes and links of a communication network, and can comprise either or both a physical topology and a logical topology. The physical topology conveys the location of each node and characteristics of the links, and can include distances between nodes, node interconnections, transmission rates, signal types, and other physical-layer attributes. The logical topology conveys the data flows within a network, which can be independent of the physical design.

In some aspects, at least some of the nodes **301**.**1**-**301**.N in the network fabric can comprise aerial platforms, such as unmanned aerial vehicles (UAVs). By way of example, mobile radio communication services (such as a radio access network (RAN)) can be provided by using a network fabric comprising UAVs configured for network fronthaul and/or backhaul operations. The use of such mobile aerial platforms can be advantageous when there is a need to quickly deploy a radio network and/or dynamically adapt to changing user-demand topologies.

With the use of broadband data links between nodes in an aerial network fabric, such as can be implemented via short-range wideband radio, infrared, and/or free-space optical links, data rates over the network fabric can be commensurate with computer bus speeds. Not only can the aerial network fabric serve as the fronthaul and/or backhaul to enable the RAN's data transport, the aerial network fabric can serve as a computing bus that connects computing elements (and other resources) residing on different network nodes to support other applications.

In one aspect, each node **301**.**1**-**301**.N manages its contribution of shared resources for performing at least one other application while performing its RAN data transport duties. The other application(s) could include remote sensing or other various environment-monitoring operations, transcoding or other various media-processing operations, network security operations, content delivery management, client-device services (e.g., cloud storage, cloud computing, software-as-a-service, navigation, etc.), and/or RAN-supporting applications (e.g., Cooperative-MIMO, error detection/correction, coding/decoding, etc.).

Each application can comprise a combination of a routing topology, a storage topology, and a computation topology. In one aspect, one or more of the networks **301**-**305** corresponds to a topology for a particular application. By way of example, a storage topology can comprise storage devices distributed across multiple network nodes, and the storage topology can comprise a routing topology that is specific to accessing the storage devices for cloud storage on the multiple network nodes. The routing topology for cloud storage is typically different than the routing topology for RAN data transport. Thus, each node may comprise separate routing cores dedicated to different routing topologies. Similarly, each node may comprise separate storage devices, such as one set dedicated to RAN data transport and another set dedicated to a cloud storage application.

By way of example, a computation topology can comprise computing elements distributed across multiple network nodes. In one aspect, such as depicted in FIG. **3**, a system of resources **311** (such as a network of nodes) can be abstracted as a single node in a given topology. In some aspects, virtual nodes **311**.**1**-**311**.N (where N represents the number of virtual nodes) are an abstraction that conceals a corresponding underlying physical architecture, which can comprise multiple hardware components communicatively coupled together. The hardware components of a virtual node **311**.**1**-**311**.N might change during an application, such as to scale to demand for various resources (e.g., computational processing, memory, routing, etc.). Similarly, the network topology **315** might change for any of various reasons. In some aspects, the network **315** is a hidden (or concealed) network, such as a Tor network. In one aspect, a gatekeeper node (such as node **311**.**9**) indicates the availability of certain services to the other nodes **301**.**1**-**301**.**8** or to specific applications while concealing from those nodes **301**.**1**-**301**.**8** or applications information as to how those services are acquired or arranged. In some aspects, certain services are

only available to nodes within a subnetwork and are concealed from nodes outside the subnetwork. In some aspects, the network **315** comprises a virtual network overlay to a physical network. In some aspects, a virtual node **311.1-311**.N (and/or network) may comprise nodes **301.1-301.8** (and/or components thereof), groups of nodes **301.1-301.8**, other network resources, and/or subnetworks **301-305** (or portions thereof).

The computation topology for one application, such as RAN data transport, can be different from the computation topology used for another application. Furthermore, the computation topology can comprise a storage topology and a routing topology that are different for each application. Thus, a distributed application can employ a topology comprising dedicated apparatus-level components on different nodes **301.1-301.9**, but operating together to support the application's requirements. Each instantiation of the distributed application can comprise a unique set of the apparatus-level components, and thus may employ a corresponding unique topology.

In accordance with certain aspects, a distributed computing problem can be partitioned by a combination of processes, including (but not limited to) data partitioning and computation partitioning. A first network topology can be provisioned to perform a first one of the processes and a second network topology can be provisioned to perform a second one of the processes. By way of example, the first network topology is configured to perform processing associated with data partitioning, and the second network topology is configured to perform processing associated with computation partitioning. Computation processing can be further partitioned into tasks which may be provided with their own network topologies. It should be appreciated that network topologies can be tiered. For example, a topology corresponding to a data partition may comprise multiple subnetwork topologies corresponding to computation partitions, and a computation partition may include further partitions implemented by corresponding subnetworks. It should also be appreciated that subnetwork topologies can overlap, and a device or network configured to operate in one network topology may be configured to perform (simultaneously, or in alternative time intervals) processing corresponding to another network topology. As network topologies can comprise overlapping and/or tiered topologies, in some aspects, solutions provided by a set of subnetwork topologies can be processed by a processors in an encompassing network topology, and processors in the subnetworks can be directed to a next problem in a queue and/or redirected to solve different problems. In some aspects, network topologies can be adapted, such as to adapt to corresponding processing needs. In some aspects, the topologies change as problems are completed and/or processing for new problems is commenced.

Due to the deployment of multiple UAVs to provide fronthaul and/or backhaul support for the RAN, a system for managing navigation is typically employed, which can include various combinations of centralized and decentralized air traffic control. One promising technique uses swarm intelligence.

Swarm intelligence refers generally to the collective behavior of multi-component systems that coordinate using decentralized controls and self-organization. From an engineering point of view, swarm intelligence emphasizes the bottom-up design of autonomous distributed systems that can provide adaptive, robust, and scalable behaviors. While conventional distributed air traffic control techniques provide only navigation management (e.g., collision avoidance, maintaining safe aircraft spacing, optimal routing, etc.), aspects of the invention introduce network fabric processing criteria into the navigation decision-making process. Thus, navigation may be adapted to desired network topologies for various applications. Such adaptations to a UAV's navigation decision-making may take the form of self-organizing control signals, control signals from a UAV acting as a cluster leader or local master, and/or from a ground-based processing system providing for coordinated multipoint control.

By way of example, in a MIMO wireless communication system, the arrangement of scatterers in the transmission channel affects the system's capacity (e.g., L. Hanlen, M. Fu, "MIMO Wireless Systems: Capacity Limits for Sparse Scattering," 3rd AusCTW, Canberra, Australia, February 2002, which is incorporated by reference in its entirety). Thus, UAV navigation can be configured to employ techniques to arrange active scattering platforms in a manner that enhances system capacity. In some aspects, it is recognized that UAVs can act as passive scatterers of RAN transmissions. In such aspects, UAV navigation can be adapted to produce any of various scattering structures, such as mirrors, lenses, and waveguides. These scattering structures can comprise active scattering structures, passive scattering structures, or combinations thereof.

In some aspects, swarm intelligence is configurable with respect to additional criteria, such as the aforementioned Cooperative-MIMO processing, network topology control, scattering management, and the like. For example, local navigation decision-making may be adapted to produce complex scattering structures. In some aspects, local navigation decision-making can be adapted to produce or shape a network topology. In such aspects, the local rule base employed for navigation by each UAV can be adapted such that complex structures and/or topologies can be achieved with minimal or no centralized control. In other aspects, at least a small amount of centralized control, whether from a ground-based controller or an airborne cluster master, may provide for at least some navigation control. Such centralized control and management can be configured with other control and management activities. By way of example, such centralized control may be configured with timing management operations, such as disclosed in the other patents and patent applications which are incorporated by reference. Thus, aspects of the disclosure include devices, methods, and cooperating systems of devices configured for performing aerial fabric acrobatics.

In accordance with aspects of the disclosure, precoding aspects (including devices, device components, systems of devices, methods, and instructions for configuring a processor(s)) are disclosed herein for use in a variety of network configurations, including cellular networks (such as LTE networks), WPANs, WLANs, ad-hoc peer-to-peer networks, and multi-hop networks, to advanced network configurations, such as any of the variety of Cooperative-MIMO networks and airborne networks disclosed herein. It should be appreciated that aspects disclosed herein, including the precoding aspects, can be configured for any type of wireless network mentioned in any of the references incorporated herein.

FIG. **4**A is a block diagram of a spread-OFDM transmitter in accordance with an aspect of the disclosure. A baseband data processor **401** generates original data symbols from user data, reference signals, or some combination thereof. A spreader **402** spreads the original data symbols into spread data symbols. A mapper **403** maps the spread data symbols to OFDM subcarriers, such as to input bins of an over-

sampled inverse discrete Fourier transform (IDFT) **404**, which is typically implemented as an oversampled fast transform (e.g., an FFT). The spread-OFDM signal output from the IDFT **404** is prepended with a cyclic prefix (in "+CP" circuit **405**) before amplification and up-conversion to RF in an RF front end **406**. Inter-symbol interference can be avoided if the cyclic prefix (or a guard interval) is longer than the delay spread of the impulse response of the channel.

In spread-OFDM, N subcarriers can be shared by every original data symbol in a block of up to N original data symbols if the spreading codes are configured to be orthogonal. The spreader **402** enables the N subcarriers to be shared by a block of up to N original data symbols. In one aspect, the function of the spreader **402** can be explained as follows: Each original data symbol of the block is replicated into N parallel copies. Each copy is then multiplied by a code chip from a corresponding spreading signature. A spreading signature can comprise a row or column of a spreading matrix, and may be referred to as a spreading code or a code space. The products are summed such that each sum (referred to as a spread data symbol) comprises one of N linear combinations of the original data symbols, wherein the coefficients are the code chips (e.g., a row or column of a corresponding spreading matrix), and the unknowns are the original data symbols. Each spread data symbol is modulated onto one of the N subcarriers, all of which are to be transmitted in parallel. The usual implementation of OFDM calls for the IDFT **404** to convert the parallel chips into serial form for transmission. In OFDM, the IDFT **404** is typically implemented via oversampling, so the input symbol block to the IDFT **404** is typically zero-padded, since zero padding in one domain (e.g., time or frequency) results in an increased sampling rate in the other domain (e.g., frequency or time). The cyclic prefix is appended to remove the interference between successive symbols and to accommodate the circulant convolution provided by the FFT.

In a receiver configured to receive spread-OFDM signals (such as the receiver block diagram depicted in FIG. **5**A), a received spread-OFDM transmission is filtered, converted to baseband, and digitized by an RF front end **501**, and then the cyclic prefix is removed (such as by a cyclic prefix removal circuit **502** or some equivalent). The receiver can comprise N matched filters, which can be implemented in the discrete baseband domain, such as by performing a DFT **503**. The output of the DFT **503** has the form of the transmitted signal multiplied by a diagonal channel matrix whose diagonal values are flat-fading coefficients, which allows for simple equalization **504**. The IDFT **404** and DFT **503** operations and the role of the cyclic prefix are implicitly absorbed through the diagonal structure of the channel response. Thus, aspects of the disclosure can provide for configuring the spreader **402** to provide various benefits, including (but not limited to) orthogonal codes, use of a fast-transform algorithm, and low PAPR.

In accordance with some aspects of the disclosure, a processor-based transceiver can include a non-transitory computer-readable memory with instructions stored thereon and configured to perform any of the algorithms disclosed herein. In reference to the spreader **402**, by way of example, each original data symbol in a block can be multiplied by a complex-valued spreading code, such as via a matrix multiplication operation. For example, a jth original data symbol d_j is multiplied by a jth column vector of an N×N spreading matrix S, where the jth column vector corresponds to the spreading code for symbol d_j, and N(which equals the number of subcarriers onto which the spread data is modulated) corresponds to the bandwidth expansion factor (e.g., spreading gain) to produce a jth spread data-symbol vector. The N different spread data vectors are summed to produce a vector of spread data symbols (of length N) before serial-to-parallel conversion and processing by the IDFT. It should be appreciated that if fewer than N original data symbols (e.g., n<N) are in a block, then N−n of the symbols in the block may be set to zero while still producing a length-N vector of spread data symbols.

FIG. **4**B is a block diagram of a spread-OFDM spreader (such as spreader **402**) in accordance with some aspects of the disclosure. An OFDM schedule processor **431** receives scheduling information which assigns a set of OFDM subcarriers to the corresponding transmitter. For example, if the transmitter is a UE, then the OFDM network assigns specific resource blocks (which includes a set of OFDM subcarriers) to be used by the UE for uplink transmissions. The OFDM schedule processor **431** obtains subcarrier parameters (e.g., number of subcarriers N, subcarrier spacing, and the like) which are conveyed to a spreading code generator **432**.

The spreading code generator **432** can be configured to process the subcarrier parameters and one or more criteria elements to select spreading codes. For example, the criteria can include code space orthogonality (i.e., orthogonal spreading codes), low PAPR, and enabling a fast transform operation for code generation and/or for encoding original data symbols. Other criteria may be employed. For example, a criterion which relates to pulse shaping (e.g., time-domain and/or frequency-domain shaping, or windowing) can further reduce PAPR by sacrificing some bandwidth efficiency. In one aspect, a mask (e.g., a spectral mask) may be applied to the subcarriers, such as by way of the coding or directly following the coding, in order to shape the spread-OFDM signal. This can achieve pulse shaping without directly processing the output of the IDFT **404**.

In one aspect, spreading is achieved via a fast transform operation (such as an FFT spreader **433**). The FFT spreader's **433** input parameters can be controlled by the spreading code generator in accordance with the criteria elements. In one aspect, FFT spreader **433** parameters, such as FFT size, input data block size, input data values, can be controlled by the spreading code generator **432**. In some aspects, the spreading code generator **432** can select how a fast transform is performed, such as by directly controlling the transform's operations or by indirectly controlling the transform via FFT size, and the like.

In one aspect, a user data processor **435** provides user data symbols to the spreader **433** for spreading. In another aspect, a reference signal data processor **437** provides reference signal data symbols to the spreader **433** for spreading. In some aspects, the user data processor **435** and the reference signal data processor **437** are configured to multiplex user data and reference signal data to produce the original data symbols, which are then spread by the spreader **433** to produce the spread data symbols.

Orthogonal Spreading

In accordance with an aspect of the disclosure, in a client device (such as a UE) configured to operate in an OFDM network, the spreading-code generator **432** is responsive to OFDM scheduling that assigns a particular set of uplink subcarriers to the client device, such as based on favorable channel conditions between the client device and one or more base transceiver stations. For example, channel-dependent scheduling of the uplink subcarriers to the client device can be made to avoid interference, such as deep fades experienced by one or more subcarrier frequencies in a flat-fading environment, and/or interference caused by other transmitters. Responsive to the number of assigned uplink

subcarriers, the spreading-code generator **432** selects a set of orthogonal complex spreading codes. Orthogonal functions (that is, signals or sequences) have zero cross-correlation. Zero correlation occurs if the product of two signals summed over a period of time (or sequence length) is zero. A set of signals or sequences in which all have zero cross-correlation with each other constitutes an orthogonal code space(s).

In one aspect, responsive to an assignment of N OFDM subcarriers, the spreading-code generator **432** selects an orthogonal N×N complex spreading matrix that comprises DFT coefficients. Some matrices comprising DFT coefficients are not orthogonal. While it is well known that some orthogonal functions can be generated or expanded using various algorithms, such as a seed algorithm or some other recursive technique, some of these algorithms do not provide codes with desirable features, such as orthogonality and low PAPR. For example, an N×N spreading matrix constructed by concatenating rows or columns of an N/2×N/2 DFT spreading matrix can yield fewer than N orthogonal spreading codes. Similar deficiencies result from concatenations and other combinations of different-size DFT matrices, permutations of DFT matrices, punctured DFT matrices, truncated DFT matrices, and the like. Thus, in some aspects, the spreading-code generator **432** advantageously provisions an N×N spreading matrix (or corresponding set of complex codes) to provide for N orthogonal spreading codes. This can be referred to as an orthogonal code space with dimension N.

In some aspects of the disclosure, the spreading-code generator **432** can orthogonally spread a block of up to N original data symbols with DFT-based complex spreading codes to produce a length-N vector of spread data symbols. In other aspects, the spreading-code generator **432** can employ complex spreading codes to spread N'>N original data symbols onto N subcarriers. While these complex spreading codes are not all orthogonal, the codes can be configured to have low cross correlation. Various techniques may be employed to select a code set having optimal features, such as low cross correlation, low PAPR, or a combination thereof. In some aspects, at least some of the spreading codes can be orthogonal to each other.

Low PAPR

In addition to providing for orthogonal spreading, the spreading code generator **432** can be responsive to OFDM scheduling to configure the complex spreading matrix to provide the spread-OFDM signal with a low PAPR. Unlike other PAPR-reduction techniques (such as clipping, peak cancellation, and others) which employ the IDFT **404** output (i.e., the spread-OFDM signal), the spreader **402** employs complex orthogonal spreading codes to spread original data symbols (which provides frequency diversity gain) while shaping the spread-OFDM signal to provide low PAPR.

Parameters of the assigned subcarriers, such as subcarrier frequency spacing and the number of subcarriers, can be used to determine complex orthogonal spreading codes that also produce a low-PAPR signal at the IDFT output. By way of example, the spreading-code generator can generate an orthogonal N×N spreading matrix wherein Nis the number of subcarriers assigned to the transceiver, and the complex values of the spreading matrix can be generated based on the configuration of the assigned subcarriers, such as frequency spacing.

In one aspect, responsive to an assignment of a block of contiguous subcarrier frequencies, the spreading-code generator **432** can generate a complex spreading matrix with constant-modulus (e.g., constant magnitude) polyphase values derived from a DFT. In another aspect, if the subcarrier assignment comprises non-contiguous subcarriers with different frequency spacings, the complex spreading matrix that provides for low PAPR might comprise values with different magnitudes. Even in such aspects, the spreading-code generator **432** can generate a complex spreading matrix which achieves desired features corresponding to the criteria list, including low PAPR.

Fast Transforms

In accordance with some aspects of the disclosure, in a client device (such as a UE) configured to operate in an OFDM network, the spreading-code generator **432** is responsive to OFDM uplink scheduling to employ a complex spreading matrix that can be implemented via a fast transform algorithm. For example, based on a number of assigned OFDM subcarriers, an N×N complex spreading matrix can be selected in which the matrix-generation algorithm exploits the factorization of N. In some aspects, the number of assigned OFDM subcarriers equals N. In other aspects, a spreading matrix with dimension less than the number of assigned OFDM subcarriers might be selected, such as to facilitate spreading with a small sacrifice in data bandwidth, enable further PAPR reduction, or provide for other benefits. In some aspects, the scheduling is configured by the OFDM network such as to provide a number of assigned subcarriers that facilitates use of a fast transform algorithm by the spreading-code generator **432**.

The implementation of the DFT spreading as a fast algorithm (e.g., an FFT) can provide an efficient alternative to conventional Carrier Interferometry (CI) coding. In some aspects, an OFDM transceiver can employ the same FFT processor (e.g., such as FFT spreading module **433**, which can be an application-specific processor, a general purpose processor programmed to perform an FFT, or some other hardware configured to perform an FFT) and/or reuse a software program configured to perform spreading to perform other transceiver functions, such as OFDM modulation (e.g., IDFT **404**) and/or demodulation (e.g., DFT **503**). In such aspects, a common FFT hardware (e.g., module **433**, **404**, **503**, or **505**) or software module (e.g., program, object, function, or some other program construct) can be configured to adjust FFT processing parameters, such as relative to whether the FFT is being used for spread-OFDM coding, spread-OFDM decoding, OFDM modulation, or OFDM demodulation. FFT processing parameters can include one or more of oversampling factor, sampling rate, FFT length, zero-padding, truncating, modulo-length data wrapping, Radix-2 implementation, FFTW implementation, decimation in time, decimation in frequency, output ordering, input data format, rounding mode, saturate on integer overflow, sine table data type, product output data type, accumulator data type, output data type, output minimum, output maximum, and lock data type. Other FFT processing parameters can be employed.

A fast DFT algorithm, such as the Cooley-Tukey algorithm, can express a DFT of size $N=N_1N_2$ in terms of smaller DFTs of size N_1 and N_2 recursively to reduce the computation complexity to order of N log N for highly composite N (e.g., smooth numbers). The 2-smooth numbers are powers of 2 (i.e., a number of the form 2^n where n is an integer). Radix-2 implementation can comprise various algorithms, including (but not limited to) butterfly operation, double-signal algorithm, half-length algorithm, decimation-in-time algorithm, and decimation-in-frequency algorithm.

Since the Cooley-Tukey algorithm breaks the DFT into smaller DFTs, it can be combined with other DFT algorithms. For example, Rader's algorithm, Bluestein's algo-

rithm, Bruun's algorithm, or other FFT algorithms can be used to handle large prime factors that cannot be decomposed by Cooley-Tukey, or the prime-factor algorithm can be exploited for greater efficiency in separating out relatively prime factors.

In many OFDM systems, the number N of subcarriers assigned to a transceiver is commonly a power of 2, which enables efficient OFDM modulation and demodulation. Thus, a radix-2 FFT of size N for DFT coding can also provides notable computational advantages. A processor for an OFDM transmitter configured to perform an IFFT, for example, can be easily configured to perform fast DFT spreading. Accordingly, some aspects of the disclosure employ a radix-2 DFT matrix to spread data symbols. This enables computationally efficient spreading, and like CI spreading, when the spread-DFT data is input to selected bins of an IFFT used in an OFDM transmitter, the resulting spread-DFT OFDM signal can have a low PAPR.

In accordance with some aspects of the invention, in an OFDM transmitter apparatus, a radix-2 DFT spreader (e.g., spreader **402**) and the subcarrier mapper **403** are configured in a manner such that the combination of DFT spreading and subcarrier allocation produces a transmitted OFDM signal with low PAPR. By way of example, the size N can equal the number of subcarriers allocated to the OFDM transmitter apparatus, and wherein the allocated subcarriers are uniformly spaced in frequency. The allocated subcarriers can comprise a block of contiguous subcarriers, such as may be assigned to the OFDM transmitter apparatus based on favorable channel conditions between the OFDM transmitter apparatus (e.g., a UE) and at least one server-side WWAN terminal (e.g., a base transceiver station). A determination of favorable channel conditions may be made by either or both the OFDM transmitter apparatus and the at least one server-side WWAN terminal (including a scheduler communicatively coupled to multiple WWAN terminals) and may be based on measurements and/or estimates of the channel at either or both the OFDM transmitter apparatus and the at least one re server-side WWAN terminal.

A processor for an OFDM receiver configured to perform an FFT, for example, might be configurable to perform the DFT spreading. In some aspects, the receiver processor does not normally operate while its associated transceiver device is in transmit mode, so the receiver's FFT is available to support transmit processing, such as to provide for the DFT spreading. In some aspects, the transmitter may employ the same processor to perform both DFT spreading and the IFFT. Such implementations can provide various benefits (e.g., reduce complexity, improve efficiency, reduce cost, reduce power consumption, etc.) by employing the same hardware to perform both spreading and OFDM modulation. With regard to software, such implementations disclosed herein can enable code reuse. In some aspects, pipelined FFT processing can be provided. By way of example, pipelined processing can be configured to provide multiple simultaneous FFT operations, such as DFT-spreading and subcarrier modulation (e.g., via IFFT). In some aspects, pipelined processing can be performed as part of cooperative processing between multiple processing cores (such as in a data center), or residing on different WWAN terminals (e.g., UEs and/or base transceiver stations) in a cooperating cluster.

In accordance with other aspects of the disclosure, an FFT processor configured for at least one transmitter operation can be configured for a receiver operation. In some aspects, a single FFT processor can be employed to enable multiple operations, including any combination of OFDM modulation, OFDM demodulation, DFT spreading, and DFT de-spreading.

In accordance with some aspects of the disclosure, the block diagram shown in FIG. **4**A comprises the transmitter part of a UE configured to transmit an uplink spread-OFDM signal with low PAPR, and the block diagram in FIG. **5**A comprises the receiver part of a server-side WWAN device (or system) configured to receive the UE's uplink spread-OFDM signal. In the server-side WWAN device (or system), an RF front-end system **501** filters, amplifies, down-converts, and digitizes the received spread-OFDM signal to produce a received baseband signal. The cyclic prefix is stripped (in "-CP" circuit **502**) and the OFDM signal is demodulated by the DFT **503**. Equalization and demapping **504** (which can include soft and/or hard decision processing) produces received spread-OFDM symbols. The de-spreader **505** can comprise an IFFT to efficiently de-spread DFT-spread symbols to produce estimates of the original data symbols. The baseband processor **506** performs additional down-stream baseband processing on the estimates, such as error detection, error correction, transcoding, formatting, and/or other post-processing operations.

FIG. **5**B is a block diagram that depicts a portion of a receiver, such as a receiver that may be employed in a server-side WWAN terminal or system. In one aspect, the de-spreader **505** comprises the system shown in FIG. **5**B. A de-spreading code generator **552** processes subcarrier parameters corresponding to the received spread-OFDM signal to control decoder **553**. Since the server side of the WWAN can schedule the uplink OFDM subcarriers used by each UE, the subcarrier parameters can be retrieved from a UE scheduler **551**.

In some aspects, the UE scheduler **551** assigns uplink subcarriers to a UE based on favorable channel conditions for that UE (which is referred to as channel-dependent scheduling). In addition to favorable channel conditions, a criteria list employed by the UE scheduler for assigning uplink subcarriers might include providing for orthogonal spreading codes, enabling spreading codes that produce a transmitted spread-OFDM signal with low PAPR, and/or enabling a fast transform to be used for spreading and de-spreading. While channel-dependent scheduling might identify a particular group of candidate subcarriers to be assigned to a UE uplink channel, the other criteria can specify the number N of subcarriers, the subcarrier spacing, as well as other signal parameters assigned by the scheduler **551**. For example, selecting N to be a power of 2 can enable certain fast transforms to be used in spreading and/or de-spreading. Selecting contiguous subcarriers or uniformly spaced subcarriers can facilitate (and possibly ensure) the UE's implementation of orthogonal spreading codes that provide low PAPR features.

In one aspect, a de-mapped data processor **555** can provide spread data symbols comprising spread user data symbols, spread reference signals, or both to the decoder **553**. The decoder **553** can employ a fast transform, such as an IFFT, to de-spread the spread data symbols and produce de-spread data symbols which are output for further processing. The de-mapped data processor **555** may be part of the equalizer and de-mapper **504** or it may be part of the de-spreader **505**.

DFT-Spreading Method:

In accordance with one aspect of the disclosure, as depicted in FIG. **6**A, a method performed in a radio transceiver is provided, which can employ a fast algorithm to generate a spread data sequence from an original data

sequence. The algorithm which generates the spread data sequence is configured to provide a low PAPR to an OFDM signal modulated with the spread data sequence. Specifically, the spreading causes the transmitted OFDM signal (such as a signal output from IDFT **404**) to have a low PAPR compared to an un-spread OFDM signal (such as the resulting transmitted OFDM signal if spreading is not performed).

In some aspects, the method depicted in FIG. **6**A comprises functional steps implemented via software instructions operable to cause a processor (such as a general-purpose processor) to execute the steps in a process which produces a spread-OFDM signal. In some aspects, one or more of the functional steps are embodied in hardware, such as circuits.

By way of example, application-specific integrated circuits (ASICs), field-programmable gate arrays (FPGAs), and/or other circuits can be provided as embodying one or more of the functional steps disclosed throughout the specification and depicted in the drawings. In some aspects, multiple ones of the functional steps can be implemented by a common processor or circuit. For example, certain efficiencies might be achieved by configuring multiple functional steps to employ a common algorithm (such as an FFT and/or some other algorithm), thereby enabling a circuit, a processor, or some other hardware component to be used for different functions, and/or enabling software instructions to be shared for the different functions.

The radio transceiver, such as a UE, receives an OFDM channel assignment **601** from a scheduler in the WWAN. For example, OFDM channels in the WWAN might be assigned via channel-dependent scheduling. The OFDM channel assignment is processed to acquire OFDM subcarrier parameters pertinent to operation of the transceiver **602**. Based on the subcarrier parameters, orthogonal spreading codes are configured in a manner to cause a corresponding spread-OFDM signal to have low PAPR **603**. For example, the spread-OFDM signal is configured to have a lower PAPR than if spreading was not performed. Configuring the spreading codes in accordance with step **603** can comprise a combination of a) determining a spreading code length(s) based on the number of subcarriers assigned to the transceiver; b) determining spreading code values based on the spreading code length(s) and the configuration of subcarriers (e.g., subcarrier spacing) assigned to the transceiver; and c) arranging the spread data symbols (which can include re-ordering the output of a spreading function) in a particular order or arrangement such that each spread data symbol maps to a particular one of the assigned subcarriers to achieve at least one objective, such as to provide the spread-OFDM signal with a low PAPR.

In aspects of the disclosure, one or more spreading code parameters (such as code length) can optionally be configured to enable use of a fast spreading algorithm, such as an FFT, to perform spreading **604**. In other aspects, the spreading codes may be retrieved from a memory and employed in a matrix multiply or equivalent operation. For example, spreading codes might be generated for different subcarrier parameters (e.g., number of subcarriers, subcarrier spacing, and the like), possibly using a fast spreading algorithm, and stored in the memory. Then spreading codes corresponding to particular subcarrier parameter(s) can be retrieved from the memory to be used in spreading **604**.

Code parameters, such as code length and the code values, can be selected to allow a fast algorithm (such as the FFT) to be used for spreading-code generation and/or to spread original data symbols, such as via a fast transform. This can include selecting a block size of input original data symbols (and corresponding spreading matrix dimension) to facilitate use of a fast transform and/or achieve other processing efficiencies. In some aspects, zero values can be added to the block of original data symbols to provide a predetermined block size.

By way of example, but without limitation, a spreading code matrix can comprise complex spreading codes selected from a larger set of spreading codes, such as CI codes, which are complex spreading codes that exist for any code length. For example, restricting the code length (or matrix dimension) N to a length that is a power of 2 enables a specific set of spreading code values that permit a fast transform algorithm (such as a radix-2 decimation-in-time (DIT) FFT) to be employed as the spreading algorithm **604**. In other aspects, N can be selected to equal a product of small prime numbers which can include numbers other than 2.

Selecting the code length and the code values (such as specific code values corresponding to particular OFDM subcarriers assigned to the radio transceiver) can provide for configuring the spreading code **603** to produce a spread-OFDM signal (at the output of step **606**) with low PAPR. For example, in one aspect, an OFDM network might employ non-contiguous blocks of subcarriers (such as for opportunistic transmissions, cognitive radio applications, channel optimization, and/or for other purposes). Thus, the code values (and optionally, the code length) can be selected **603** to provide a low PAPR to the resulting transmitted OFDM signal. The code values and code length can also be selected to affect the orthogonality of the codes as part of step **603**, such as to provide orthogonal codes, sacrifice orthogonality for lower PAPR, sacrifice bandwidth efficiency for lower PAPR, or some combination thereof.

The spread data symbols are mapped to particular OFDM subcarriers **605**. In some aspects, mapping **605** comprises sequence reordering to map specific spread symbols to specific subcarriers, which can achieve certain advantages. For example, a preferred mapping of the spread data symbols to the OFDM subcarriers achieves the low PAPR, whereas an alternative mapping may not. Even when contiguous subcarriers and spread-DFT or CI codes are employed, the selection of the spreading codes **603** and the mapping **605** affects the PAPR. A proper mapping **605** of the spread data symbols to specific subcarriers achieves the low PAPR.

In one aspect, besides the trivial case of all ones, a spread-DFT code (which is a constant-modulus complex code) can be regarded as comprising a uniform phase increment in the complex plane from one code value to each successive value in the DFT code vector. In the trivial case, the phase increment is zero. Each spread data symbol comprises a sum of the products of each original data symbol with a code value from the original data symbol's corresponding spread-DFT code. This spreading can be implemented via a matrix multiply, such as between a spreading code matrix and a vector of original data symbols. The spreading can be implemented via a DFT, such as an FFT. However, the spread data symbols are markedly different from the frequency responses derived from a spectrum analyzer, which also uses a DFT.

Each spread data symbol comprises a linear combination of the original data symbols, wherein each coefficient in the linear combination comprises the code value corresponding to the original data symbol's code and a common location in the code vector of that code. Stated another way, consider an n* original data symbol d_n spread by a corresponding n^{th}

DFT spreading vector $c_n=[C_{n1}, C_{n2}, \ldots, C_{nm}, \ldots, c_{nN}]$. An mth spread data symbol in a spread data symbol vector x is the sum,

$$x_m = \sum_{n=1}^{N} c_{nm} s_n,$$

which indicates that the mth spread data symbol is the sum of each data symbol s_n multiplied by the mth code value in its corresponding code vector c_n. The mth code value c_{nm} represents the mth uniform phase increment in the complex plane for that code c_n. Thus, the mth spread data symbol can be associated with an mth set of uniform phase increments. Spreading yields N spread data symbols, whereas spectrum analysis (which uses a DFT) produces frequency responses corresponding to N/2 (orthogonal) tones due to the Nyquist limit.

In one aspect, the mapping **605** comprises arranging the spread data symbols in accordance with increasing uniform phase increments, and matching the spread data symbols according to this arrangement to a set of OFDM subcarriers having increasing uniform frequency increments. The mapping **605** of the spread data symbols having increasing uniform phase increments to the OFDM subcarriers with corresponding increasing frequency increments provides for producing a spread-OFDM signal with low PAPR. In serial implementations, arranging the spread data symbols can take the form of sequencing the symbols in ascending or descending order relative to their corresponding phase increments. In parallel implementations, arranging the spread data symbols can take the form of arranging the symbols relative to input bins of an IFFT for corresponding increasing OFDM subcarrier frequencies. Thus, in some aspects, the mapping **605** can comprise sequence reordering of a DFT output.

In some aspects, the mapping **605** order of symbols to IFFT bins may be fixed. Thus, configuring the spreading codes **603** and/or spreading **604** may be provisioned to configure the mapping **605** which ensures a low-PAPR spread-OFDM signal. For example, configuring the spreading codes **603** can comprise arranging the order of values in a spreading code matrix to produce a vector of spread symbol values arranged in a manner that the fixed mapping **605** results in a spread-OFDM signal with low PAPR, the order relating to a mathematical relationship with the subcarrier frequencies that achieves the low PAPR regardless of the arrangement of the original data symbols. In another aspect, the spreading **604** is configured to arrange the spread data symbols in a manner that the mapping **605** results in a spread-OFDM signal with low PAPR regardless of the order of the original data symbols.

In accordance with some aspects of the disclosure, such as in relationship to methods, software instructions, and devices which perform step **603**, the code length N can correspond to a number of OFDM subcarriers allocated to the radio transceiver. For example, the code length N might equal the number of OFDM subcarriers, which is commonly a power of 2. In some aspects, the code length N might be less than the number of assigned OFDM subcarriers. In other aspects, the code length N might be greater than the number of OFDM subcarriers, such as a multiple thereof. In some aspects, the code length N might equal the number of OFDM subcarriers assigned as user-data channels for the radio transceiver. In some aspects, the code length N might equal the number of OFDM subcarriers assigned as reference signals for the radio transceiver. In some aspects, unlike in conventional spread-OFDM, transmitted reference signals are spread. In some aspects, the reference data can be spread with the user data.

In one aspect, an N×N spreading code matrix is selected wherein Nis a power of 2 and the code matrix values are selected from the set of basic CI code values to permit use of a radix-2 FFT for spreading a set of original data symbols. The CI coding may be provided via a DFT in order to provide for DFT spreading, which can be implemented by a fast transform, such as an FFT. The input to the radix-2 FFT can comprise a block of up to N original data symbols, and the fast spreading algorithm generates N spread data symbols.

At least one of an original data sequence length and a spread data sequence length is selected to enable use of a fast DFT transform. By way of example, the original data sequence length can equal the spread data sequence length, and this length can be selected to be a power of 2, which permits a radix-2 decimation-in-time (DIT) FFT to spread the original data sequence.

It should be appreciated that in alternative aspects, the spreading code matrix need not be a square matrix. In some aspects, the spreading codes can comprise alternative complex-valued code families, and the code values and code length can be selected to permit use of a fast spreading algorithm to spread the original data symbols and provide a resulting transmitted spread-OFDM signal with low PAPR.

Various types of fast spreading algorithms can be employed to spread the original data symbols to produce spread data symbols. In some aspects, the fast spreading algorithm comprises a DFT spreading operation.

The DFT spreading operation is defined by

$$x_k = \sum_{n=0}^{N-1} s_n e^{-i2\pi nk/N}$$

Where x_k represents the kth spread data symbol, s_n are the original data symbols, and N is the length. In this example, both the index k and the index n range from 0 to N−1.

The Radix-2 DIT FFT computes the DFTs of the even indexed inputs ($s_{2m}=s_0, s_2, \ldots, S_{N-2}$) and the odd indexed inputs ($s_{2m+1}=s_1, S_3, \ldots, S_{N-1}$), and then combines the results to produce the DFT-spread data sequence. For example, the Radix-2 DIT algorithm expresses the DFT-spreading of original data symbols sa as a sum of spread even-numbered indices (n=2m) and spread odd-numbered indices (n=2m+1):

$$x_k = \sum_{m=0}^{N/2-1} s_{2m} e^{-i2\pi(2m)k/N} + \sum_{m=0}^{N/2-1} s_{2m+1} e^{-i2\pi(2m+1)k/N}$$

The common multiplier $e^{-i2\pi k/N}$ can be factored out of the second sum, so the spread data symbols can be represented as:

$$x_k = x_{even(k)} + e^{-2\pi k/N} x_{odd(k)}$$

Where $x_{even(k)}$ is the even-indexed part, and $x_{odd(k)}$ is the odd-indexed part of x_k.

Due to the periodicity of the DFT, $x_{even(k+N/2)}=x_{even(k)}$ and $x_{odd(k+N/2)}=x_{odd(k)}$. Thus,

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$$x_k = \begin{cases} x_{even(k)} + e^{-i2\pi k/N} x_{odd(k)} & \text{for } 0 \le k < N/2 \\ x_{even(k-N/2)} + e^{-i2\pi k/N} x_{odd(k-N/2)} & \text{for } N/2 \le k < N \end{cases}$$

Since the "twiddle" factor

$$e^{-i2\pi\left(k+\frac{N}{2}\right)/N} = -e^{-i2\pi k/N},$$

this educes the number of these calculations by half. The spread sequence of length-N can be expressed recursively in terms of two spreading operations of size N/2 (0≤k<N/2)

$$x_k = x_{even(k)} + e^{-2\pi k/N} x_{odd(k)}$$

$$x_k = x_{even(k)} - e^{-2\pi k/N} x_{odd(k)}$$

This decimation operation can be performed down to the 2×2 DFT. The final outputs are obtained by a +/−combination of $x_{even(k)}$ and $e^{-i2\pi k/N}x_{odd(k)}$, which is simply a size-2 DFT.

It should be appreciated that other fast algorithms may be employed, including algorithms that exploit symmetry, remove redundant parts of a computation, and/or achieve other efficiencies, as well as other divide-and-conquer algorithms.

It should be appreciated that in practice, the actual performance of a fast algorithm depends on additional factors which affect computation speed, memory use, power consumption, and various processing overheads, such as communications between processors. In some aspects, in-place algorithms, bit reversal, data reordering, non-blocking pipelined configurations, and the like can be implemented in the fast algorithm. As such, operations of the fast algorithm can be configured to employ the required mapping that achieves the lowest possible PAPR for a given code set.

In some cases, performance metrics depend on the computing architecture employed. Thus, in accordance with some aspects of the disclosure, in addition to configuring the fast spreading algorithm **503** to improve performance on a given computing architecture, configuring the spreading code parameters to enable use of a fast spreading algorithm **501** can include selecting and/or adapting the spreading code parameters in a manner that improves the performance of the fast spreading algorithm.

In OFDM, active subcarriers are typically assigned with data symbols. For unassigned subcarriers, OFDM provides for zero-valued inputs for the IFFT (transmitter) and zero-valued outputs for the FFT (receiver). Often, conventional FFT/IFFT algorithms are not efficient due to the unwanted operations on zero values. Therefore, in some aspects of the disclosure, efficient FFT/IFFT algorithms can be employed to dynamically eliminate the multiplication and addition operations associated with deactivated subcarriers. For example, FFT pruning methods eliminate operations on input and output values which are not required. The basic concept involves determining the index of the butterflies to be chosen for computations and those to be discarded. Thus, FFT computation time can be significantly reduced by pruning the operations on zero values in the discarded butterflies. Most of these algorithms are suitable for applications with specific zero-input or zero-output pattern distributions. These types of efficient algorithms can be used in the FFT spreading and/or IFFT de-spreading operations, such as when zero-valued inputs and/or outputs are employed.

FIG. **6**B is a flow diagram that can be employed in accordance with various aspects of the disclosure, such as for processing received spread-OFDM signals. In one aspect, for example, the method depicted in FIG. **6**B is performed by a server-side device or system in a WWAN. A scheduler in the WWAN arranges OFDM assignment blocks in a manner that facilitates low-PAPR spreading **611**. Different block sizes may be allocated to accommodate different data rates. For example, if the blocks are configured such that resources assigned to a UE comprise contiguous (or otherwise equally spaced) OFDM subcarriers, then this can facilitate uplink spreading (by the UE) which achieves a low-PAPR spread-OFDM signal.

In some aspects, the scheduler arranges the OFDM assignment blocks in a manner that facilitates fast transforms to be employed for spreading (and, optionally, de-spreading) **612**. For example, the number of OFDM subcarriers in each block might be selected to equal a product of small prime numbers. In some aspects, the block sizes are configured to enable a Radix-2 DIT FFT for spreading (and optionally, a Radix-2 DIF IFFT for decoding).

As described herein and in patents and applications incorporated by reference, the uplink OFDM subcarriers can be assigned for use by the UEs **613**, such as via channel-dependent scheduling. The server-side device or system typically demodulates received uplink OFDM signals **614** by using a DFT, such as an FFT. Demodulation **614** can include equalization. In some aspects, the demodulated symbols, which are DFT-spread data symbols, are de-mapped **615**, such as via an OFDMA de-multiplexer, which separates the received uplink signals by UE. Thus, for each UE, a received uplink signal can be de-spread by determining the de-spreading codes based on the UE's channel assignment (which indicates the number of OFDM subcarriers and the subcarrier spacing) **616**, followed by employing a fast algorithm (e.g., an IFFT) configured to de-spread the spread data symbols **617**.

FIG. **7**A is a flow diagram that depicts a method for generating spread-OFDM signals in accordance with some aspects of the disclosure. Responsive to the subcarrier assignment and/or selection, the spreading code parameters can be configured to enable use of a fast spreading algorithm **701** and configured to produce a transmitted spread-OFDM signal with low PAPR **702**. The fast spreading algorithm, such as an FFT, is configured to spread the original data symbols with orthogonal spreading codes to produce the spread data symbols **703**, which are then mapped to an IFFT **704**. The IFFT modulates the spread data symbols onto the assigned (or selected) OFDM subcarriers to produce a spread-OFDM signal **705**. The spreading **703** and the IFFT **705** can each employ one or more of the FFT pruning methods, including modified FFT pruning, partial FFT pruning, split-radix FFT pruning, or traced FFT pruning. In some aspects, such as in hardware implementations of FFTs, a transform decomposition can be performed.

In accordance with some aspects of the disclosure, instead of separately calculating the spreading **703** and IFFT **705**, both transforms are combined into a single transform. In one aspect, this can be accomplished by using a unified butterfly so that the number of arithmetic operations, delays, and indexing are reduced. One approach can employ an algorithm based on a sparse matrices factorization method, such as via the Kronecker product technique. In another aspect, the spreading **703** and IFFT **705** are combined into a single fast transform that comprises a fast orthonormal unitary transform. The aforementioned techniques for spreading and

OFDM modulation can also be adapted for OFDM demodulation and de-spreading operations.

In accordance with some aspects of the disclosure, non-contiguous subcarriers can be employed, such as due to assignment of non-contiguous OFDM subcarriers to the radio transceiver or due to selection of a subset of subcarriers (e.g., reference signals or user data signals) to be provided with separate coding from the rest of the subcarriers. In such aspects, one or more of the steps in FIG. **7**A can be configured accordingly. In some cases, certain trade-offs can be made between PAPR, orthogonality, and/or bandwidth efficiency.

In one aspect of the disclosure, the spread data symbols are critically sampled (one sample per information symbol/subcarrier) and grouped in information signal blocks of length N. By way of example, but without limitation, the spread data symbols are generated at the critical sampling rate $f_s=1/T_s$ and modulated **705** onto the N orthogonal subcarriers during a time interval defined for one OFDM symbol with period N/f_s. In practice, the output of the IFFT **705** is a well-interpolated baseband signal. For example, oversampling in the time domain is usually achieved via frequency-domain interpolation, which is achieved by zero-padding the IFFT. If the oversampling rate is $f_{os}=Lf_s$, where L is the oversampling factor, the IDFT matrix has dimension (NL×NL). Although not shown, following block **705**, a cyclic prefix or guard interval is typically added to each OFDM symbol, followed by filtering, D/A conversion, frequency up-conversion, amplification, and possibly other radio front-end processing.

FIG. **7**B is a flow diagram that depicts a method of processing received spread-OFDM signals in accordance with some aspects of the disclosure. By way of example, the method depicted in FIG. **7**B can be performed by a server-side WWAN device or system to receive spread-OFDM uplink signals from at least one UE.

The WWAN assigns uplink OFDM subcarriers to UEs, such as via channel-dependent scheduling or some other scheduling scheme **710**. Uplink OFDM subcarriers can be scheduled dynamically, such as in response to specified bandwidth needs. Different blocks of subcarriers can be configured prior to assignment or on the fly, and in a manner that subcarrier parameters (such as the number of subcarriers and their spacing) are configured to enable orthogonal spreading codes (or at least spreading codes with low cross correlations), complex spreading codes with low PAPR, and/or coding/decoding that can utilize fast algorithms (such as FFTs).

In some aspects, a WWAN device has subcarrier parameter information available from the scheduling **710**. In other aspects, the WWAN device receives the subcarrier parameter information by some other means. In one aspect, the WWAN device reads the subcarrier parameter information transmitted in a control channel, which might include a broadcast channel containing scheduling information. In other aspects, the WWAN device reads and/or determines subcarrier parameter information from uplink UE transmissions. The subcarrier parameter information can then be used in subsequent steps or blocks, such as depicted in FIG. **7**B.

Received spread-OFDM signals are demodulated **711**. In some aspects, the subcarrier parameter information can be used to demultiplex received OFDMA signals, followed by demodulation **711** of the OFDM subcarriers corresponding to each UE. Although not shown, demodulation **711** can include RF front-end processing (such as amplification, filtering, down-conversion, ADC, etc.), cyclic prefix removal, equalization, and/or matched filtering. In some aspects, demodulation **711** can comprise spatial demultiplexing (such as MIMO subspace processing). Other types of demultiplexing may be performed. Demodulation **711** typically comprises performing an over-sampled FFT, although other types of demodulation may be employed. In some aspects, demodulated OFDM signals can be equalized, such as via frequency-domain equalization (not shown).

Estimated spread data symbols produced from demodulation **711** are de-mapped **712**. In one aspect, demodulation **711** comprises performing an FFT on all the received signals, and de-mapping **712** can comprise demultiplexing (e.g., separating the estimated spread data symbols with respect to corresponding UE). The subcarrier parameter information can be used to group the estimated spread data symbols according to their respective UEs. Demodulation **711** and/or de-mapping **712** can employ data re-ordering (e.g., symbol re-ordering and/or bit re-ordering) to facilitate de-spreading **713**.

De-spreading **713** can comprise utilizing a fast algorithm, such as an FFT, to de-spread the estimated spread data symbols. Input parameters to the de-spreading algorithm can be selected based on the subcarrier parameter information, such as to provide a correct de-spreading code length and/or appropriate de-spreading code values for de-spreading the estimated spread data symbols. Outputs from the de-spreading **713** comprise de-spread data symbols, which can be processed to generate estimates of the original data symbols. These estimates may be grouped by UE.

In one aspect, a spread-OFDM transceiver comprises a non-transitory computer-readable memory storing DFT-spread OFDM software instructions thereon and at least one processor configured to execute the DFT-spread OFDM software instructions to operate as a spread-OFDM transmitter. Such a transceiver is depicted in FIG. **9**.

In one aspect of the disclosure, FIG. **8**A depicts a set of modules, each comprising instructions stored on a non-transitory computer-readable memory and configured to instruct a general-purpose processor (such as a processor core, a server, a distributed computing system, etc.) to perform functions disclosed herein. In other aspects, one or more modules can comprise a specific-purpose processor, such as an application-specific integrated circuit or some other circuit.

A baseband modulator, which can be implemented as a software module **801**, transforms a binary input to a multi-level sequence of complex numbers in one of several possible modulation formats, including binary phase shift keying (BPSK), quaternary PSK (QPSK), 16-level quadrature amplitude modulation (16-QAM) and 64-QAM. The modulator **801** can adapt the modulation format, and thereby the transmission bit rate, to match current channel conditions of the transceiver. The output signal is referred to as original data symbols.

A spreader, which can be implemented as a software module **802** which provides spreading instructions to a processor, groups the original data symbols into blocks, each comprising N symbols. The spreader is configured to perform an N-point discrete Fourier transform (DFT) to produce a set of spread data symbols. In accordance with certain aspects of the disclosure, it is instructive to note that the DFT-spread output signal (i.e., the set of spread data symbols) differs from the customary frequency-domain representation of a spectral analysis that produces frequency responses according to tones (i.e., OFDM tones constitute the transform's basis functions). For example, the DFT-spreading output signal comprises N spread data symbols,

whereas the spectral analysis produces only N/2 frequency responses, as the bandwidth of the baseband frequency response signal is limited to the range of positive frequencies, 0 to half the sampling rate (=$f_{Nyquist}$).

We begin with the definition of frequency, which Merriam-Webster Dictionary defines as the number of repetitions of a periodic process in a unit of time; the number of complete alternations per second of an alternating current; and the number of complete oscillations per second of energy (as sound or electromagnetic radiation) in the form of waves. The definition of frequency offers no distinction between a negative frequency and a positive frequency. Rather, what differentiates a negative frequency from a positive frequency relates to direction, not tone.

The mathematical representation of negative frequency can be found in the expression of physical signals as a sum of complex exponential components. For example, the negative frequency can be seen in the representation of cosine and sine functions as the weighted sums of the corresponding exponential function:

$$\cos(\omega t)=\mathrm{Re}\{e^{i\omega t}\}=(e^{i\omega t}+e^{i\omega t})/2$$

$$\sin(\omega t)=\mathrm{Im}\{e^{i\omega t}\}=(e^{i\omega t}-e^{-i\omega t})/2i$$

In discrete systems, the frequency $f=\omega/2\pi$ of an analysis interval can range from 0 to f_{sam}, or equivalently, from $-f_{sam}/2$ to $+f_{sam}/2$, where f_{sam} is the sampling frequency (i.e., the number of samples per interval). In discrete-time systems, the frequency response is constrained by the Nyquist frequency, which is half the sampling rate f_{sam}.

In general, when a sinusoid of frequency f is sampled with frequency f_{sam}, the resulting number of cycles per sample is f/f_{sam} (known as normalized frequency), and the samples are indistinguishable from those of another sinusoid (called an alias) whose normalized frequency differs from f/f_{sam} by any integer (positive or negative). Replacing negative frequency sinusoids by their equivalent positive frequency representations, all the aliases of frequency f can be expressed as $f_{alias}(n)=|f-nf_{sam}|$ for any integer n, with $f_{alias}(0)$ being the true value.

Aliasing matters when analyzing a signal, such as performing spectrum analysis, which expresses the discrete signal of N complex data symbols as a set of N/2 frequency responses, sometimes referred to as tones. Tones are defined herein in the usual and customary sense with regard to the fields of OFDM and Fourier transforms as orthogonal frequencies, e.g., spectral components. The typical analysis technique employs the smallest of the $f_{alias}(n)$ frequencies. So it is important that $f_{alias}(0)$ be the unique minimum. A necessary and sufficient condition for this is $f_{sam}/2|f|$, where $f_{sam}/2$ is the Nyquist frequency of a system with sampling rate f_{sam}. For example, with Fourier transform analysis in a digital spectrum analyzer, it is necessary to sample the input signal with a sampling frequency that is at least twice the bandwidth of the input signal due to the Nyquist limit. The Fourier transform will then produce a spectrum containing frequencies from 0 to $f_{sam}/2$. While only N/2 frequency responses are achievable, N-point spreading disclosed herein can produce N spread data symbols.

The following software code can be used to implement DFT spreader **802** in accordance with aspects of the disclosure. By way of example, the FFTW program (such as can be found at www.fftw.org, all the descriptions and documentation described therein and the contents of the links provided, being incorporated by reference in their entireties) can be employed to compute a DFT, such as a one-dimensional DFT of size N:

```
#include <fftw3.h>
. . .
{
  fftw_complex*in, *out;
  fftw_plan p;
  . . .
  in =(fftw_complex*) fftw_malloc(sizeof(fftw_complex)*N);
  out=(fftw_complex*) fftw_malloc(sizeof(fftw_complex)*N);
  p=fftw_plan_dft_1d(N, in, out, FFTW_FORWARD, FFTW_ESTIMATE);
  . . .
  fftw_execute (p); /*repeat as needed*/
  . . .
  fftw_destroy_plan(p);
  fftw_free(in); fftw_free(out);
}
```

To use the FFTW program, this code example is linked with the fftw3 library. The example code first allocates the input and output arrays using the fftw_malloc function.

The data is an array of type fftw_complex, which is by default a double [2] composed of the real (in [i] [0]) and imaginary (in [i] [1]) parts of a complex number. The next step is to create a plan, which is an object that contains all the data that FFTW needs to compute the FFT. This function creates the plan:

```
fftw_plan fftw_plan_dft_1d(int N, fftw_complex*in,
  fftw_complex*out, int sign, unsigned flags);
```

The first argument, N, is the size of the transform that will be computed. While the size N can be any positive integer, sizes that are products of small factors can be transformed most efficiently, such as described herein. The next two arguments are pointers to the input and output arrays of the transform. These pointers can be equal, indicating an in-place transform. The fourth argument, sign, can be either FFTW_FORWARD (−1) or FFTW_BACKWARD (+1) to indicate the direction of the transform. Technically, it is the sign of the exponent in the spreading codes. While aspects of the disclosure discuss forward transforms for spreading, other aspects can employ the backward (e.g., inverse) transform for spreading. For example, an IDFT can be implemented as an IFFT to provide for spreading or generating the spreading code(s). Thus, the term DFT as used herein is meant to include its corresponding backward (e.g., inverse) transform. The flags argument is usually either FFTW_MEASURE or FFTW_ESTIMATE. FFTW_MEASURE instructs FFTW to run and measure the execution time of several FFTs in order to find the best way to compute the transform of size N.

Once the plan has been created, it can be used multiple times for transforms on the specified input and output arrays by computing the transforms via

```
fftw_execute(plan).
void fftw_execute(const fftw_plan plan);
```

The DFT results are stored in-order in the output array (out), with the zero-frequency (DC) component in out [0]. If in !=out, the transform is out-of-place and the input array (in) is not modified. Otherwise, the input array is overwritten with the transform. To transform a different array of the same size, a new plan is created with fftw_plan_dft_1d, and FFTW automatically reuses the information from the previous plan, if possible. The plan can be deallocated by calling fftw_destroy_plan (plan).

FFTW uses the standard "in-order" output ordering, meaning that the n^h output corresponds to the frequency n/N (or n/T, where T is the total sampling period). In terms of

positive and negative frequencies, this means that the positive frequencies are stored in the first half of the output and the negative frequencies are stored in backwards order in the second half of the output (i.e., the frequency −n/Nis the same as the frequency (N−n)/N).

The output ordering of the FFT depends on the type of FFT employed, including whether the FFT is implemented in hardware or software. For example, an FFT block can output the frequency indices in linear or bit-reversed order. Linear ordering of the frequency indices requires a bit-reversal operation. Thus, in some aspects, it may be necessary for the FFT or the mapper to re-order the output, such as to provide a mapping to the OFDM subcarriers which yields the low PAPR.

In some aspects of the disclosure, spreader **802** may be implemented via the following steps. A DFT can be used to generate the spreading codes, which are then stored in memory. Based on OFDM subcarrier assignment, subcarrier parameter(s) is (are) input, and a corresponding set of codes is selected from the memory and used to spread the original data symbols, such as via a matrix multiplication operation. For example, the input vector (in) can be a kernel used by the FFTW program to generate the spreading matrix, which can then be stored in non-transitory memory, and selected thereafter (such as with respect to the number of subcarriers N, subcarrier spacing, and/or any other subcarrier parameter(s)) for use in a matrix multiplication operation with a matrix comprising the original data symbols.

In aspects disclosed herein, the input vector comprises the data symbols, wherein the vector length N can be selected to have small prime factors (which can provide certain processing performance advantages). The input data vector can be configured, such as via zero insertion and scaling, to affect the distribution and/or scaling of non-zero terms in the output vector.

In one aspect, a spreading configuration module **811** processes subcarrier parameters corresponding to resource blocks (e.g., OFDM subcarriers) assigned to the transmitter. The subcarrier parameters can be determined from scheduling information received in a control channel, such as a downlink broadcast channel in a WWAN used to communicate resource block assignments to the UEs for use in uplink transmissions. The spreading configuration module **811** might receive scheduling information or subcarrier parameters from a UE's RAN control module (not shown) configured to process network control information.

While aspects disclosed herein provide examples of uniformly spaced OFDM subcarriers, alternative spreading algorithms (which may employ a DFT) can be used to produce complex spreading codes adapted to other subcarrier topologies to provide for an advantageous combination of orthogonality (i.e., cross correlation) and low PAPR. Some of these spreading codes can be poly-magnitude as well as polyphase. In some aspects, better cross correlation can be sacrificed for improved PAPR. Bandwidth efficiency might be sacrificed to achieve better PAPR and/or orthogonality. Thus, in some aspects, various performance metrics (which can include PAPR, orthogonality, bandwidth efficiency, as well as others) can be employed in an optimization scheme in which the values of such metrics are weighted, and optimization comprises evaluating a weighted sum (or some other function) of the performance metrics.

The spreading configuration module **811** can configure (including dynamically adapting) the spreader **802** to produce the spread data symbols in accordance with the subcarrier parameter(s) and at least one spreading criterion. Spreading criteria can include objectives, such as providing a PAPR below a predetermined threshold, providing orthogonality (which can comprise an evaluation, such as whether spreading code cross correlations are below a threshold value), and enabling efficient spreading (such as via a fast transform algorithm, or other types of processing). Other spreading criteria may be employed.

By way of example, in IEEE 802.11a, the FFT size is typically 64 with a sample rate of 20 MHz. This yields a subcarrier spacing of 312.5 kHz. Of these 64 potential subcarriers, 12 of them are unused (sometimes referred to as "virtual carriers"). Of the remaining 52 subcarriers, 4 contain pilot tones, so only 48 subcarriers carry information at any given time. Instead of transmitting one original data symbol per 312.5 kHz subcarrier, the spreader **802** provides spread data symbols, each representing a linear combination of the original data symbols, which allows a portion of each original data symbol to be transmitted on all 48 or 52 subcarriers. While this IEEE 802.11a example is described, it should be appreciated that aspects of the disclosure described herein can be employed in other cases, which can include other systems.

In one aspect, the spreading configuration module **811** might configure the spreader **802** to employ a 52-point FFT to generate the spread data symbols corresponding to the reference signals plus user data signals. The resulting 52 spread data symbols are then mapped by the mapper **803** to the IFFT **804**. Since 52 has prime factors of 2,2,13 and 48 has prime factors of 2,2,2,2,3, the spreading configuration module **811** could configure the spreader **802** to employ a 48-point FFT to spread the user data signals and a 4-point FFT to spread the reference signals, which might provide more efficient spreading than the 52-point FFT spreading. However, employing separate spreading of the reference signals and user data signals could result in a higher PAPR. Thus, the spreader **802** might employ an algorithm that weighs the efficiency and PAPR criteria to select which spreading mode to employ. It should be appreciated that the algorithm employed by the spreader **802** can employ various additional criteria. In some cases, the additional criteria can affect the weights of the spreading criteria (e.g., efficiency and PAPR). For example, operating criteria, such as (but not limited to) the UE's transmitted signal power, modulation scheme, modulation constellation size, pre-coding, MIMO operation, etc., can affect how the spreading configuration module **811** configures the spreader **802** to spread the original data symbols. In some aspects, operating conditions, such as determined from channel state information, network traffic, network topology information, received signal strength, routing tables, and the like, can affect how the spreading configuration module **811** configures the spreader **802** to spread the original data symbols. In some aspects, the operating conditions may be measured to infer the UE's operating parameters (such as transmit power, modulation, pre-coding, etc.). In some aspects, higher PAPR might be tolerable when a small constellation size (e.g., BPSK modulation) and/or low transmit power is employed, so spreading can be configured to improve processing efficiency and/or orthogonality at the expense of allowing for a higher PAPR. When high transmission power and/or modulations that produce a high-PAPR signal are employed, there might be less PAPR budget for the spreader **802** to exploit. Thus, the spreading configuration module **811** might configure the spreader **802** to sacrifice processing efficiency and/or orthogonality in favor of lower PAPR.

In another aspect, with respect to the IEEE 802.11a example, the spreading configuration module **811** might configure the spreader **802** to employ a 64-point FFT to

generate the 52 spread data symbols corresponding to the reference signals plus user data signals. For example, the spreader **802** might be configured to generate a pre-spread input of 64 pre-spread original data symbols to the 64-point FFT, wherein the pre-spreading causes the FFT output to comprise only 52 non-zero spread data symbols. The resulting 52 spread data symbols are then mapped by the mapper **803** to the IFFT **804**. It should be appreciated that aspects of spreading configuration can be used in other scenarios and in other systems to employ N-point transforms for generating fewer than N non-zero outputs, the outputs comprising spread data symbols that satisfy one or more criteria, which can include low PAPR and/or orthogonality.

In some aspects of the disclosure, instead of a fixed algorithm for computing the DFT, the spreading configuration module **811** can adapt the DFT algorithm in the spreader **802** relative to details of the underlying hardware in order to maximize performance. For example, while FFTW's planner determines the fastest way to compute the transform for the machine on which it resides, other factors that depend on the subcarrier parameters can affect the processing efficiency. Thus, the spreading configuration module **811** can interface with the planner (or perform functions of the planner) to adapt the DFT algorithm relative to specific features of the calculations that will be performed. Various features, such as DFT size, sparseness of the spreading matrix, and/or characteristics of the input data, can be employed along with information about the underlying hardware to configure the DFT algorithm. The planner produces a data structure called a plan that contains this information. Subsequently, the plan is executed to transform the array of input data as dictated by the plan.

In some aspects, pulse shaping can be performed by "windowing" the output of the spreader **802**. This can be performed as part of the spreading, or it may be performed by the mapper **803**, such as applied to inputs of the IFFT **804**. For example, a tapered window can taper the amplitudes of at least some of the spread data symbols such that the taper is applied to the edges of the allocated spectrum. Raised cosine and Gaussian filter shapes are often used, but other types of pulse shaping can be employed.

The spreader **802** and/or the mapper **803** can configure the spread data symbols by arranging their order relative to the IFFT **804** input. Output values of the FFT are appropriately mapped to OFDM subcarriers in a manner that produces a low-PAPR spread-OFDM signal (regardless of the order or values of the original data symbols). In one aspect, ordering provides for mapping spread data symbols (relative to ascending spreading-code index) to ascending subcarrier frequencies, such as wherein the zero-frequency (DC) value corresponds to the lowest subcarrier frequency, in order to provide low-PAPR spread-OFDM signal.

The mapper **803** maps each of the NDFT outputs to one of the M>N IFFT **804** bins. As in OFDMA, a typical value of M is 256 subcarriers and N=M/Q is an integer submultiple of M. Q is the bandwidth expansion factor of the symbol sequence. The result of the subcarrier mapping is a set of complex subcarrier amplitudes, where N of the amplitudes are non-zero. As in OFDMA, the M-point IDFT **804** transforms the subcarrier amplitudes to a complex time domain signal, which is the spread-OFDM signal.

The transmitter can comprise a cyclic prefix appender **805**, which inserts a cyclic prefix in order to provide a guard time to prevent inter-block interference (IBI) due to multipath propagation. In general, the cyclic prefix is a copy of the last part of the block, which is added at the start of each block. If the length of the cyclic prefix is longer than the maximum delay spread of the channel, or roughly, the length of the channel impulse response, then, there is no IBI. Since the cyclic prefix is a copy of the last part of the block, it converts a discrete time linear convolution into a discrete time circular convolution. Thus, transmitted data propagating through the channel can be modeled as a circular convolution between the channel impulse response and the transmitted data block, which, in the frequency domain, is a pointwise multiplication of the DFT frequency samples. Then, to remove the channel distortion, the DFT of the received signal can simply be divided by the DFT of the channel impulse response point-wise, or a more sophisticated frequency domain equalization technique can be implemented.

Additional baseband processing **806** can be performed. For example, pulse shaping can reduce out-of-band signal energy. In electronics and telecommunications, pulse shaping is the process of changing the waveform of transmitted pulses. Its purpose is to make the transmitted signal better suited to its communication channel, typically by limiting the effective bandwidth of the transmission. In RF communication, pulse shaping is essential for making the signal fit in its frequency band. At baseband, the time sequence of the spread-DFT signal is filtered by the pulse-shaping filter. The spectrum of the transmission is thus determined by the filter.

Digital-to-analog conversion (DAC), frequency up-conversion, and amplification are typically performed to produce a transmitted signal. In practical implementations, typical DACs use digital interpolation filtering before implementing the D-to-A conversion. By interpolating the data samples, the performance of the reconstruction filter is improved, as increasing the sampling frequency can be seen to directly reduce the analog filter requirements for alias suppression.

Interpolation in OFDM is typically performed by the IFFT **804**. Interpolators in OFDM are described in U.S. Pat. No. 6,597,745, which is incorporated by reference, wherein a transform-domain interpolation unit expands a length-N transform domain vector by inserting zeros in the length-N transform domain vector to produce a length-**2**N transform domain vector. This transform-domain up-sampling unit interpolates the transform domain vector.

Interpolators in spread-OFDM transmitters can be employed in various aspects of the disclosure. By way of example, interpolation is disclosed throughout U.S. Pat. No. 6,686,879 (such as illustrated in FIG. **19**), which is incorporated by reference, wherein a data sequence is serial-to-parallel converted and then modulated onto multiple OFDM subcarriers, which are provided with phase offsets to synthesize a desired pulse shape for the resulting data-modulated pulse waveform. This process of transforming a serial data stream into a sequence of data-modulated pulses is implemented using an invertible transform function, such as an IFFT. Interpolation can also be provided via pulse shaping.

Aspects of the disclosure can include any of various types of interpolation. In order to perform frequency-domain interpolation, the input data is up-sampled before IFFT **804** processing. The up-sampling can be performed by zero-padding the middle samples of the input sequence. One disadvantage of frequency-domain interpolation is the increase in the IFFT size. For this reason, the oversampling rate is often kept relatively low.

As discussed above, in accordance with certain aspects of the disclosure, DFT-spreading **802** employs an N-point DFT to spread a sequence of data symbols s(n) to produce N spread symbols, x(n), which are to be modulated onto N

OFDM subcarriers. To the contrary, in spectrum analysis, the transform of a discrete signal produces frequency responses corresponding to tones. The limitation of the transform's orthonormal basis to tones discards the negative-frequency components. Whether a pair of signals have negative and positive frequencies, or they have a relative phase offset (e.g., in-phase and quadrature phase), if they have the same frequency, then they are the same tone. The basic idea behind employing a DFT on a discrete signal to calculate frequency responses corresponding to tones is that the negative frequency components of the Fourier transform are superfluous due to Hermitian symmetry. These negative frequency components are discarded with no loss of information, leaving a complex-valued function. But in aspects of the disclosure, it is unnecessary to discard spread-DFT symbols produced by the DFT-spreading **802**.

To generate a spread-OFDM up-sampled-by-M analytic time signal (assuming Nis even) from the spread symbols, x(n), a method, circuit, and/or processor, for example, according to one aspect of the disclosure can provide for performing the following steps.

1. Create an M_N-point spectral sequence $x_{int}(m)$ initially set to all zeros. In some aspects, the product MW can be an integer power of two.
2. Assign $x_{int}(0)=x(0)$, and $x_{int}(N/2)=x(N/2)$.
3. Assign $x_{int}(m)=2x(m)$, for $1\leq m\leq=(N/2)-1$. For example, when performed by a UE, this step and the previous one can provide for mapping non-zero symbol values to the OFDM subcarriers assigned to the UE.
4. Compute an M·N-point IFFT of $x_{int}(m)$ to yield the desired M·N-length analytic (complex) $x_{c,int}(n)$ sequence.
5. Optionally, multiply $x_{c,int}(n)$ by M to compensate for the 1/M scaling factor.

In the domain of digital signal processing, the term interpolation refers to the process of converting a sampled digital signal to that of a higher sampling rate (i.e., up-sampling) using various digital filtering techniques (e.g., convolution with a frequency-limited impulse signal). In such applications, there is a specific requirement that the harmonic content of the original signal be preserved without creating aliased harmonic content of the original signal above the original Nyquist limit of the signal (i.e., above $f_s/2$, which is half of the original signal sample rate, 1/T). For example, Let X(f) be the Fourier transform of a function, x(t), whose samples at some sampling interval, T, equal the x[n] sequence. The passband bandwidth of the corresponding interpolation filter is defined by its cut-off frequency, 0.5/L, where L is the oversampling factor. In terms of actual frequency, the cutoff is ½·(1/T) Hz, which is the Nyquist frequency of the original x[n] sequence.

Bandwidth is the difference between the upper and lower frequencies in a continuous set of frequencies. The passband bandwidth is the difference between the upper and lower cut-off frequencies of, for example, a band-pass filter, a communication channel, or a signal spectrum. In the case of a low-pass filter or baseband signal, the bandwidth is equal to its upper cut-off frequency, $f_s/2$.

FIG. **8**B is a block diagram that depicts modules corresponding to processing functions that can be implemented by a computer processor programmed to perform methods in accordance with aspects of the disclosure. In accordance with an aspect of the disclosure, a server-side device or system receives spread-OFDM transmissions from one or more UEs in a WWAN. After processing by one or more RF front-ends (not shown), a server-side processor (or processors) can receive the down-converted baseband signal(s). A baseband processor(s) **821** can process the received baseband signal, typically providing ADC processing, matched filtering (e.g., pulse shape filtering), amplification, and/or possibly other baseband processing operations to produce a spread-OFDM signal(s), which possibly has a cyclic prefix. A cyclic prefix remover **822** can optionally remove any cyclic prefix. The spread-OFDM signal(s) is processed by an M-point DFT (or some equivalent time-domain to frequency-domain converter) **823** to produce spread data symbols, which may be estimates of the spread original data symbols that were transmitted on each OFDM subcarrier. In some aspects, the DFT **823** may be configured to perform frequency-domain windowing, such as via control of a windowing module **833**. A demultiplexer **824** may optionally be used to provide OFDMA demultiplexing if necessary. The spread data symbols are usually equalized by an equalizer **825** prior to despreading. However, equalization may not be necessary in certain aspects. In some aspects, the equalizer **825** may comprise a spatial demultiplexer. In some aspects, the spatial demultiplexer is configured to perform MIMO subspace demultiplexing, such as Cooperative-MIMO subspace demultiplexing.

A despreader **826** despreads the spread data symbols to produce estimates of the original (despread) data symbols. The despreader **826** can employ a fast transform algorithm, such as an IFFT, which can be implemented with the FFTW software. The despreader **826** is controlled by a despreading configuration module **836**, which can receive one or more subcarrier parameters corresponding to the OFDM subcarriers assigned to a particular UE(s). Subcarrier parameters, which can include number of subcarriers, subcarrier spacing, and the like, provide an indication of spreading parameters (and thus, despreading parameters), which the despreader **826** can use to despread received spread data symbols. In some aspects, subcarrier parameters are understood to comprise spreading (and/or despreading) parameters associated with OFDM resource blocks. In some aspects, such spreading (and/or despreading) parameters may be pre-associated with each resource block assignment and communicated via the scheduler **835** to the despreading configuration module **836**. In some aspects, the despreading configuration module **836** listens to a scheduling channel broadcast by an uplink scheduler **835** to determine the subcarrier parameters. In other aspects, the despreading configuration module **836** might determine the subcarrier parameters from the UE transmissions.

The despreader **826** can be configured to perform hard decisions, soft decisions, or mixed-decision processing to produce the estimated data symbols. A baseband demodulator **827** may optionally be provided to perform further baseband processing of the estimated data symbols.

As depicted in FIG. **9**, a transceiver configured in accordance with aspects disclosed herein can include a controller, such as at least one computer or data processor **910**, at least one non-transitory computer-readable memory medium embodied as a memory **920** that stores a program of computer instructions **921**, and at least one suitable radio frequency (RF) transmitter/receiver **901** for bidirectional wireless communications with at least one other transceiver via one or more antennas **905**. The exemplary aspects of the disclosure (including those depicted in the flow diagrams and block diagrams) may be implemented, at least in part, by computer software executable by the data processor **910**. The transceiver shown in FIG. **9** can be a UE, a base transceiver station, a relay, or some other transceiver.

Aspects disclosed herein can include Cooperative-MIMO precoding, and can comprise configuring the spreading

codes to provide for spreading across a combination of subcarriers and antennas (such as across multiple UEs). In such aspects, precoding can be configured to achieve a combination of cooperative spatial multiplexing across a plurality of UEs and a low PAPR for each UE's transmissions. In other aspects, precoding may comprise pre-equalizing the transmitted signal. In such aspects, for example, pre-equalization weights applied to transmitted OFDM subcarriers, such as may be implemented by incorporation into the spreading codes, can be derived from channel information. Various techniques, including multi-objective optimization and other multi-objective algorithms can be employed to generate spreading codes that optimize (or at least achieve a predetermined performance threshold relative to) certain objectives, such as low PAPR, low cross correlations, and/or other objectives.

A transceiver configured in accordance with aspects of the disclosure is depicted in the block diagrams of FIGS. **10**A and **10**B. The transceiver can comprise a client-side device or system, a server-side device or system, a relay device or system, and/or other WWAN transceivers. In some aspects, the blocks can comprise hardware components, such as circuits. The blocks can comprise processors, such as general-purpose processors programmed to perform functions in accordance with methods disclosed herein. The blocks are also indicative of functions that can be performed by a transceiver (which includes a network of transceivers) in accordance with aspect disclosed herein. In some aspects, the blocks can comprise separate devices communicatively coupled together via at least one network. In some aspects, at least some of the separate devices can be coupled together via a WLAN, which can include a radio and/or optical network.

In FIG. **10**A, the transceiver comprises a WWAN precoder **1010**, which is configured to calculate precoder weights for use in a distributed antenna system **1020**. The precoder **1010** receives information from a WWAN scheduler, such as a WWAN schedule processor **1001** and a WWAN CSI processor **1002**. A data source **1003** provides original data symbols to the WWAN precoder **1010**. The precoder **1010** is communicatively coupled to a fronthaul router **1012**, which is connected to the distributed antenna system **1020**.

In FIG. **10**B, the transceiver comprises a WWAN decoder **1030**, which is configured to calculate decoder weights for processing received signals, such as signals received from the distributed antenna system **1020**. The decoder **1010** receives information from the WWAN schedule processor **1001** and the WWAN CSI processor **1002**. A data sink **1033** processes decoded data symbols from the WWAN decoder **1030**. The decoder **1010** is communicatively coupled to the fronthaul router **1012**, which is connected to the distributed antenna system **1020**. In some aspects, the WWAN precoder **1010** and the WWAN decoder **1030** can be a single component or system.

In some aspects, blocks disclosed herein comprise processing elements that provide necessary computing facilities for the device or system. By way of example only, processing elements can include special purpose hardware, such as FFT, coding and/or decoding processors, or programmable CPUs. In aspects wherein one or more of the blocks are communicatively coupled together via a network, such as may be implemented in a distributed system, the blocks can comprise interfaces which contain appropriate traffic format conversion circuitry between the blocks and the interconnect network input and output. In some aspects, the system further includes internal resources with shared usage among various system blocks. By way of example only, these internal resources may comprise memory and a memory access controller.

In some aspects, the router **1012** includes Input-Output (I/O) device interface units that provide connection between the precoder **1010** and external devices of the distributed antenna system **1020** through one or more fronthaul interfaces. By way of example only, these devices may include Ethernet, wireless standard compliant networking, fiber networking, and/or an expansion interface for creating larger systems using multiple systems of the type shown in figure.

In one aspect, the transceiver is a server-side device or system, and the WWAN schedule processor **1001** is a scheduler, which assigns resource blocks (e.g., blocks of OFDM subcarriers) for uplink and downlink communications with one or more client-side devices (e.g., UEs). The WWAN precoder **1010** can use the scheduling information to determine a set of OFDM subcarriers for which precoding weights will be generated. The precoder **1010** can also use the scheduling information to help determine which antennas in the distributed antenna system **1020** to allocate for possible use in serving the client devices. For example, the scheduling information might contain geographical information about each corresponding client device. This can assist in allocating distributed computing resources operated by the WWAN precoder **1010**, for example, when multiple processing cores are employed. The WWAN precoder **1010** couples precoded-data signals or precoding weights and the original data signals to selected antennas of the distributed antenna system **1020** via the fronthaul router **1012**.

In another aspect, the transceiver is a client-side device or system, and the WWAN schedule processor **1001** receives WWAN scheduling information, such as is typically broadcast in the WWAN. However, the schedule processor can receive the WWAN scheduling information by other means. In one aspect, cooperating client devices may convey their corresponding scheduling information to the WWAN schedule processor **1001**, such as via the fronthaul network. The WWAN precoder **1010** can use the scheduling information to determine a set of OFDM subcarriers for which precoding weights will be generated. In some aspects, the WWAN precoder **1010** comprises a distributed computing system, such as may comprise multiple processing cores residing on different client-side devices. In some aspects, at least some of the processing cores of the WWAN Precoder **1010** might reside in a non-client device, such as a relay or a server-side device. The WWAN Precoder **1010** might be configured to use the scheduling information to allocate distributed computing resources (e.g., processing cores, memory, fronthaul resources, etc.), such as for precoding and/or other processing operations. The WWAN precoder **1010** can couple precoded-data signals or precoding weights and the original data signals to selected antennas of the distributed antenna system **1020** via the fronthaul router **1012**.

In one aspect, the transceiver is a server-side device or system, and the WWAN CSI processor **1002** provides downlink CSI to the WWAN precoder **1010**. For example, in a reciprocal channel, the CSI processor **1002** can infer downlink CSI from uplink CSI measurements. In some aspects, the client-side devices can measure CSI in the downlink and feedback their measurements to the server-side. The WWAN precoder **1010** then provides those CSI measurements to the WWAN precoder **1010**. The WWAN precoder **1010** can use the CSI to select antennas in the distributed antenna system **1020** to serve each client device and then use the CSI to calculate the precoding weights. By way of example, the WWAN precoder **1010** might select a preliminary, or can-

didate, plurality of antennas to be used for precoding, and then refine the selection of antennas based on various criteria. One objective of the WWAN precoder **1010** might include determining a set of the antennas that enables low-PAPR pre-coded transmissions per antenna. The WWAN precoder **1010** is operable to configure the precoding in order to provide low-PAPR transmissions. The WWAN precoder **1010** may be configured to achieve additional criteria, including enabling use of a fast transform, providing for code orthogonality (e.g., code spaces with low cross correlations), limiting WLAN overhead, etc.

In accordance with some aspects of the disclosure, it should be appreciated that blocks depicted in the figures can comprise interconnects that are not shown. By way of example, the WWAN CSI processor **1002** can be communicatively coupled to at least the WWAN schedule processor **1001** (such as in FIGS. **10**A and **10**B). In some aspects, the WWAN schedule processor **1001** employs CSI and/or other channel information for scheduling, such as to provide for channel-dependent scheduling. Channel-dependent scheduling can comprise selecting OFDM resource blocks with estimated and/or measured channel conditions that are advantageous for specific client devices. In some aspects, channel-dependent scheduling can comprise scheduling resource blocks to client devices in a manner that is advantageous to the operation of the server-side system. For example, scheduling may provide for assigning the same or overlapping resources (e.g., resource blocks and/or other network resources, such as antennas, processers, fronthaul capacity, backhaul capacity, etc.) to a set of client devices, which may be clustered together or geographically separated, such as to enhance network efficiency and/or performance.

While CI coding eliminates the effect of data randomization on the PAPR of OFDM transmissions from a single user, channel-based precoding (such as MIMO precoding, pre-equalization, etc.) can introduce randomization into the transmittal signals' crest factors due to the natural randomness of the multipath channel, which translates into randomness in the precoding. Thus, some aspects of the disclosure are configured to exploit additional degrees of freedom available in a MIMO channel when the number of available transmit antennas exceeds the minimum required rank of the channel matrix to reduce the crest factors. For example, in one aspect, a set of active transmit antennas in the distributed antenna system can be selected from a larger set of candidate antennas in the distributed antenna system. In another aspect, the set of active transmitting antennas can comprise a larger number than the number of antennas receiving the precoded transmissions, the precoder **1010** exploiting the extra antennas to provide for reducing PAPR, reducing spatial cross correlation, improving diversity, and/or the like. This enables antenna selection to advantageously provide a set of antennas per OFDM tone that achieves low-PAPR transmissions per antenna and/or per device. A low-PAPR criterion might include an aggregate of PAPR across antennas and/or devices, PAPR corresponding to a subset of antennas and/or devices, an average PAPR, a mean PAPR, a peak PAPR, some other function of PAPR, or some function of PAPR weighted relative to some other criterion. In some aspects, the selection of antennas per tone can be performed for each set of original data symbols.

In one aspect, the transceiver is a client-side device or system, and the WWAN CSI processor **1002** provides uplink CSI to the WWAN precoder **1010**. For example, in a reciprocal channel, the CSI processor **1002** can infer uplink CSI from downlink CSI measurements. In some aspects, the server-side devices might measure CSI in the uplink and feedback their measurements to the clients. The WWAN precoder **1010** provides the uplink CSI to the WWAN precoder **1010**. The WWAN precoder **1010** can use the CSI to select antennas in the distributed antenna system **1020**, which can include other client devices configured to operate in a Cooperative MIMO network, and then use the CSI to calculate the precoding weights. By way of example, the WWAN precoder **1010** might select a preliminary, or candidate, plurality of antennas to be used for precoding, and then refine the selection of antennas based on various criteria. One objective of the WWAN precoder **1010** might include determining a set of the clients that enables low-PAPR pre-coded transmissions per client.

The data source **1003** provides a stream of original data symbols (which can comprise user data and/or reference signals) to the WWAN precoder **1010**. In one aspect, the WWAN precoder **1010** calculates precoding weights separately for the user data and the reference signals. In other aspects, the WWAN precoder **1010** provides precoding weights for a data set comprising both user data and reference signals. In one aspect, the WWAN precoder **1010** is configured to select a block of the original data symbols from the data source **1003** and generate the precoding weights specific to the selected block of data. In other aspects, the WWAN precoder **1010** can calculate the precoding weights without a data input and then precode blocks of data from the data source **1003**. In some aspects, the data source **1003** might reside in a client device and receive data from at least one other client device in a cluster of devices communicatively coupled together via the fronthaul network. Data from at least one other device can be input to the WWAN precoder **1010**, which performs at least one of determining the precoding weights and precoding the data.

In a server-side device or system, the fronthaul router **1012** can comprise a local network manager, such as a Coordinated Multipoint router, communicatively coupled to the distributed antenna system **1020** (e.g., base transceiver stations, relays, remote radio heads, etc.) via any combination of fiber optic and wireless links. In a client-side device, the fronthaul router **1012** can comprise a local network manager, such as a cluster master, communicatively coupled to the distributed antenna system **1020** (e.g., the other clients in the cluster, relays, etc.) via wireless links.

In some aspects, the system shown in the figures can comprise a distributed system wherein the blocks are communicatively coupled via a fronthaul interconnect and may also include an interconnect network scheduler (not shown) which can configure and service communication traffic between I/O devices, processing elements, and shared resources. The interconnect network scheduler can control and configure accesses through the fronthaul interconnect, optimize the overall system for metrics, such as performance and access latency using trade-off parameters (such as power consumption, overall system efficiency, and a fronthaul schedule program). In some aspects, the interconnect network scheduler can be implemented as a distributed mechanism, which may be inherently part of internal elements of the blocks, and may include routing units, integrated hardware with processing elements, shared resources, I/O devices, and/or software program(s) executed by processing elements.

In accordance with aspects disclosed with reference to FIG. **3**, different network topologies (such as can be employed for connecting blocks, the distributed antenna system, and/or other resources within the blocks in FIGS. **10**A and **10**B) can be representative of data traffic created or

used during precoding and/or decoding and can further comprise subnetwork topologies corresponding to partitioned processes (e.g., via data partitioning and/or computation partitioning). FIG. **3** depicts a reconfigurable interconnect network topology and scheduler wherein the scheduler provides control, configuration, and optionally status collection capabilities to and from the network nodes. There can be one or several subnetworks, each consisting of point-to-point interconnects and/or broadcasts. Each communication link can be established via routing elements, which can direct traffic streams to and/or from various processing units, memories, other shared resources, and/or distributed antennas. The quantity, topology and parameters of the links and routing elements can determined at design time and/or dynamically configured.

Network topologies can be classified based on application operation mode and global characteristics, such as bandwidth, latency, and burst behavior. By way of example, different network topologies can be employed to process data corresponding to different OFDM subcarriers, different client devices being served, and/or different antennas in the distributed antenna system. In some aspects, computational partitioning can be performed. Different network topologies can correspond to different component problems. By way of example, a first network topology can be configured for processing CSI. A set of network topologies can be configured for determining precoding weights for each of a plurality of OFDM subcarriers. At least another network topology can be configured for configuring the precoding weights to provide a low-PAPR precoded transmission for one or more antennas and/or devices.

A fronthaul interconnect network schedule program can determine configuration of various nodes that meet concurrent communication traffic requirements of one or several application modes. Alternatively, each application operation mode may have its own schedule program. Configuration and operation of interconnect nodes can be statically determined or dynamically adapted based on the schedule program. The schedule program can organize input and output data for each node into distinct categories based on characteristics of interest, such as bandwidth, latency, ordering for more efficient resource utilization, quality of service, etc.

Mechanisms to employ multiple traffic schedules, including loading and storage of the new schedule programs can be provided. A router in the fronthaul interconnect may provide internal storage, selection, and forwarding of multiple traffic streams from multiple inbound links to multiple outbound links. A router may accommodate multiple traffic types based on a predetermined fabric schedule program.

In some aspects, multiple blocks or components may share a fronthaul interface. As determined by a fronthaul scheduler, a particular link may be used to carry traffic for multiple communicating units at a variety of transfer granularity sizes, service schedules, and/or durations. Multiple links may be selected to operate in tandem to provide required services for incoming or outgoing traffic.

For some topologies, it may be desirable to subdivide a stream into several streams across different links. This enhancement may facilitate potentially more efficient system operation, and each subdivision might be accommodated by a different schedule program. Alternatively, it may be beneficial to aggregate several data streams (possibly corresponding to different topologies) into one stream over a shared link.

FIG. **11** is a flow diagram that depicts a precoding method in a distributed antenna system in accordance with some aspects of the disclosure. CSI for a MIMO-OFDM channel is collected **1101** and is used for calculating multiple precoding matrices **1102** for each tone, each precoding matrix corresponding to a different antenna set. A set of precoding matrices, one for each tone, is selected **1103** according to a predetermined criterion based on PAPR. The selected set of precoding matrices is used to precode a block of the original data symbols **1104**. In some aspects, this process may be performed for each of a plurality of original data blocks. Step **1105** provides for returning to step **1101** or step **1102**. For example, in one aspect, steps **1103**-**1104** are repeated for a next block of original data symbols. In some aspects, steps **1101**-**1104** are repeated for the next block of original data symbols.

As disclosed above, the CSI may comprise measured channel conditions and/or statistical channel conditions. CSI may be inferred from channel measurements. For example, uplink CSI may be inferred from measured downlink CSI (and vise versa). Similarly, CSI corresponding to a particular tone may be interpolated from CSI corresponding to another tone. CSI may be directly measured from training signals (e.g., pilots) received by antennas in the distributed antenna system. In some aspects, CSI may be provided via data directed channel estimation. In some aspects, CSI is measured by devices communicatively coupled to the distributed antenna system via the WWAN and then fed back to the precoder(s) configured to perform the methods disclosed herein. By way of example, in an OFDM system, CSI can comprise flat-fading channel measurements and/or estimates (including statistics) corresponding to at least a subset of the antennas and for each tone.

Based on the CSI, a set of the antennas can be selected for each antenna on a device being served by the distributed antenna system via the WWAN. In some aspects, the device's antenna may be served by a first set of the antennas corresponding to a first tone and a second (different) set of antennas corresponding to a second tone. Some aspects disclosed herein provide for the distributed antenna system comprising a larger number of antennas than the aggregate number of antennas being served. This allows a subset of the antennas of the distributed antenna system to at least equal the aggregate number of antennas being served.

In one aspect, the distributed antenna system comprises a cluster of client devices, and the device(s) being served can comprise any of various antenna systems, including a server-side distributed antenna system, a server-side antenna array, one or more relay antennas, and/or one or more client-device antennas (e.g., a cluster of client devices, a client device antenna array, or some combination thereof). In some aspects, a cluster of devices may cooperate, such as in mesh networks, ad-hoc networks, multi-hop networks, cellular networks, and in other types of networks. In another aspect, the distributed antenna system can comprise a plurality of server-side antennas, including antennas residing on multiple base transceiver stations, and possibly antennas residing on other server-side devices and/or systems, including relays, remote radio heads, and the like. The device(s) being served can include any of the aforementioned client-side, server-side, and/or any intermediary devices.

In step **1102**, multiple combinations of serving antennas can be provided for each device (and/or antenna) being served, and there can be multiple combinations of serving antennas per tone per device (and/or antenna) being served. The serving distributed antenna system can comprise a larger number of candidate antennas than the aggregate number of antennas being served, which allows each selected subset of the antennas of the distributed antenna system to at least equal the aggregate number of antennas

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being served. In some aspects, the number of active antennas in the distributed antenna system serving a cluster of served antennas is larger than the number of antennas in the cluster being served. This results in extra degrees of freedom which are ordinarily used for array processing purposes, such as to provide added antenna-array gain, diversity, redundancy, and the like. Aspects of the disclosure can exploit these extra degrees of freedom to reduce PAPR of the transmissions from each antenna and/or device. For example, the extra degrees of freedom can provide for adaptations to the precoding matrix which can achieve objectives, such as low PAPR, that are not directly related to array processing performance.

In some aspects, additional degrees of freedom can be achieved by employing extra spectrum, which may include extra tones, for transmission. By way of example, the IDFT can be configured to employ extra tones in order to reduce the PAPR of the transmitted OFDM signal.

In one aspect, the extra tones might be transmitted in a manner that avoids interfering with the WWAN system. For example, the extra tones may comprise unscheduled resources in the WWAN. In another case, the extra tones may comprise WWAN control channels which are not transmitted during the uplink timeslot. In some aspects, the extra tones can correspond to a different communication system other than the WWAN. In these aspects, the extra tones can be weighted such as to reduce PAPR of the transmitted signals. In another aspect, the extra tones might comprise pilot tones, and data corresponding to weights applied to the pilots tones such as to reduce the PAPR may be communicated to the receive side such that the receive side can compensate for the weights in the received pilots. In such aspects, some data bandwidth is sacrificed to improve PAPR performance.

In some aspects disclosed herein, additional spectral bandwidth can be used to help reduce PAPR. However, the additional spectral bandwidth does not need to comprise tones. In some aspects, signals employed for reducing the PAPR can be pseudo-orthogonal or non-orthogonal relative to the spread-OFDM signal.

In one aspect of the disclosure, step **1102** comprises generating multiple precoding matrices for at least one tone such that each precoding matrix achieves a predetermined minimum cross correlation between subspace channels. By way of example, the degree of cross correlation can be determined based on spatial subchannel eignevalues.

In step **1103**, a precoding matrix set can comprise one precoding matrix per tone. For each set, the PAPR for each antenna and/or device can be determined for the precoded transmission across the full set of tones. At least one PAPR criterion based on these PAPRs can be determined, and the precoding matrix set qualifying as "low PAPR" based on the at least one PAPR criterion can be selected.

It should be appreciated that in some aspects, step **1102** depends on the CSI but not on the data block being precoded, so it may be updated based on the channel conditions changing (such as may be determined by coherence time or some similar channel characterization). Step **1103** might depend on the data block being precoded, and may be repeated for each block of original data symbols to be precoded. In some aspects, step **1102** may be repeated for each block. For example, given a new block of original data symbols, a new set of precoding matrices may be selected. This can include adapting previous precoding matrices.

In some aspects, steps **1102** and **1103** can be combined in an iterative process wherein the precoding matrices are adapted and the PAPR criterion for the adapted set is evaluated, and the process is repeated until a predetermined criterion is satisfied, such as a maximum number of iterations, an elapsed amount of time, a predetermined PAPR threshold, or the like. In some aspects, step **1103** comprises selecting a precoding matrix set from multiple sets which correspond to a best PAPR. In some aspects, step **1102** can comprise adapting the matrices according to one or more adaptation schemes. By way of example, an adaptation scheme may comprise randomly adapting at least one precoding weight, adapting precoding weights in response to how a previous adaptation changed a metric (such as PAPR, cross correlation, etc.), and/or adapting at least one precoding weight according to a measured characteristic of the channel and/or original data symbols. In some aspects, certain configurations of CSI values and/or data can be used to determine how to adapt the precoding matrices. Such adaptations may be determined, based on a given configuration(s), to have a high probability of yielding a lower PAPR. Such determinations may be based on historical data, perhaps being associated with correlated behaviors and/or identified trends, and/or they may be determined analytically.

In some aspects, favorable cross correlation can be sacrificed for favorable PAPR, or vise versa. In some aspects, it should be appreciated that the low PAPR criteria may be weighted with respect to particular antennas and/or devices that are transmitting the precoded signals. For example, in one aspect, low PAPR can be more important for battery-powered transceivers. Thus, a precoding matrix set may be selected that allows for higher PAPR among devices that receive line power to enable lower PAPR among devices that are battery powered. In some aspects, the transmit power of each device may determine how important it is to be provided with a low-PAPR coded signal. For example, devices that are currently transmitting with low transmit power might tolerate a high-PAPR transmission better than devices transmitting at high power. In some aspects, the inherent PAPR of the modulation constellation being used by each device may determine the low-PAPR criterion. In some aspects, power consumption per device may be employed to determine the PAPR criterion. For example, it may be important to provide for uniform power consumption across the transmitting devices. In some aspects, the type of device for each transmitting device may be used to determine its weight in the low-PAPR criterion. In some aspects, an operating status of a device may be used to determine its weight. For example, it may be more important for devices with low battery power to be provided with low-PAPR coded signals. It should be appreciated that other operating parameters and device characteristics may be employed to determine the low-PAPR criterion.

FIG. **12** is a flow diagram that depicts a precoding method in a distributed antenna system in accordance with some aspects of the disclosure. CSI for a MIMO-OFDM channel is collected **1201** and can be used for selecting a set of antennas for each tone **1202**. Precoding weights are calculated for each antenna-tone set (i.e., a set of antennas for each tone) **1203**. PAPR is calculated **1204** for each active antenna and/or device in the distributed antenna system. Spatial cross correlations of the weighted transmissions may optionally be calculated **1205**. A decision is based on the PAPR (and optionally the cross correlations) **1206**, and the decision determines where control is transferred to in the flow diagram.

In one aspect, if the decision **1206** indicates that a PAPR criteria is not met with the current antenna-tone set, the method returns to step **1202** (indicated by decision result

1207.1) in order to select a new antenna-tone set. In some aspects, step **1207.1** can comprise sending information (such as decision information, precoding weights, cross correlation information, and/or instructions for selecting the new antenna-tone set) to step **1202**.

In another aspect, the decision **1206** can cause control to return to step **1201** via step **1207.2**. For instance, decision **1206** can comprise a determination of whether the CSI needs to be updated. In some aspects, the CSI is collected **1201** based on a predetermined time interval, when measured reference signals indicate a sufficient change in the channel state, for each block of original data symbols, or via some other criteria or mechanism.

In another aspect, the decision **1206** can cause control to transfer to block **1207.3** wherein a set of precoding weights is selected to precode the original data symbols. For example, when a predetermined PAPR criterion is met, the original data symbols are precoded **1207.3** using the weights that satisfy the criterion. The weights may be selected from weights of a corresponding antenna-tone set that best satisfies the PAPR criterion after a predetermined number of iterations, or the weights may satisfy the PAPR criterion, at which point the iterations cease and control is transferred to block **1207.3**. In some aspects, additional criteria may be employed in the decision **1206** as described above, and when those criteria are satisfied, the original data symbols are precoded **1207.3**.

In one aspect, step **1202** comprises selecting a destination group of antennas. For example, a server-side system can select which client devices it will serve for a given set of distributed antennas. Optionally, this can be done for each OFDM tone or set of tones. In some aspects, the selected client devices comprise a cluster (which may be in close geographical proximity with each other), such as may be advantageous when the client devices are configured to perform client-side Cooperative MIMO. In other aspects, the selected clients may be geographically distributed, such as to ensure that reused frequency channels are uncorrelated. In some aspects, a similar decision on destination antennas is made by a cluster of client devices, such as a local group of UE's communicatively coupled together and configured to perform client-side Cooperative MIMO. The system (or cluster) can then select which antennas in its distributed antenna system to serve each destination antenna (or device), and this selection can be made for each tone or set of tones. For at least one tone, the selection can comprise a number of candidate distributed antennas that is greater than the channel-matrix rank necessary to provide a sufficient number of spatial subchannels to serve the destination antennas. For example, the number of transmitting antennas can be greater than the number of receiving antennas.

As described in the patents and applications incorporated by reference, the selection of spectral components (e.g., OFDM tones) and their association with particular wireless terminals can be performed to optimize WWAN system performance relative to the current WWAN channel. For example, the spectral components can be selected to minimize the effects of deep fades and/or interference. Spectral-component selection (e.g., scheduling) may be selected and/or adapted to optimize one or more WWAN link-performance metrics, including, but not limited to, SNR, BER, PER, and throughput. Spectral-component selection may be performed to achieve other objectives, such as to distribute processing loads across devices.

In accordance with certain aspects of the disclosure, scheduling can comprise one of two types of subcarrier mapping. Localized mapping comprises a contiguous block of subcarriers (e.g., a continuous frequency band), whereas distributed mapping comprises a non-contiguous (e.g., discontinuous, or frequency-interleaved) set of subcarriers. With localized subcarrier mapping, it is possible to exploit frequency selective gain via channel-dependent scheduling (e.g., assigning uplink frequencies to each UE based on favorable channel conditions).

A set of precoding matrices, one for each tone, can be calculated **1203** according to a predetermined criterion based on PAPR. In accordance with some aspects of the disclosure, a precoder configures the precoding matrix to provide a spread-OFDM transmission(s) with low PAPR. By way of example, low PAPR can be achieved by selecting appropriate spreading codes (such as may be based on number of OFDM tones and tone spacing) and properly configuring the order in which spread data symbols are mapped to particular tones. The spreading codes can be generating using a DFT that is configured with appropriate input parameters. Thus, the precoder can provide for frequency-domain synthesis to generate a spread-OFDM signal that comprises a set of contiguous and/or non-contiguous OFDM tones. In aspects wherein the precoder is configured to perform MIMO subspace precoding in addition to spread-OFDM coding, the precoder can be configured to produce low-PAPR transmissions, such as by employing the methods corresponding to FIGS. **11-13**. In some aspects, the precoder can adapt the transmit power of certain spatial subchannels in order to effect changes in the aggregate PAPR. By way of example, the precoder can scale the weights of a particular eigenvector to adjust power in the corresponding spatial direction.

The selected set of precoding matrices is used to precode a block of the original data symbols, and then the PAPR of each precoded transmission (such as transmitted by each transmitting antenna or device) can be calculated **1204**, such as by aggregating precoded signals across all the tones allocated to the antenna or device. In some aspects, the PAPR (and thus the precoding) may be specific to each block of original data symbols, so this process may be performed for each original data block.

As precoding is adapted to reduce the PAPR of the spread-OFDM signal(s), there can be a tradeoff between desirable PAPR and spatial correlation attributes. Estimating the spatial correlation **1205** can be performed, which in one sense can be regarded as a measure of code cross-correlation, which can be used to characterize orthogonality of the codes. Although many different techniques can be employed for determining the spatial correlation **1205**, it should be appreciated that spatial correlation depends on the eigenvalue distributions of the correlation matrices. Each eigenvector represents a spatial direction of the channel, and its corresponding eigenvalue describes the average channel/signal gain in this direction. For example, for the transmit-side spatial correlation matrix, it describes the average gain in a spatial transmit direction. In some aspects, both transmit-side and receive-side spatial correlation matrices are determined. In some aspects, step **1205** can comprise determining some value derived from or otherwise based on spatial correlation. For example, channel capacity, which depends on spatial correlation, might be determined instead.

FIG. **13** is a flow diagram that depicts a precoding method in a distributed antenna system in accordance with some aspects of the disclosure. CSI is collected **1301**, and then for each OFDM tone, a set of antennas in an origin distributed antenna system is selected to serve a set of destination antennas **1302**. Precoding weights are calculated for each origin set **1303**. PAPR is calculated for each antenna (and/or

device) in the origin set **1304**. After one or more iterations, one of the origin sets is selected **1305** to be used for precoding.

In one aspect of the disclosure, a set of UEs comprises the distributed antenna system, and the method depicted in FIG. **13** provides for precoding uplink transmissions from the UEs to a set of eNodeBs. For each of a plurality Nimes of OFDM tones, step **1302** provides for selecting a number $N_{sets}(n_{tones})$ of different UE sets to transmit pre-coded signals, where a particular number $N_{sets}(n_{tones})$ denotes a number of UE sets corresponding to an n_{tones}^{th} OFDM tone. For each of the N_{tones} tones, step **1303** calculates precoding weights for all the corresponding UE sets. If there are N_{sets} UE sets for each of the N_{tones} OFDM tones, then there might be up to a total of $N_{sets} \cdot N_{tones}$ precoding matrices. A combination of precoding matrices is provided by selecting one precoding matrix for each of the N_{tones} OFDM tones. Step **1304** provides for calculating the PAPR for each of multiple combinations of the precoding matrices. By way of example, a PAPR can be calculated from an IDFT of a set of spread original data symbols comprising the original data symbols spread by a corresponding precoding matrix.

Step **1305** can comprise any of various techniques for selecting an antenna-tone set. For example, if the corresponding combination of precoding matrices satisfies a threshold criterion, such as can be based on PAPR, then the antenna-tone set is selected and the combination of precoding matrices is used to encode the original data symbols. In other aspects, a "best" metric (such as may be based on PAPR) may be determined, such as from an exhaustive search or a combinatorial search. A combinatorial search is one that might exploit one or more pruning strategies to avoid testing all possible candidate combinations. Combinatorial searches can include branch and bound, greedy, local search methods, and a variety of heuristics that use partial knowledge about the structure of the solution space, which can achieve a "good" solution, if not the "best" solution.

The various blocks shown in the figures may be viewed as method steps, and/or as operations that result from operation of computer program code, and/or as a plurality of coupled logic circuit elements constructed to carry out the associated function(s).

In general, the various exemplary aspects may be implemented in hardware or special purpose circuits, software, logic or any combination thereof. For example, some aspects may be implemented in hardware, while other aspects may be implemented in firmware or software which may be executed by a controller, microprocessor or other computing device, although the invention is not limited thereto. While various aspects of the exemplary embodiments of this disclosure may be illustrated and described as block diagrams, flow charts, or using some other pictorial representation, it is well understood that these blocks, apparatus, systems, techniques or methods described herein may be implemented in, as non-limiting examples, hardware, software, firmware, special purpose circuits or logic, general purpose hardware or controller or other computing devices, or some combination thereof.

It should thus be appreciated that at least some aspects of the exemplary aspects of the disclosure may be practiced in various components such as integrated circuit chips and modules, and that the exemplary aspects of this disclosure may be realized in an apparatus that is embodied as an integrated circuit. The integrated circuit, or circuits, may comprise circuitry (as well as possibly firmware) for embodying at least one or more of a data processor or data processors, a digital signal processor or processors, baseband circuitry and radio frequency circuitry that are configurable so as to operate in accordance with the exemplary aspects of this disclosure.

Various modifications and adaptations to the foregoing exemplary aspects of this disclosure may become apparent to those skilled in the relevant arts in view of the foregoing description, when read in conjunction with the accompanying drawings. However, any and all modifications will still fall within the scope of the non-limiting and exemplary aspects of this disclosure.

The invention claimed is:

1. A method for communication in a wireless network, comprising:

producing a set of subcarrier values that equals a product of a complex-valued code matrix with a matrix of data symbols;

selecting a set of subcarriers assigned for use by a user device; and

modulating the subcarrier values onto the set of subcarriers to produce a plurality of modulated subcarriers; and

producing a time-domain waveform from a superposition of the plurality of modulated subcarriers, the time-domain waveform to be transmitted in the wireless network by the user device;

wherein producing the set of subcarrier values employs a plurality of complex-valued codes that shapes interference patterns of the superposition to produce a plurality of cyclic-shifted waveforms that each have one of the data symbols modulated thereon.

2. The method of claim **1**, wherein each of the plurality of complex-valued codes comprises a different vector of linear phase offsets.

3. The method of claim **1**, wherein the cyclic shifted waveforms are orthogonal waveforms.

4. The method of claim **1**, wherein the cyclic shifted waveforms are Sinc waveforms.

5. The method of claim **1**, wherein the set of subcarriers have a frequency spacing f_s, and the plurality of cyclic-shifted waveforms are each periodic over a symbol interval $T_s=1/f_s$.

6. The method of claim **1**, wherein modulating and producing the time-domain waveform is performed using an inverse discrete Fourier transform.

7. The method of claim **1**, wherein selecting the set of subcarriers comprises selecting one of a plurality of selectable subcarrier spacings.

8. The method of claim **1**, further comprising prepending the data symbols with zeros before producing the set of subcarrier values, or adding at least one of a cyclic prefix and a cyclic postfix to the time-domain waveform.

9. The method of claim **1**, wherein selecting the set of subcarriers provides for orthogonal frequency division multiple access for the user device and at least one other user device.

10. The method of claim **1**, wherein an mth one of the plurality of complex-valued codes is expressed as a set of N code chips, wherein each code chip is expressed by $e^{i2\pi nm/N}$, where e is Euler's number, i is the square root of −1, π is Pi, and n is an integer.

11. The method of claim **1**, wherein producing the set of subcarrier values employs a fast transform.

12. The method of claim **11**, wherein selecting the set of subcarriers comprises selecting a subset of a plurality of input frequency bins of the fast transform to be zero or non-zero.

13. An apparatus for communication in a wireless network, comprising:

at least one processor; and

at least one non-transitory computer-readable memory in electronic communication with the at least one processor, wherein instructions stored in the at least one non-transitory computer-readable memory are executable by the at least one processor for:

producing a set of subcarrier values that equals a product of a complex-valued code matrix with a matrix of data symbols;

selecting a set of subcarriers assigned for use by a user device; and

modulating the subcarrier values onto the set of subcarriers to produce a plurality of modulated subcarriers; and

producing a time-domain waveform from a superposition of the plurality of modulated subcarriers, the time-domain waveform to be transmitted in the wireless network by the user device;

wherein producing the set of subcarrier values employs a plurality of complex-valued codes that shapes interference patterns of the superposition to produce a plurality of cyclic-shifted waveforms that each have one of the data symbols modulated thereon.

14. The apparatus of claim 13, wherein each of the plurality of complex-valued codes comprises a different vector of linear phase offsets.

15. The apparatus of claim 13, wherein the cyclic shifted waveforms are orthogonal waveforms.

16. The apparatus of claim 13, wherein the cyclic shifted waveforms are Sinc waveforms.

17. The apparatus of claim 13, wherein the set of subcarriers have a frequency spacing f_s, and the plurality of cyclic-shifted waveforms are each periodic over a symbol interval $T_s=1/f_s$.

18. The apparatus of claim 13, wherein modulating and producing the time-domain waveform is performed using an inverse discrete Fourier transform.

19. The apparatus of claim 13, wherein selecting the set of subcarriers comprises selecting one of a plurality of selectable subcarrier spacings.

20. The apparatus of claim 13, further comprising instructions stored in the at least one non-transitory computer-readable memory are executable by the at least one processor for prepending the data symbols with zeros before producing the set of subcarrier values, or adding at least one of a cyclic prefix and a cyclic postfix to the time-domain waveform.

21. The apparatus of claim 13, wherein selecting the set of subcarriers provides for orthogonal frequency division multiple access for the user device and at least one other user device.

22. The apparatus of claim 13, wherein an mth one of the plurality of complex-valued codes is expressed as a set of N code chips, wherein each code chip is expressed by $e^{i2\pi nm/N}$, where e is Euler's number, i is the square root of −1, π is Pi, and n is an integer.

23. The apparatus of claim 13, wherein producing the set of subcarrier values employs a fast transform.

24. The apparatus of claim 23, wherein selecting the set of subcarriers comprises selecting a subset of a plurality of input frequency bins of the fast transform to be zero or non-zero.

25. A computer program product, comprising at least one non-transitory computer-readable memory having computer-readable program code stored thereon, the computer-readable program code containing instructions executable by one or more processors for:

producing a set of subcarrier values that equals a product of a complex-valued code matrix with a matrix of data symbols;

selecting a set of subcarriers assigned for use by a user device; and

modulating the subcarrier values onto the set of subcarriers to produce a plurality of modulated subcarriers; and

producing a time-domain waveform from a superposition of the plurality of modulated subcarriers, the time-domain waveform to be transmitted in the wireless network by the user device;

wherein producing the set of subcarrier values employs a plurality of complex-valued codes that shapes interference patterns of the superposition to produce a plurality of cyclic-shifted waveforms that each have one of the data symbols modulated thereon.

26. The computer program product of claim 25, wherein each of the plurality of complex-valued codes comprises a different vector of linear phase offsets.

27. The computer program product of claim 24, wherein the cyclic shifted waveforms are orthogonal waveforms.

28. The computer program product of claim 25, wherein the cyclic shifted waveforms are Sinc waveforms.

29. The computer program product of claim 25, wherein the set of subcarriers have a frequency spacing f_s, and the plurality of cyclic-shifted waveforms are each periodic over a symbol interval $T_s=1/f_s$.

30. The computer program product of claim 24, wherein modulating and producing the time-domain waveform is performed using an inverse discrete Fourier transform.

31. The computer program product of claim 25, wherein selecting the set of subcarriers comprises selecting one of a plurality of selectable subcarrier spacings.

32. The computer program product of claim 24, further comprising computer-readable program code containing instructions executable by the one or more processors for prepending the data symbols with zeros before producing the set of subcarrier values, or adding at least one of a cyclic prefix and a cyclic postfix to the time-domain waveform.

33. The computer program product of claim 25, wherein selecting the set of subcarriers provides for orthogonal frequency division multiple access for the user device and at least one other user device.

34. The computer program product of claim 25, wherein an mth one of the plurality of complex-valued codes is expressed as a set of N code chips, wherein each code chip is expressed by $e^{i2\pi nm/N}$, where e is Euler's number, i is the square root of −1, π is Pi, and n is an integer.

35. The computer program product of claim 24, wherein producing the set of subcarrier values employs a fast transform.

36. The computer program product of claim 34, wherein selecting the set of subcarriers comprises selecting a subset of a plurality of input frequency bins of the fast transform to be zero or non-zero.

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Shattil

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(54) **TRANSMIT PRE-CODING**

(71) Applicant: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

(72) Inventor: **Steve Shattil**, Cheyenne, WY (US)

(73) Assignee: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

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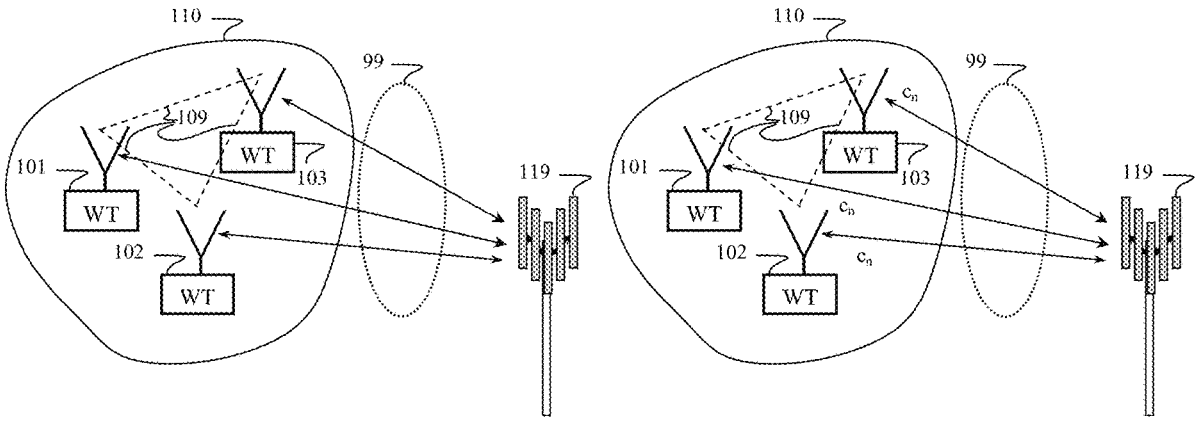
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Primary Examiner — Samina F Choudhry
(74) *Attorney, Agent, or Firm* — Steven J Shattil

(57) **ABSTRACT**

A user device communicates in a wireless network by encoding a set of data symbols with a set of complex-valued codes to produce a set of subcarrier values. The subcarrier values are modulated onto a set of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers assigned to the user device to produce a time-domain waveform that comprises a superposition of modulated subcarriers, and the time-domain waveform is transmitted in the wireless network. The set of subcarrier values comprises a first polyphase code that encodes a first of the set of data symbols and at least a second polyphase code that encodes at least a second of the set of data symbols. The first polyphase code causes constructive and destructive interference between the modulated subcarriers to produce a first periodic pulse waveform having a peak value centered at a first time in an OFDM symbol interval, and the second polyphase code causes constructive and destructive interference between the modulated subcarriers to produce a second periodic pulse waveform having a peak value centered at a second time in the OFDM symbol interval, wherein the second time is different from the first time.

30 Claims, 32 Drawing Sheets



Related U.S. Application Data

continuation of application No. 14/276,309, filed on May 13, 2014, now Pat. No. 9,048,897, which is a continuation of application No. 12/545,572, filed on Aug. 21, 2009, now Pat. No. 8,750,264, which is a division of application No. 11/187,107, filed on Jul. 22, 2005, now Pat. No. 8,670,390.

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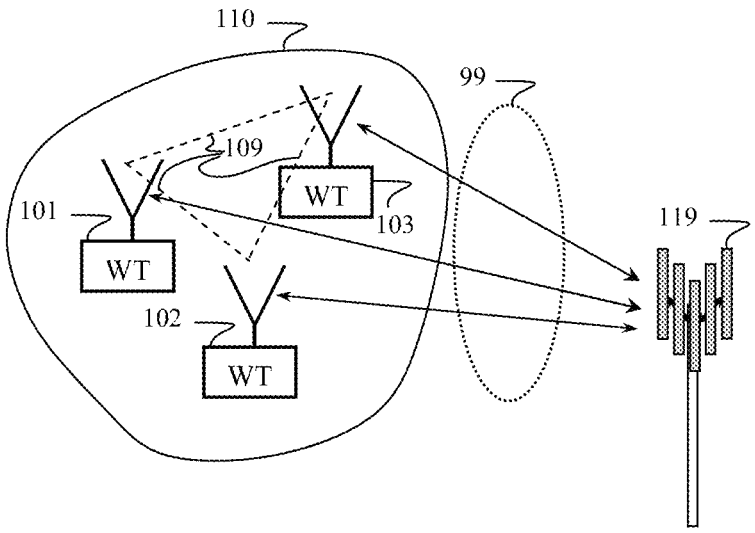


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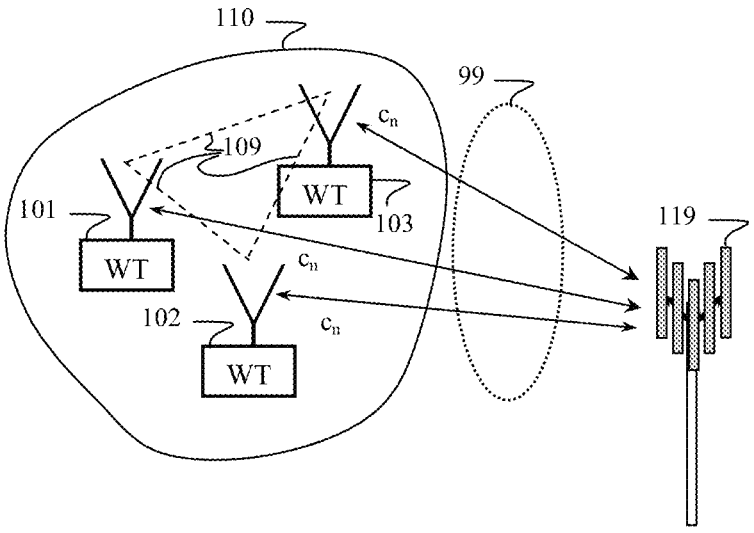


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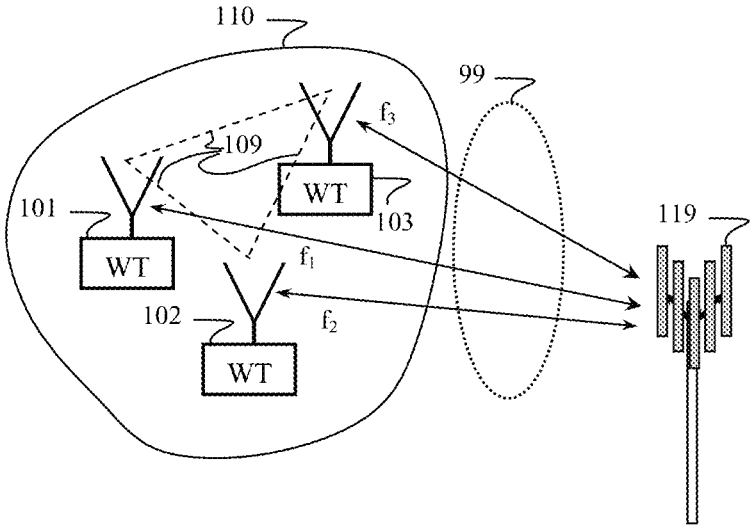


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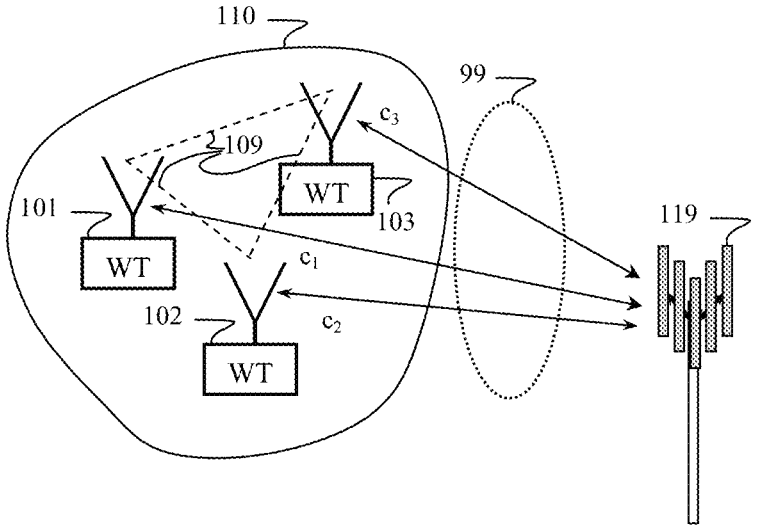


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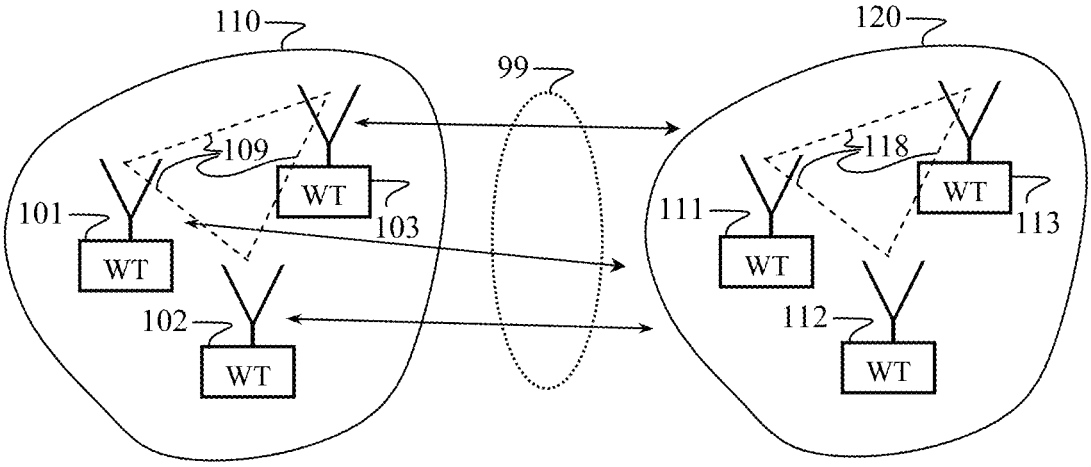


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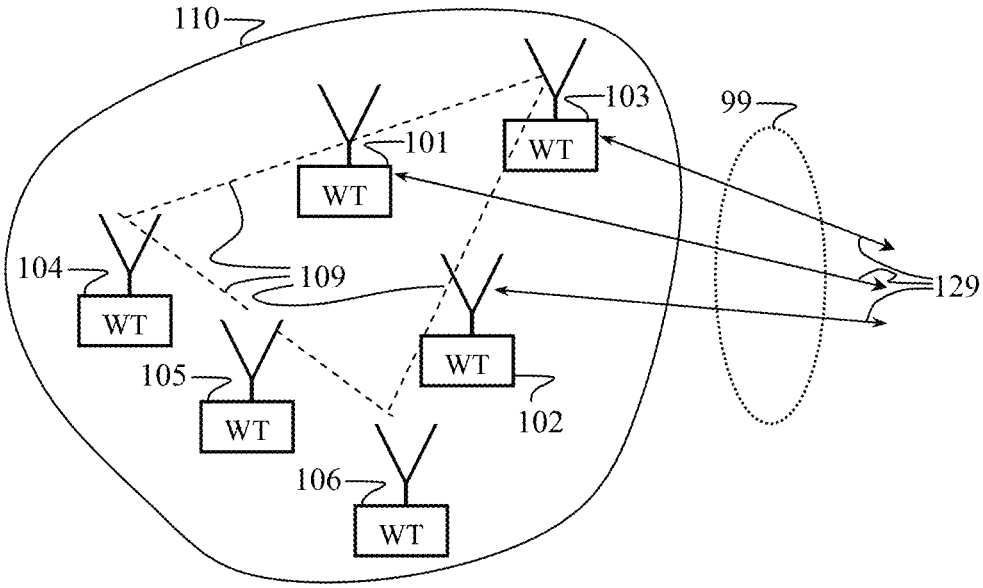


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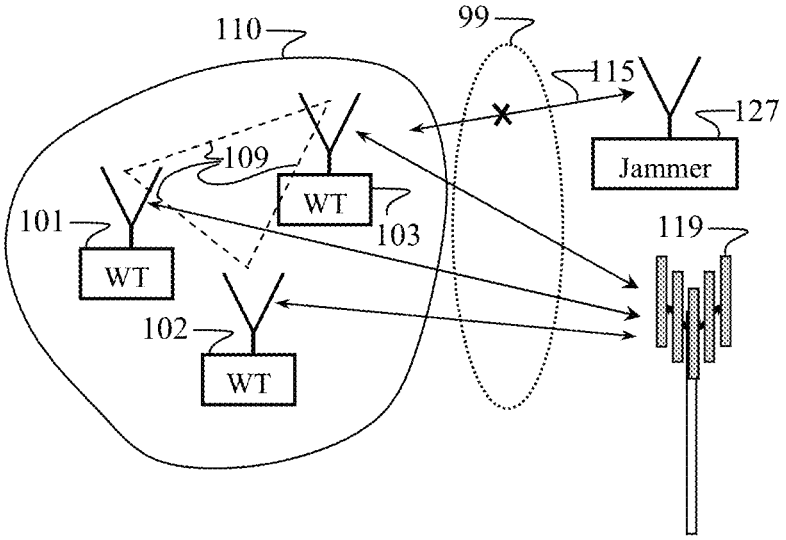


FIGURE 1G

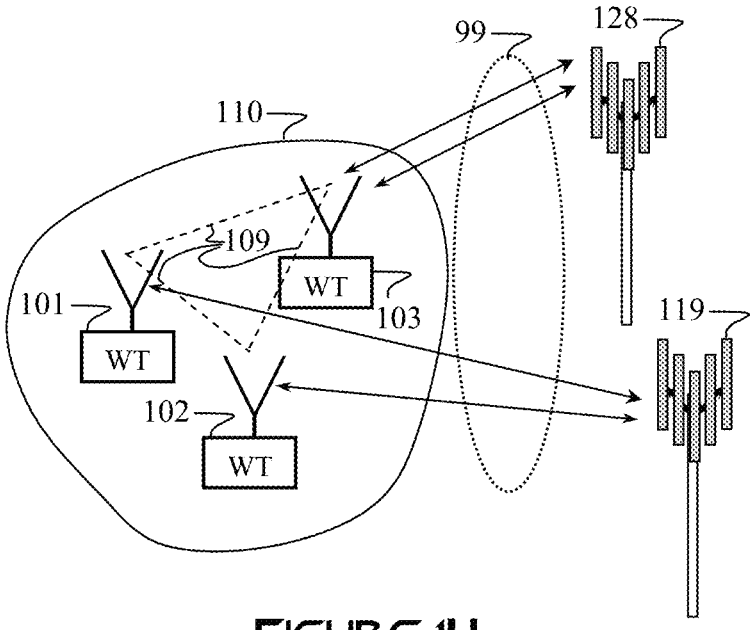


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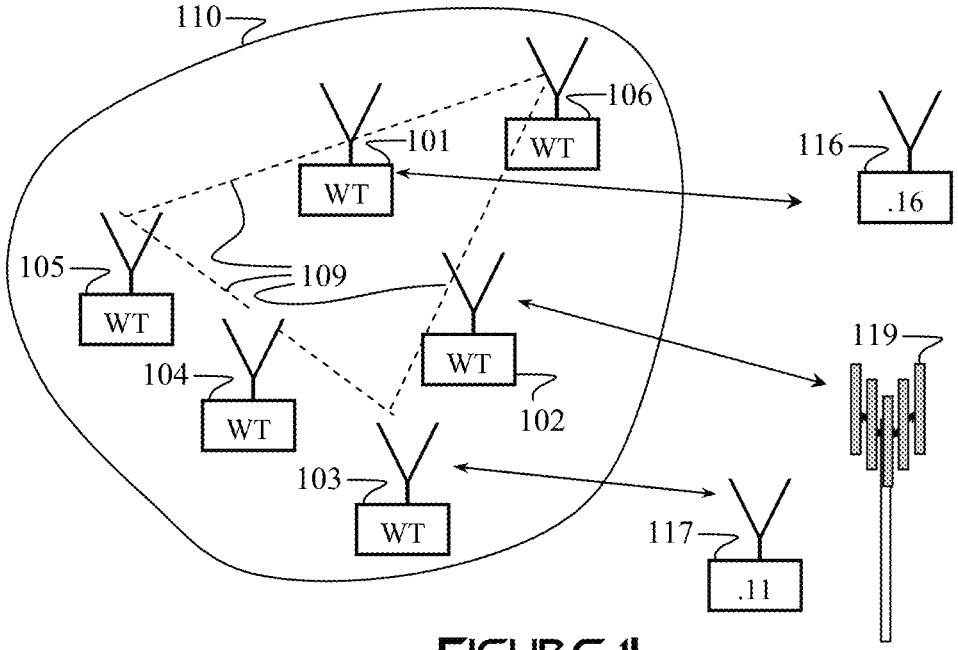


FIGURE 1I

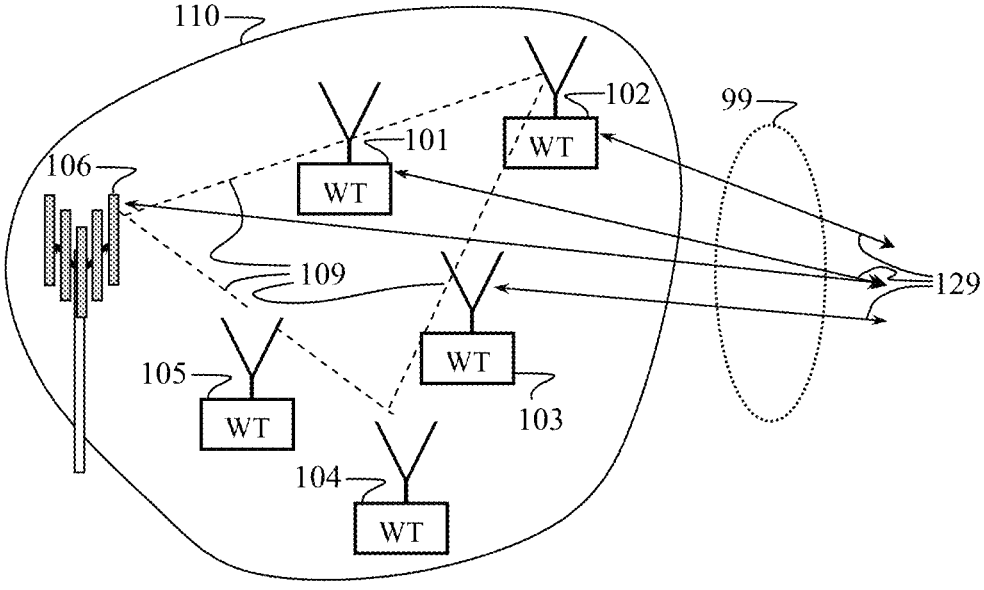


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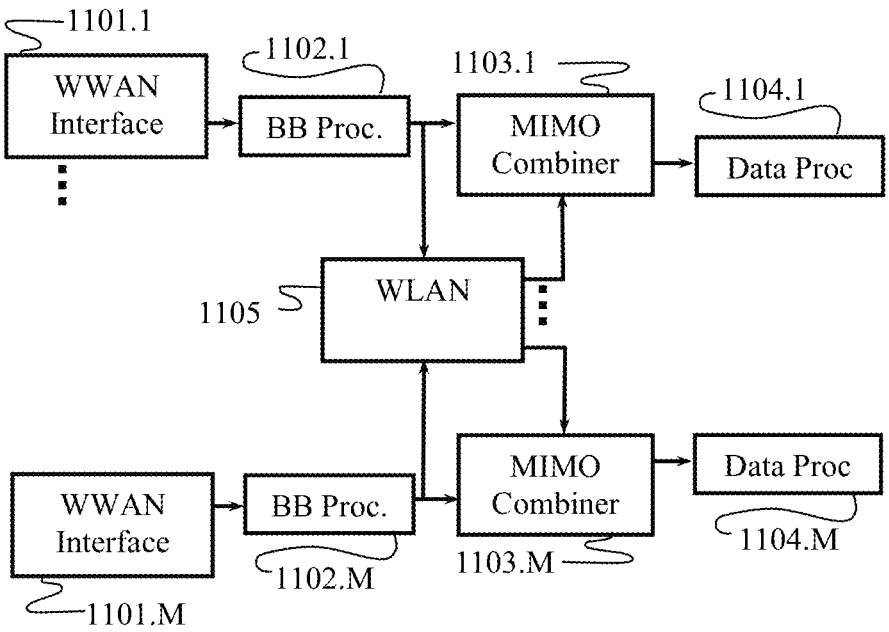


FIGURE 2A

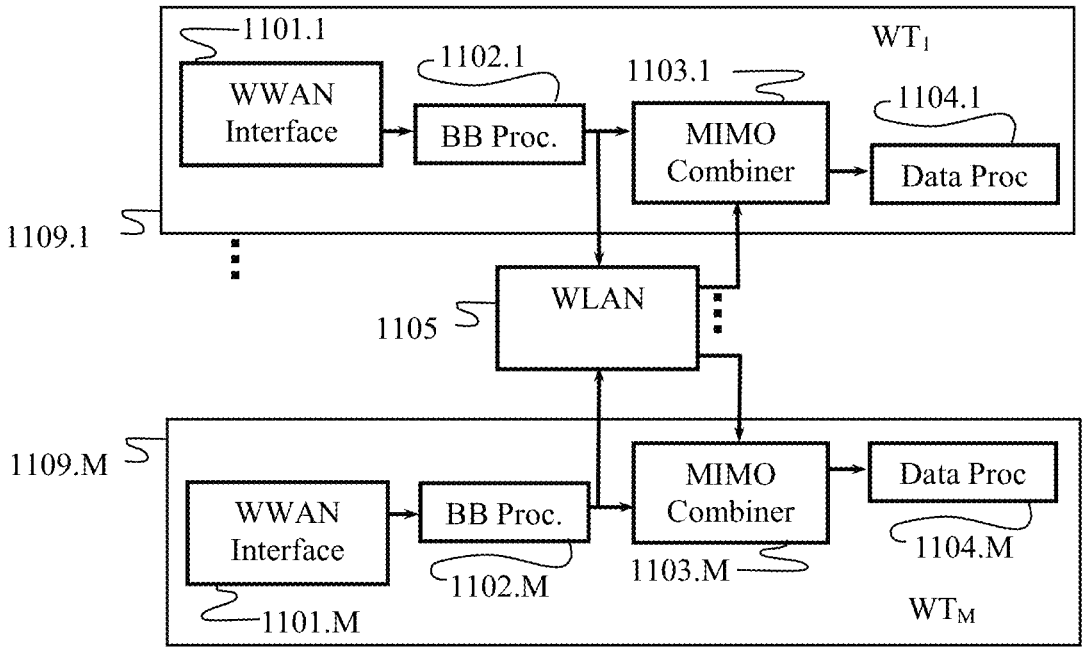


FIGURE 2B

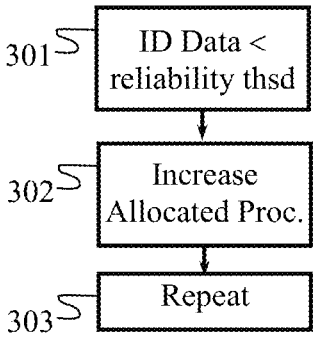


FIGURE 3A

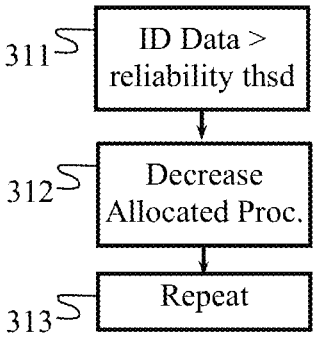


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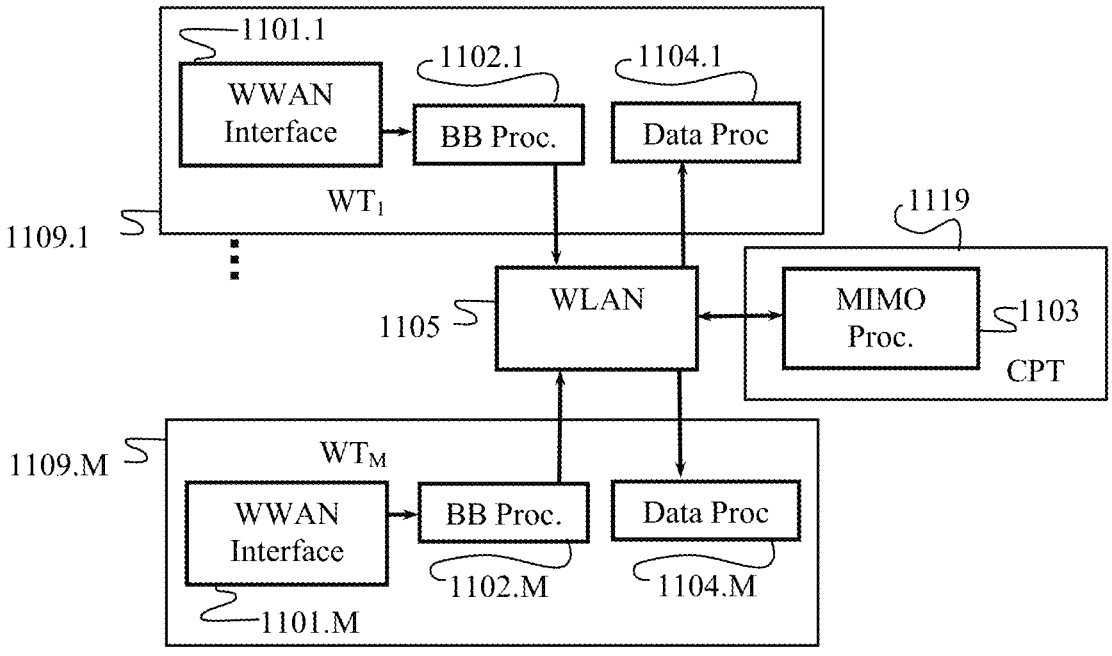


FIGURE 4A

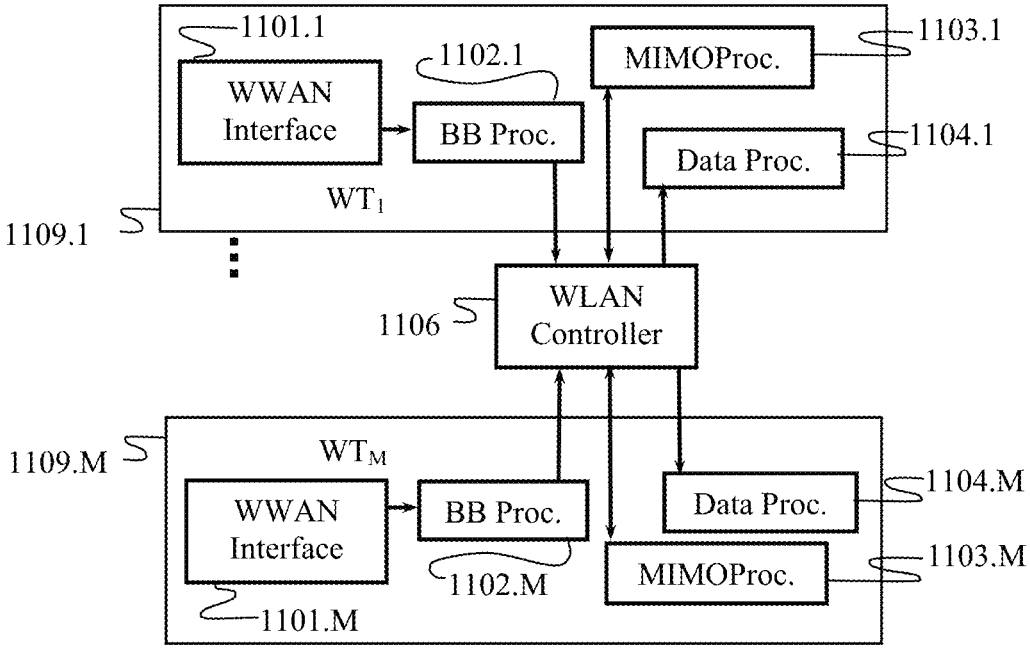


FIGURE 4B

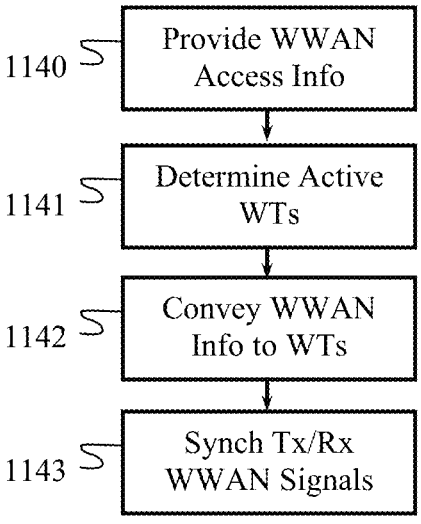


FIGURE 4C

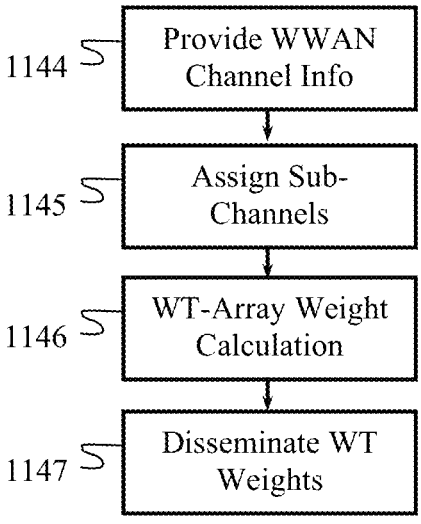


FIGURE 4D

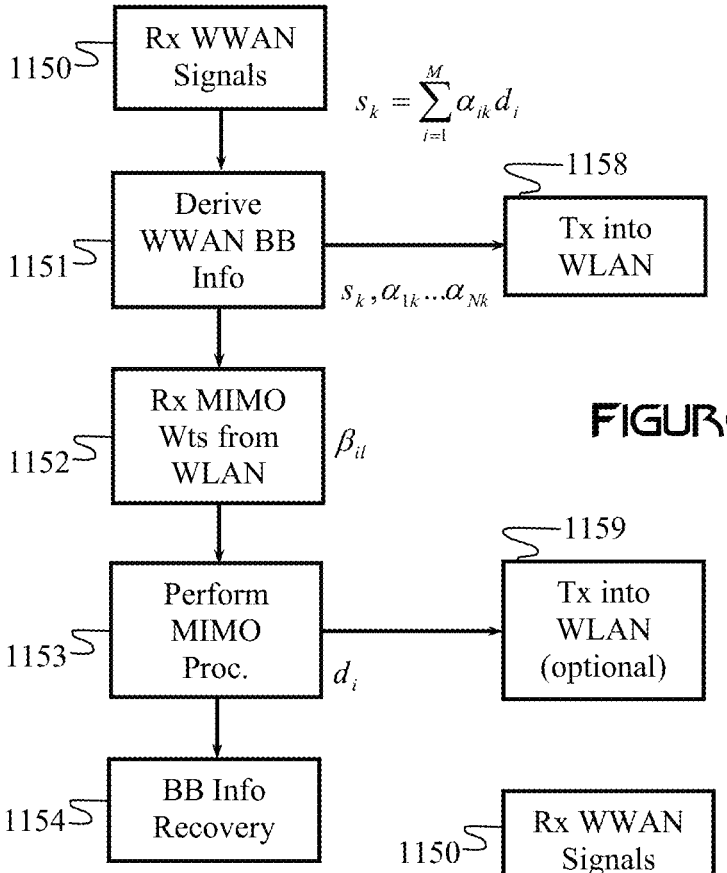


FIGURE 5A

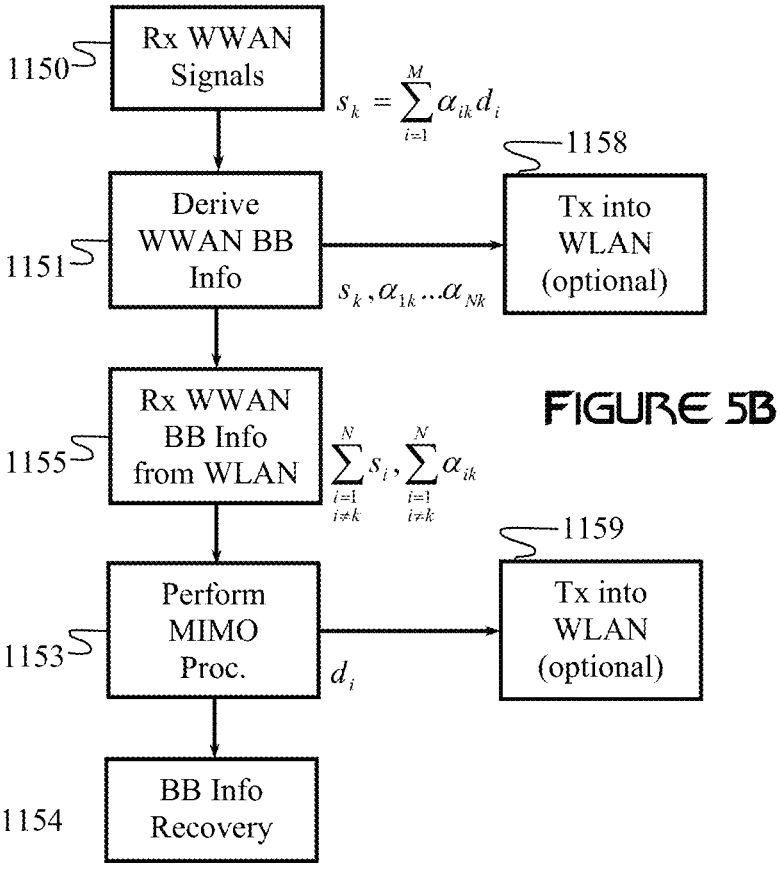


FIGURE 5B

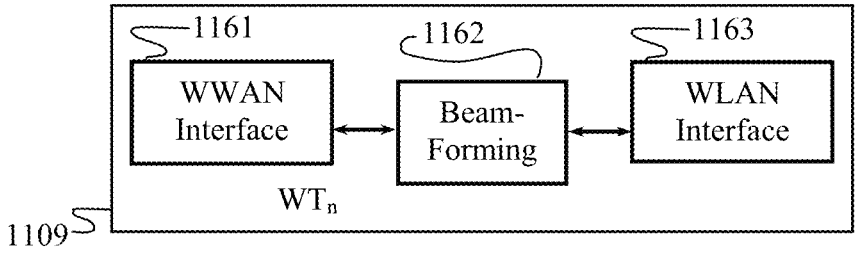


FIGURE 6A

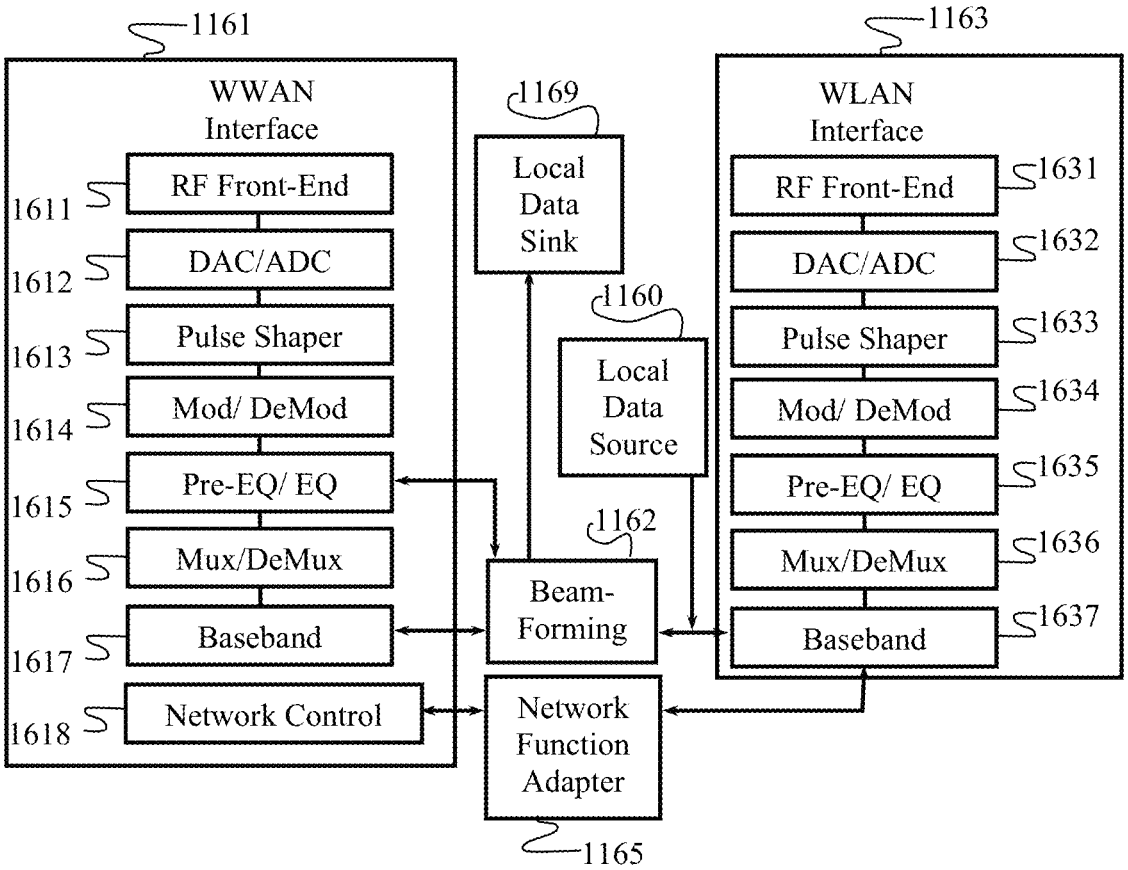


FIGURE 6B

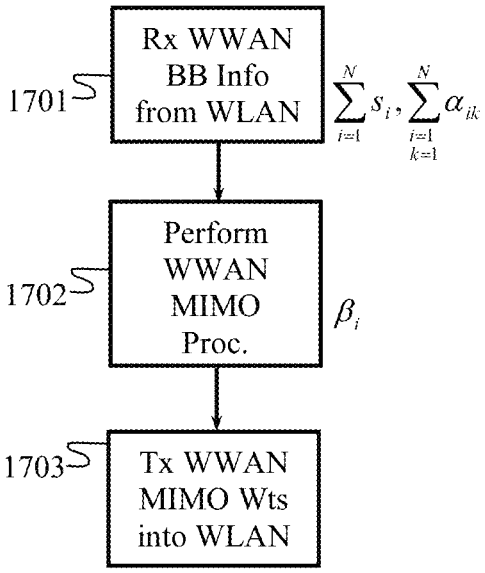


FIGURE 7A

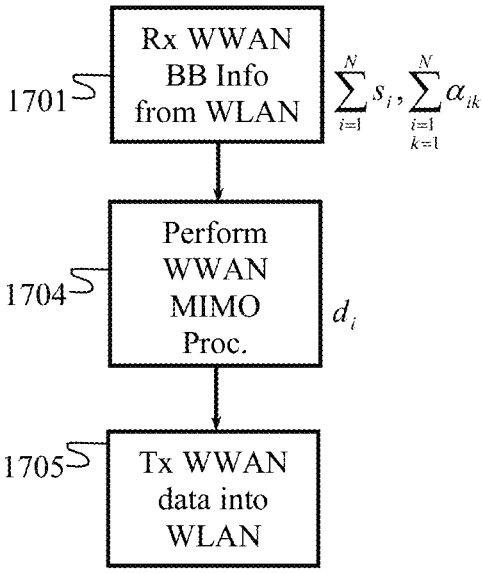


FIGURE 7B

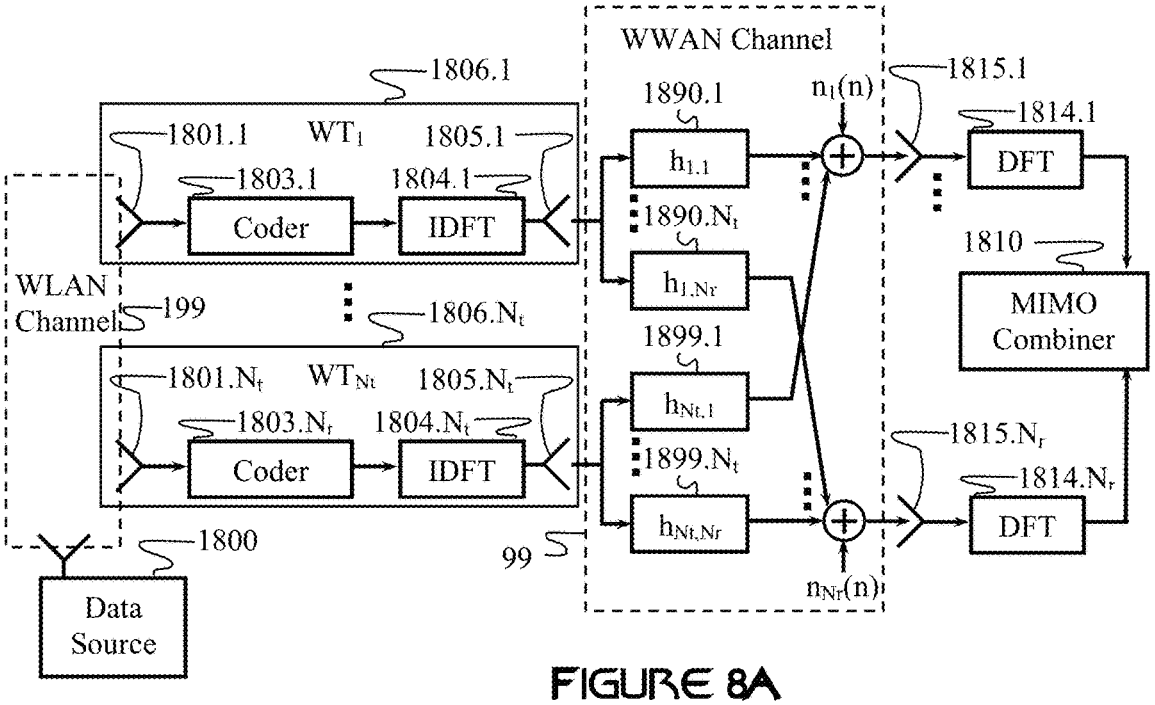


FIGURE 8A

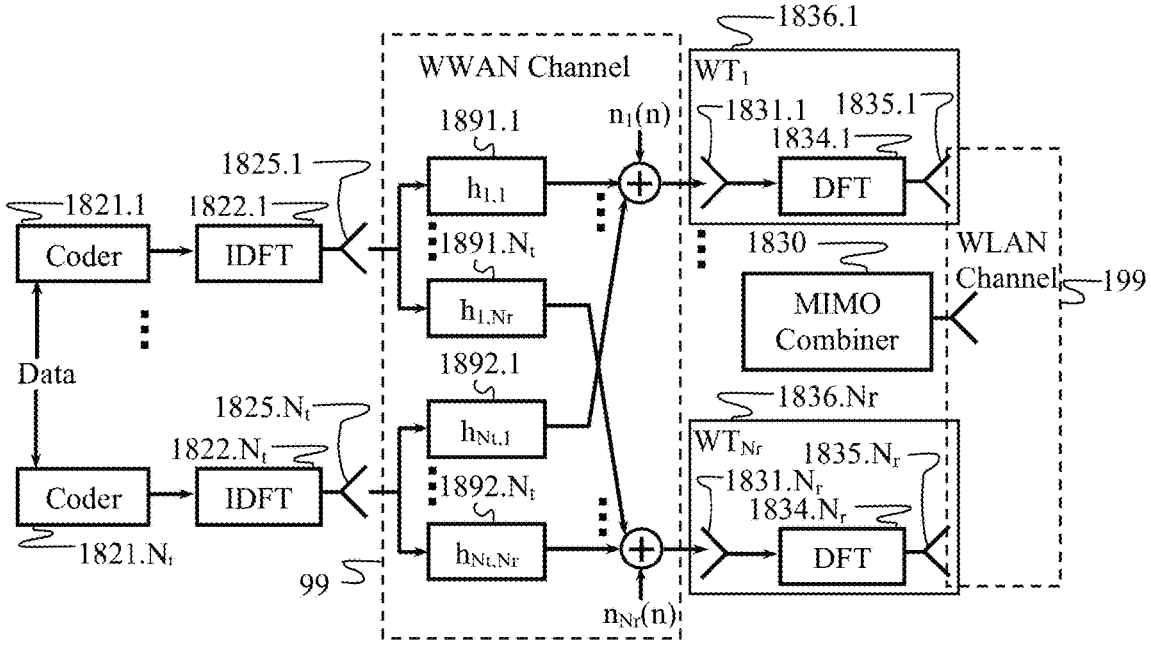


FIGURE 8B

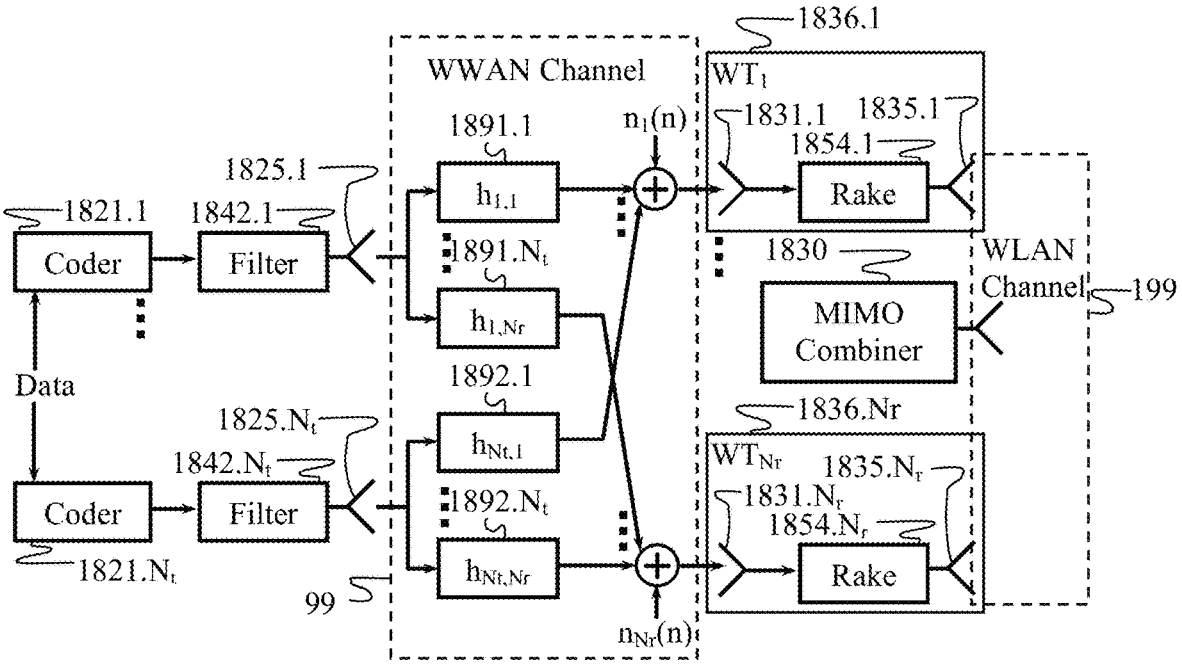

1836.1
WWAN Channel
WT1
1891.1
n1(n)
1831.1
1835.1
1854.1
1825.1
h1,1
Rake
1821.1
1842.1
Coder
Filter
1891.Nt
1830
WLAN
h1,Nr
MIMO
Channel
199
Combiner
Data
1892.1
1836.Nr
1825.Nt
WTNr
1835.Nr
1842.Nt
1831.Nr
1892.Nt
1854.Nr
Coder
Filter
hNt,1
hNt,Nr
Rake
1821.Nt
99
nNr(n)

FIGURE 8C

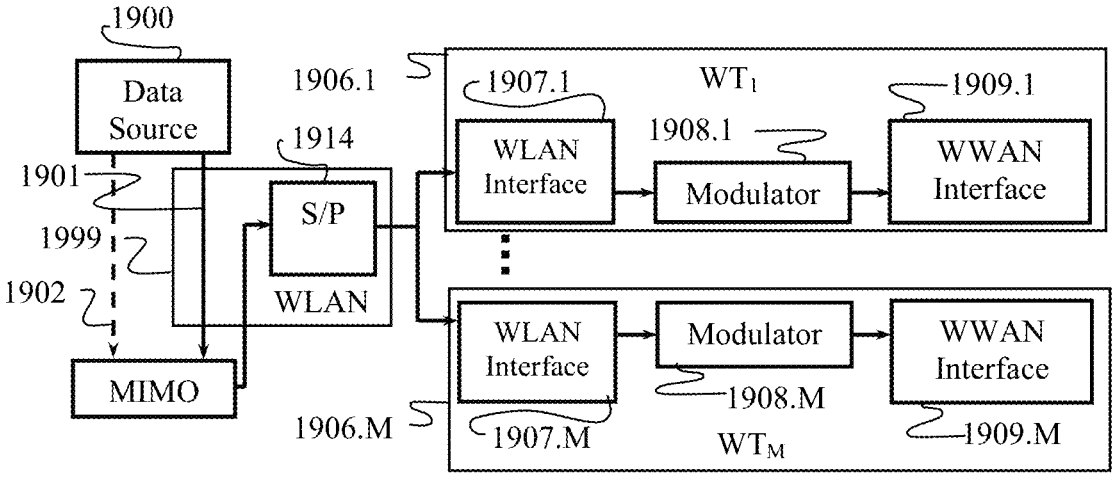


FIGURE 9A

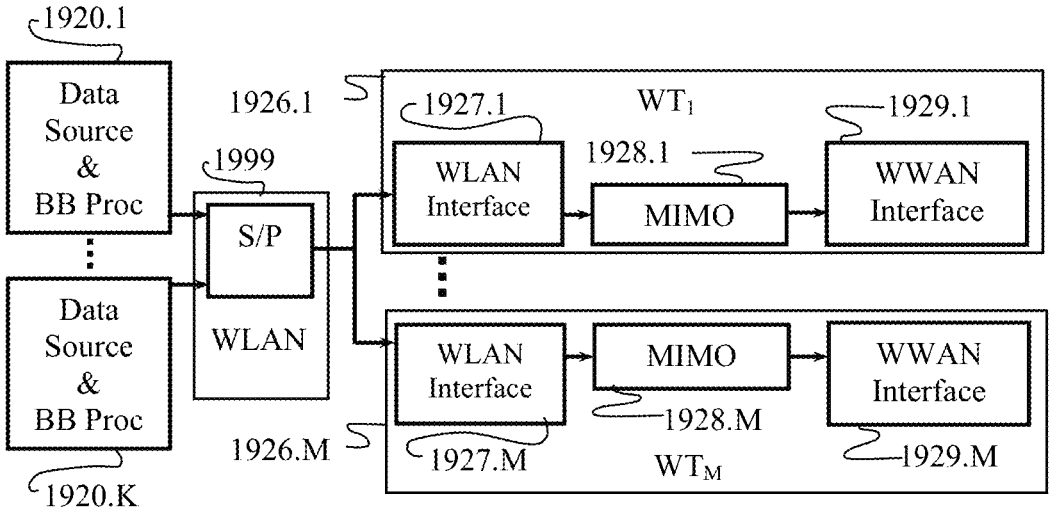


FIGURE 9B

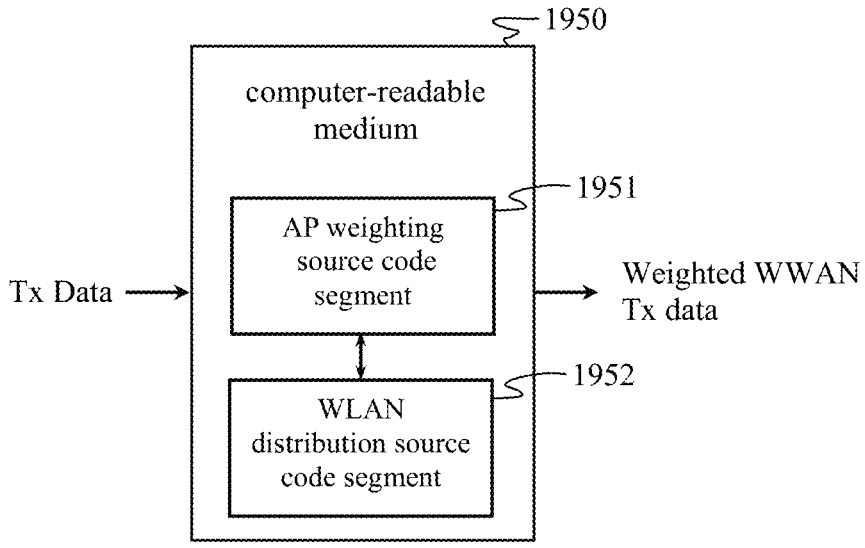


FIGURE 10A

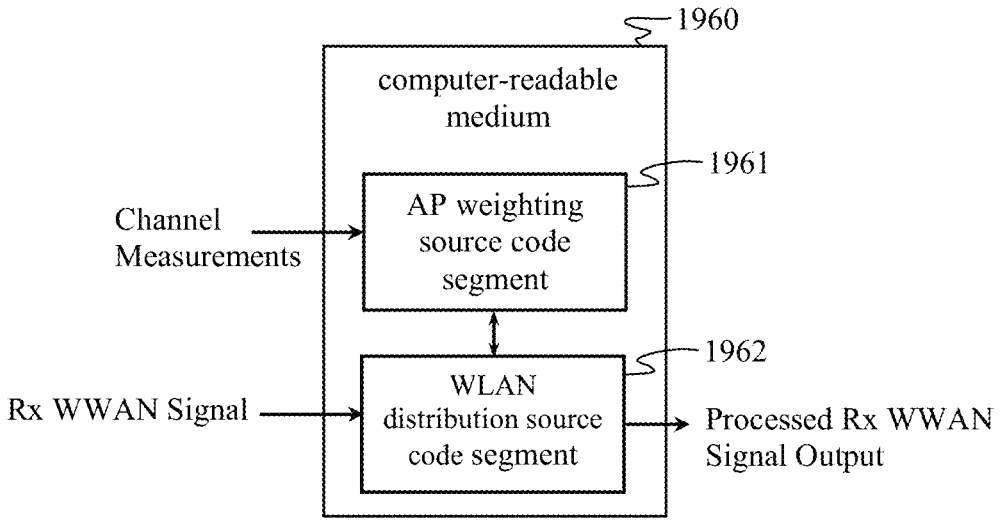


FIGURE 10B

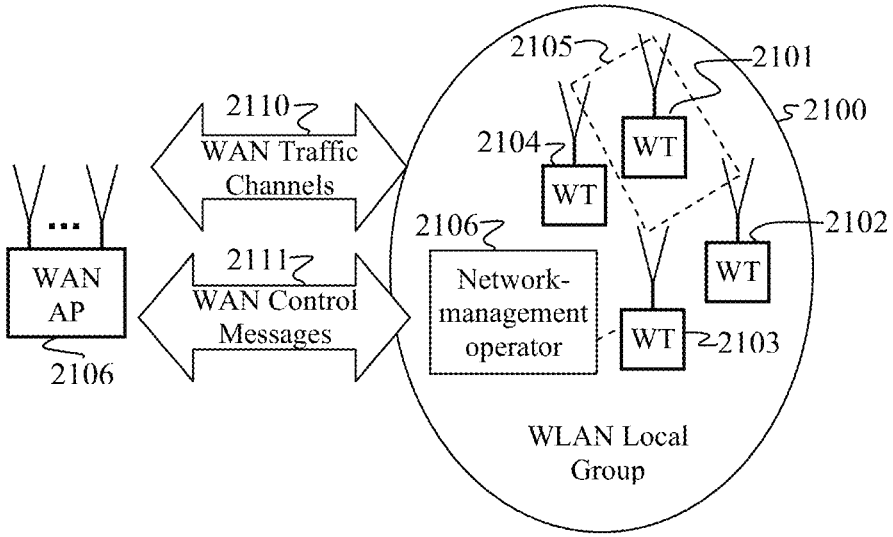

2105
2101
2100
2110
WAN Traffic Channels
2104
WT
WT
2106
2102
2111
WAN Control Messages
WAN AP
2106
Network-management operator
WT
WT
2103
WLAN Local Group

FIGURE 11

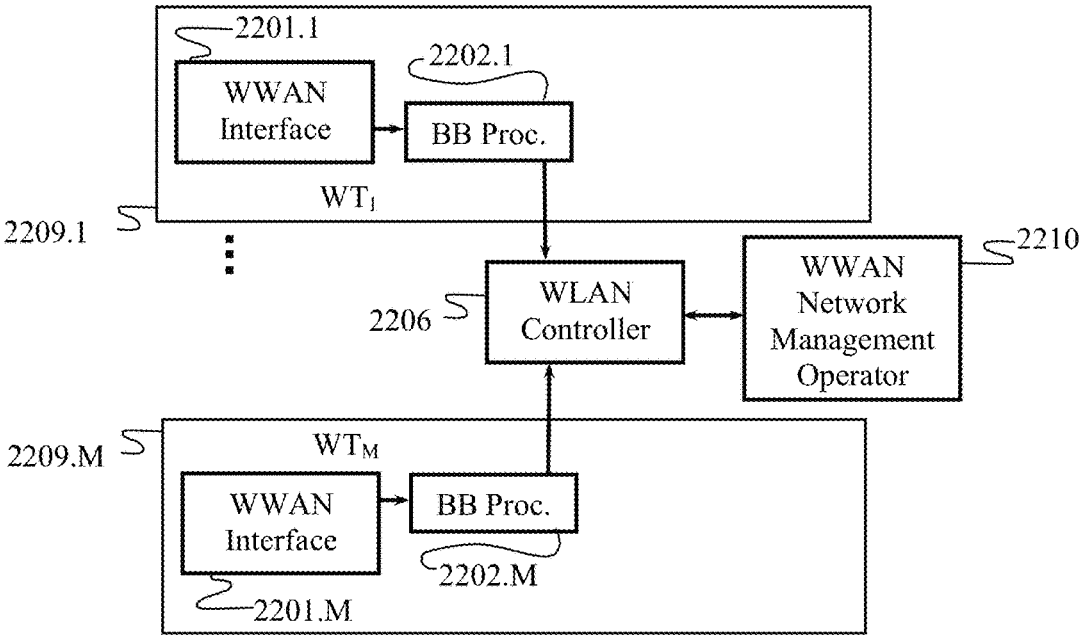


FIGURE 12

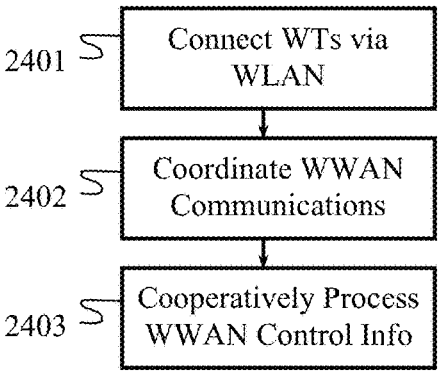


FIGURE 14

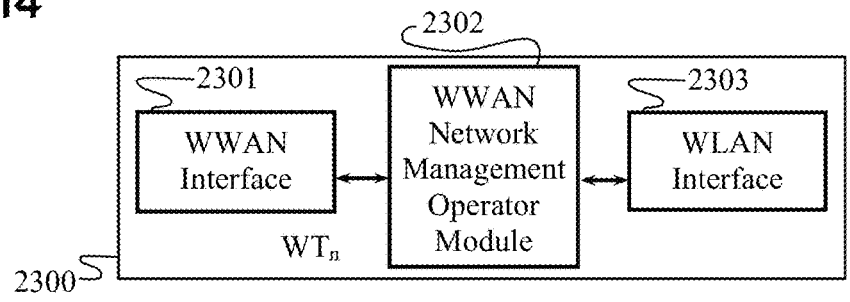


FIGURE 13

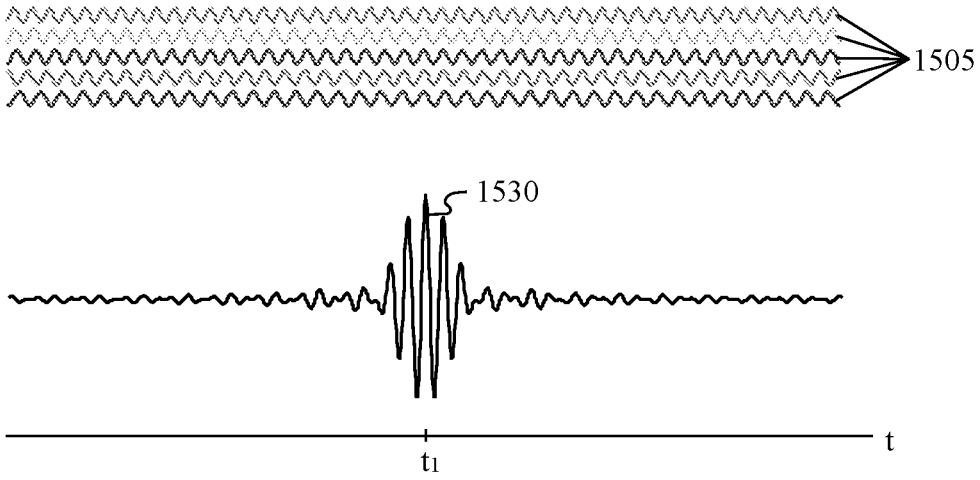


FIGURE 15

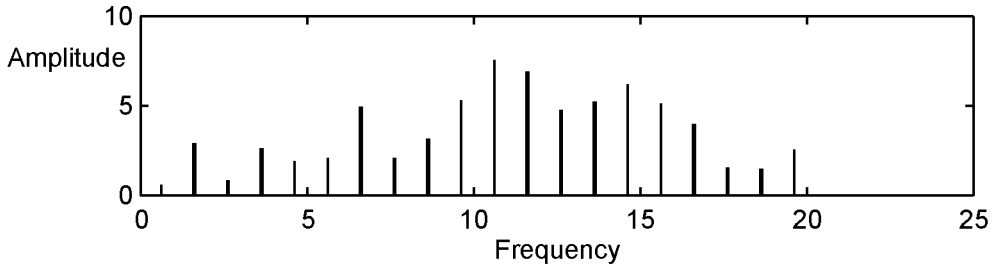


FIGURE 16A

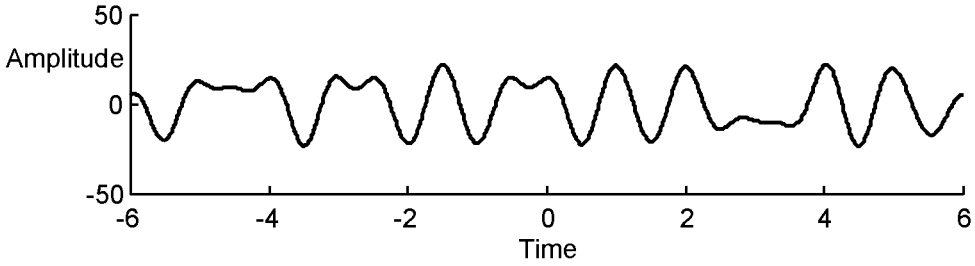


FIGURE 16B

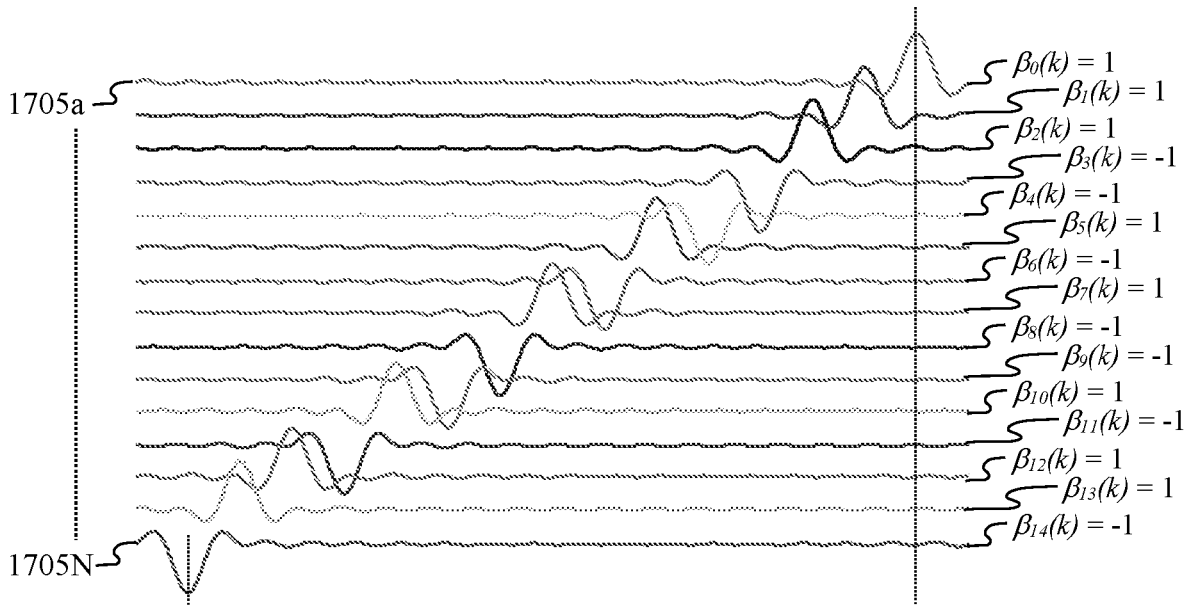


FIGURE 17A

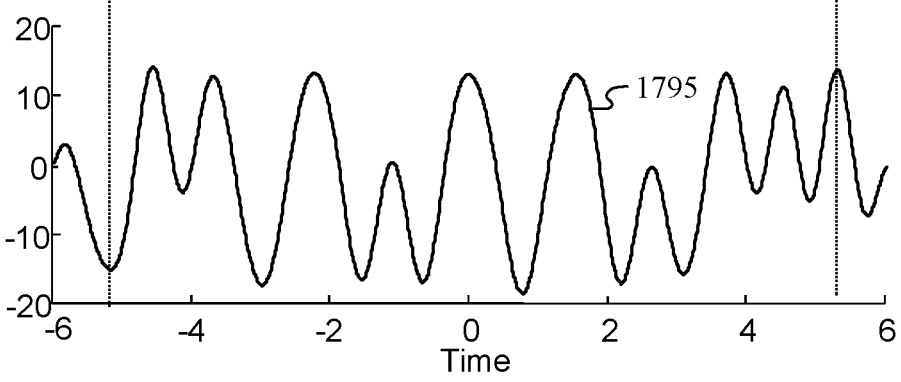


FIGURE 17B

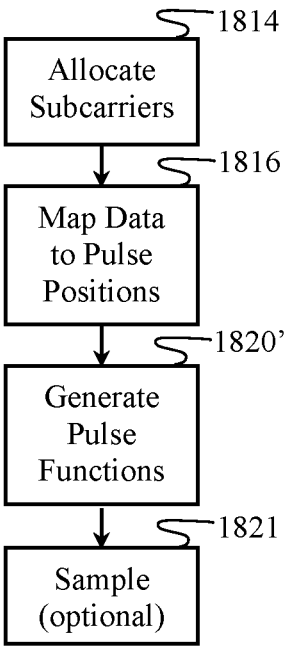


FIGURE 18A

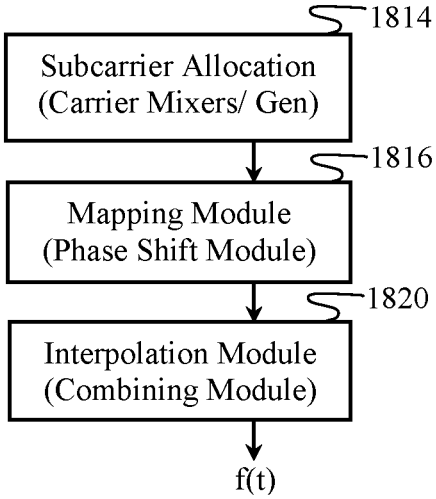


FIGURE 18B

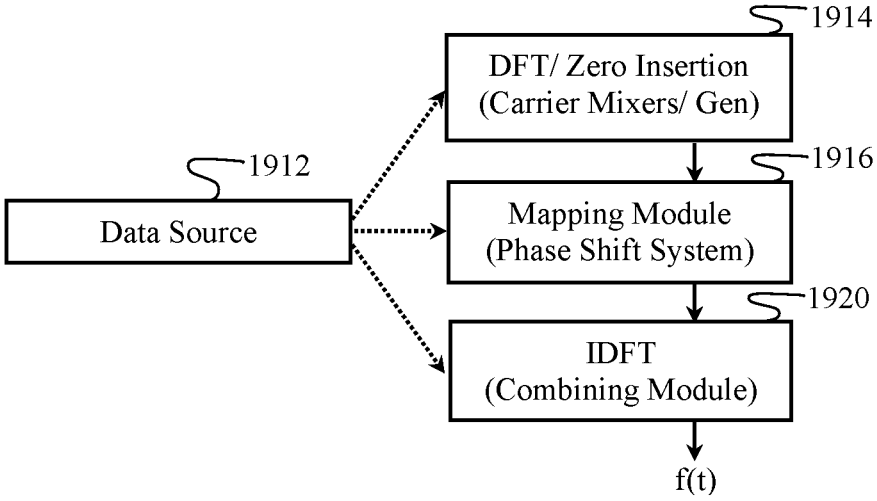


FIGURE 19

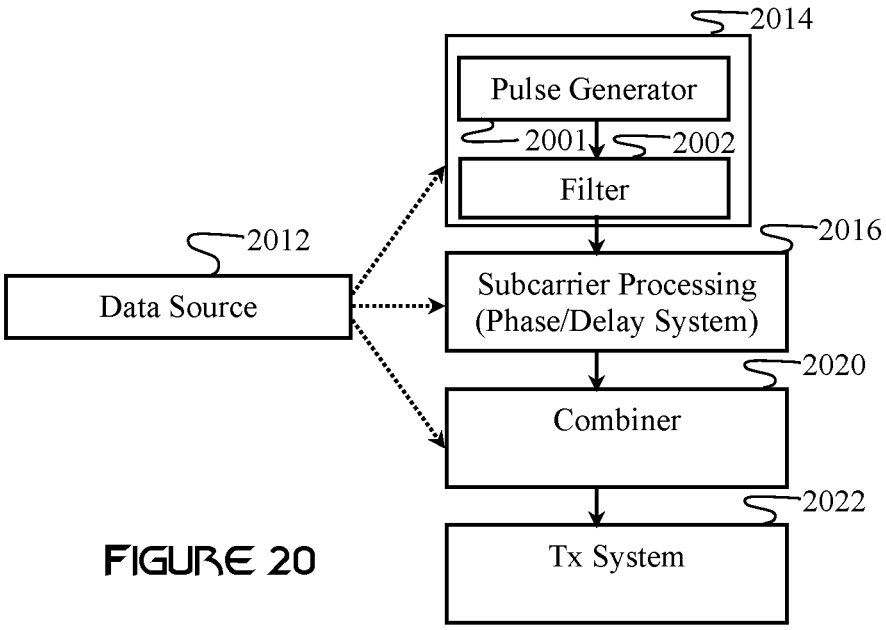


FIGURE 20

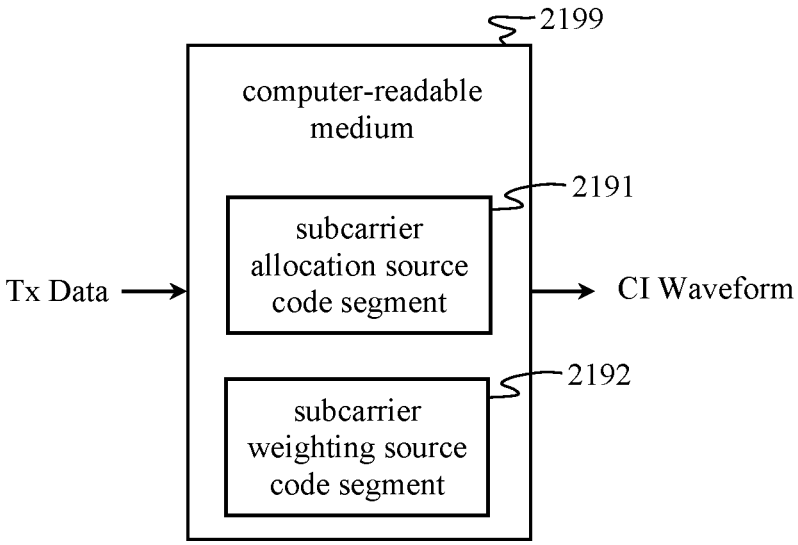


FIGURE 21

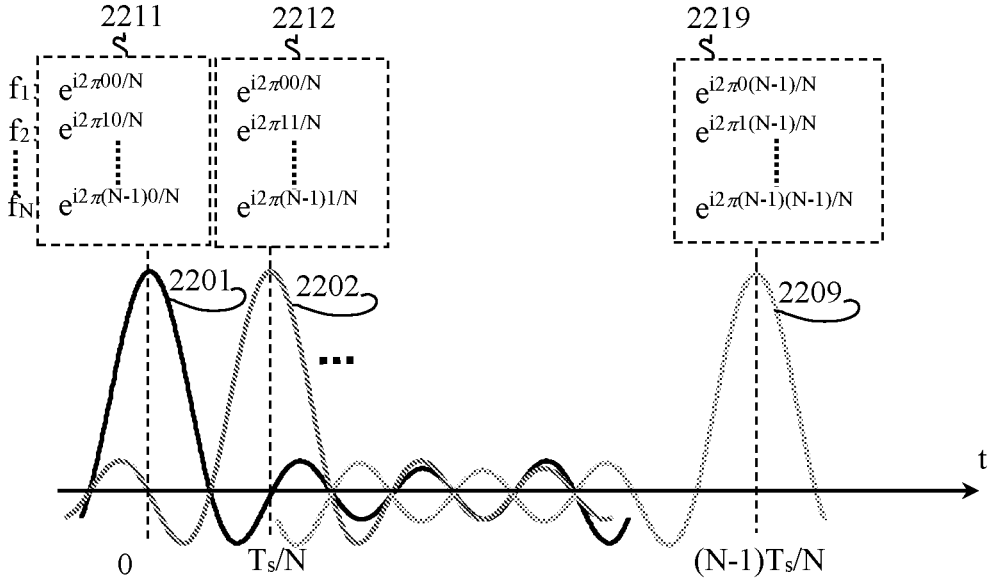


FIGURE 22A

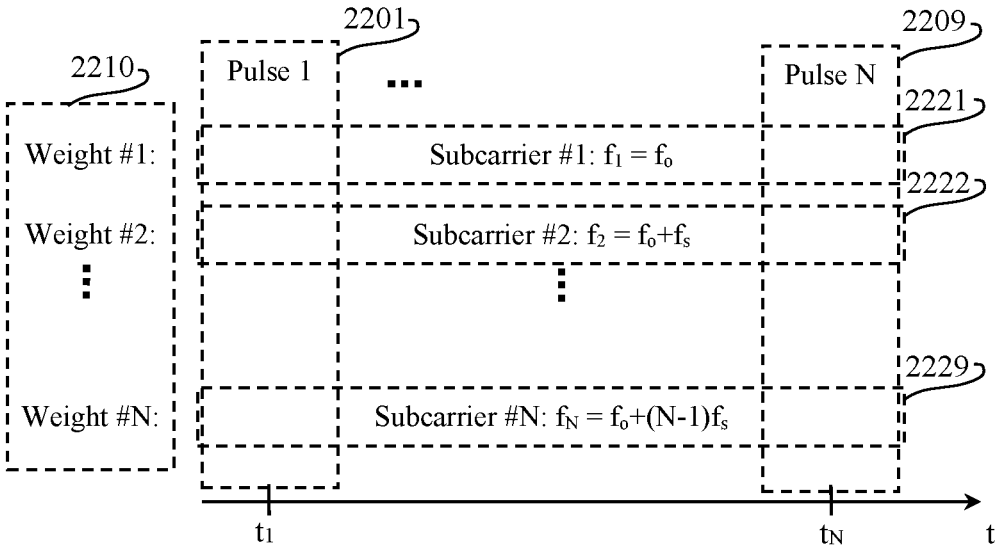


FIGURE 22B

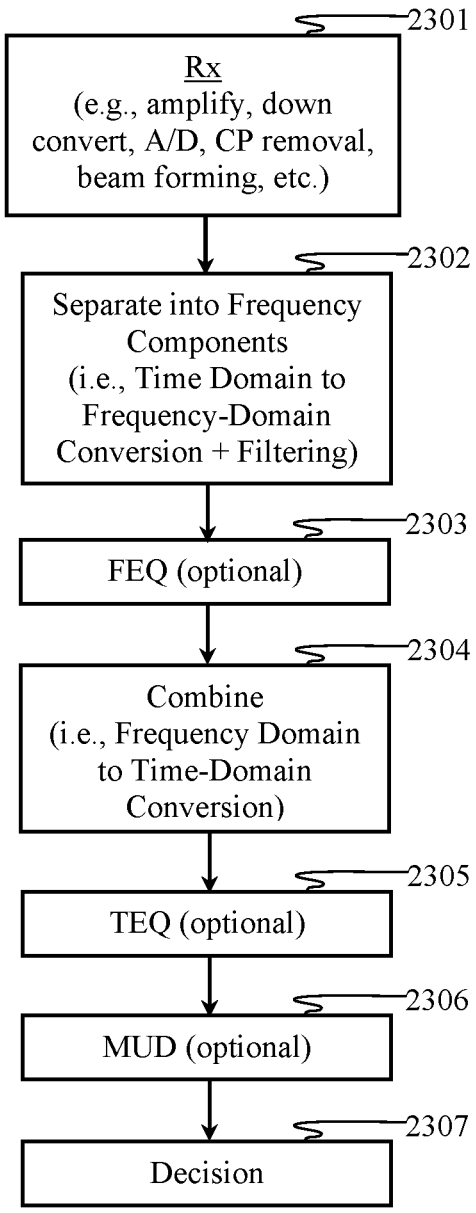


FIGURE 23A

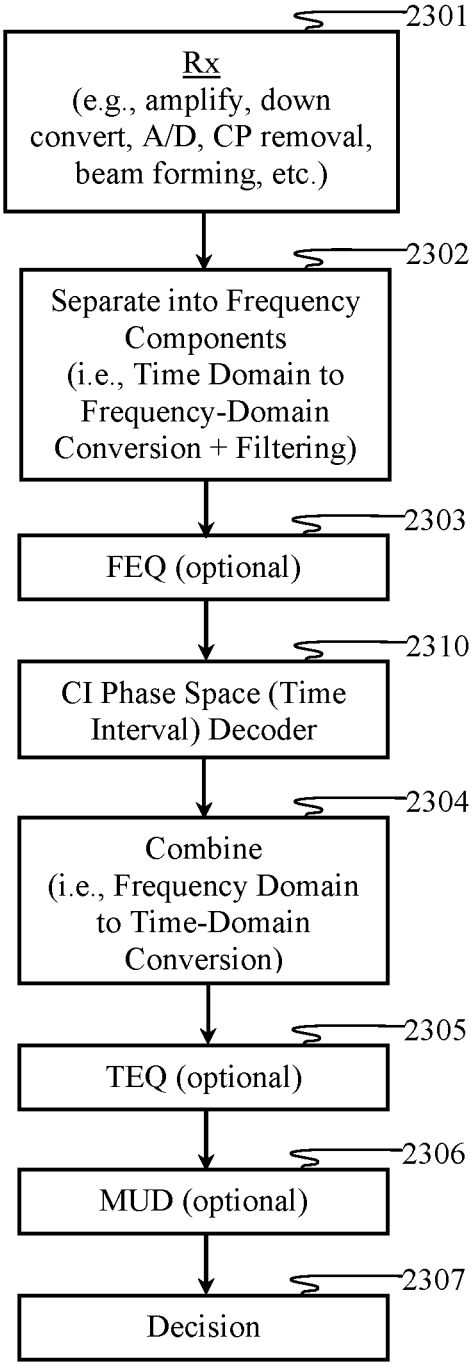


FIGURE 23B

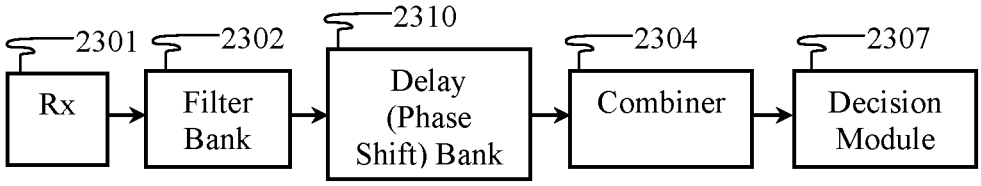


FIGURE 24A

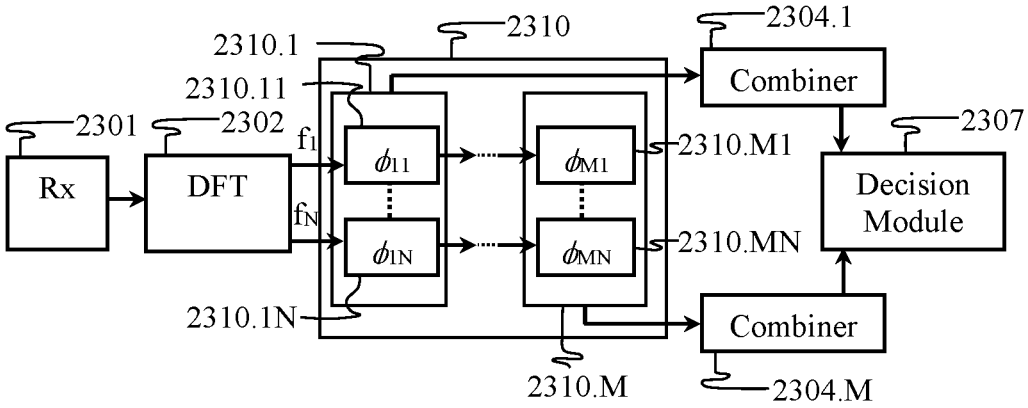


FIGURE 24B

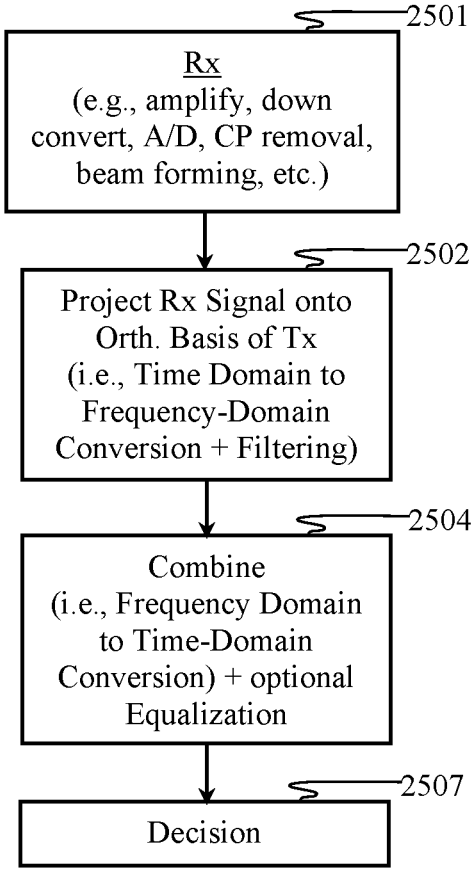


FIGURE 25A

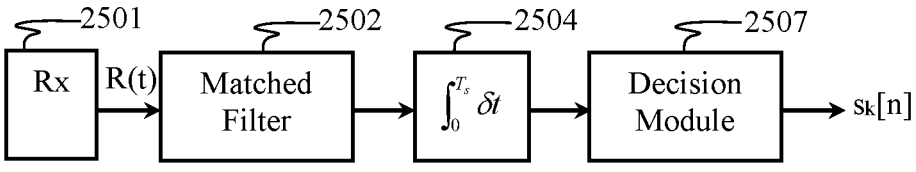


FIGURE 25B

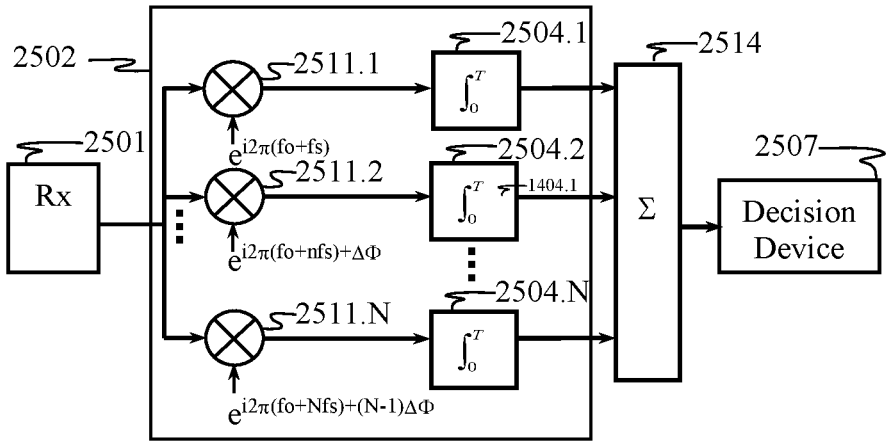


FIGURE 26A

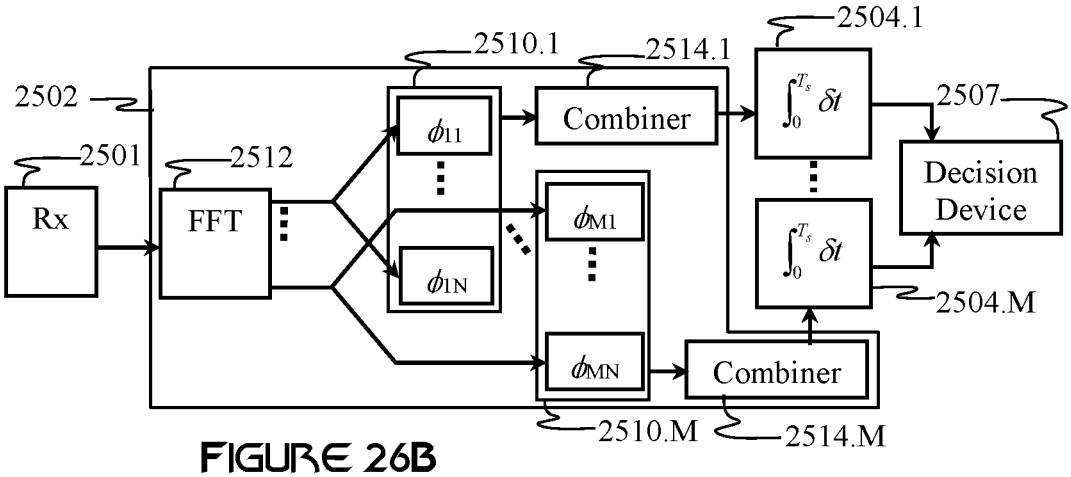


FIGURE 26B

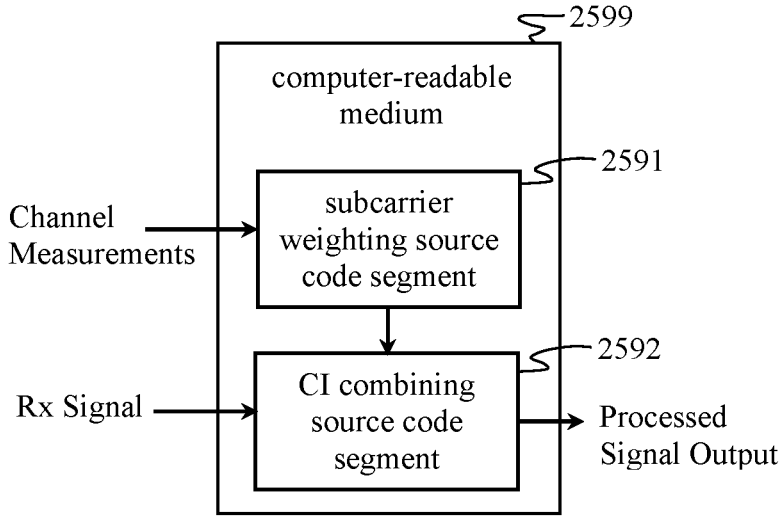


FIGURE 26C

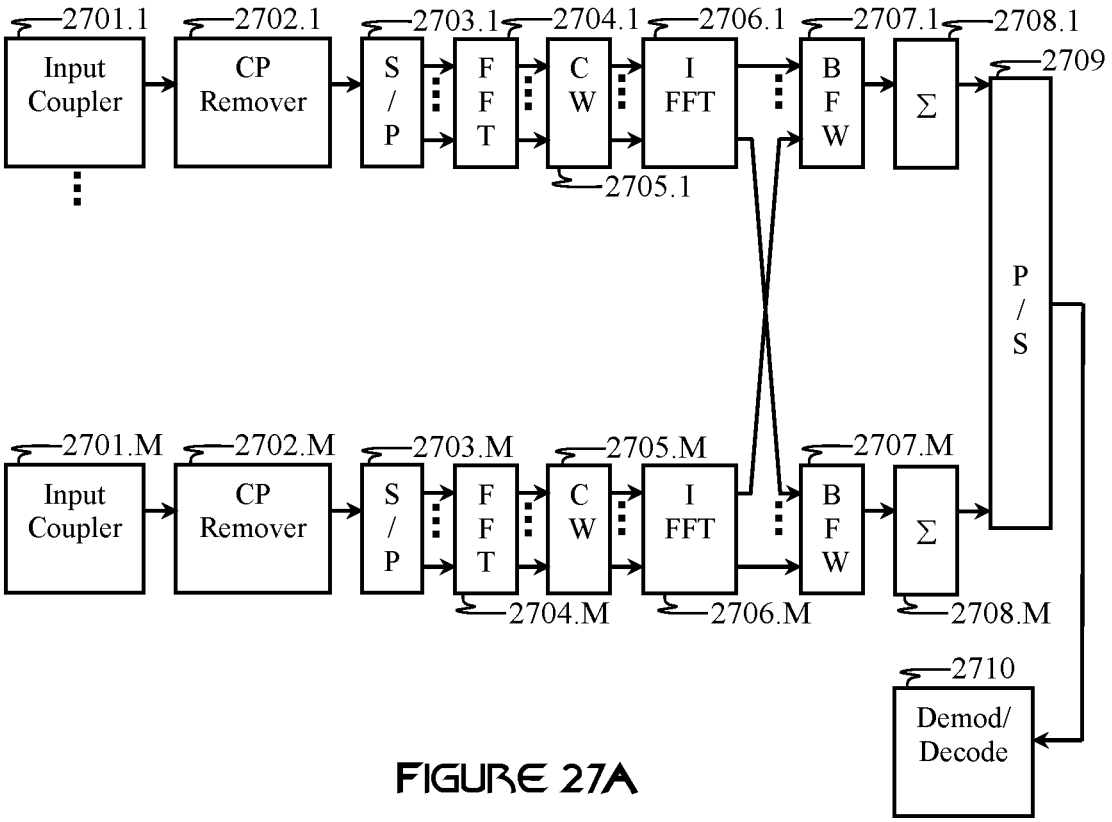


FIGURE 27A

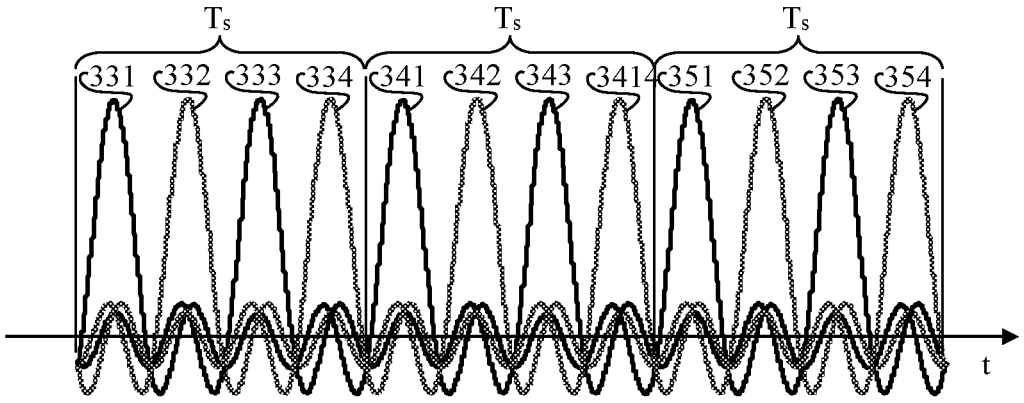


FIGURE 27B

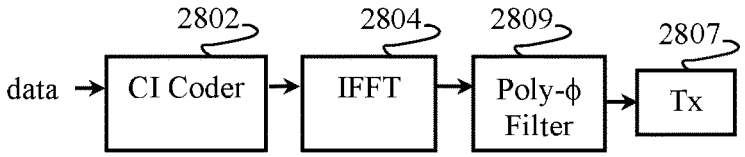


FIGURE 28A

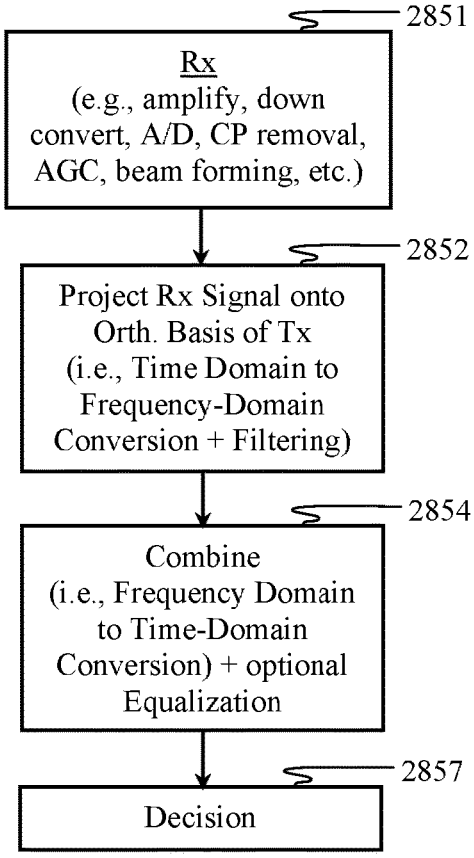


FIGURE 28B

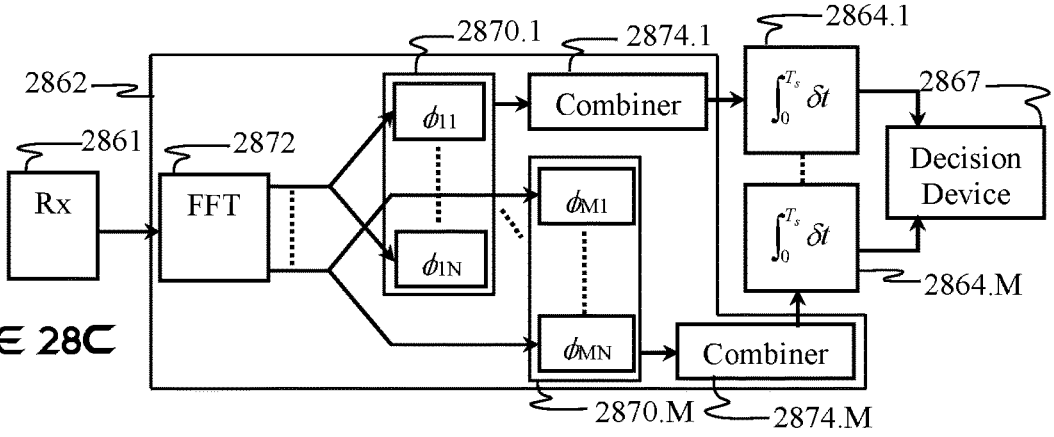


FIGURE 28C

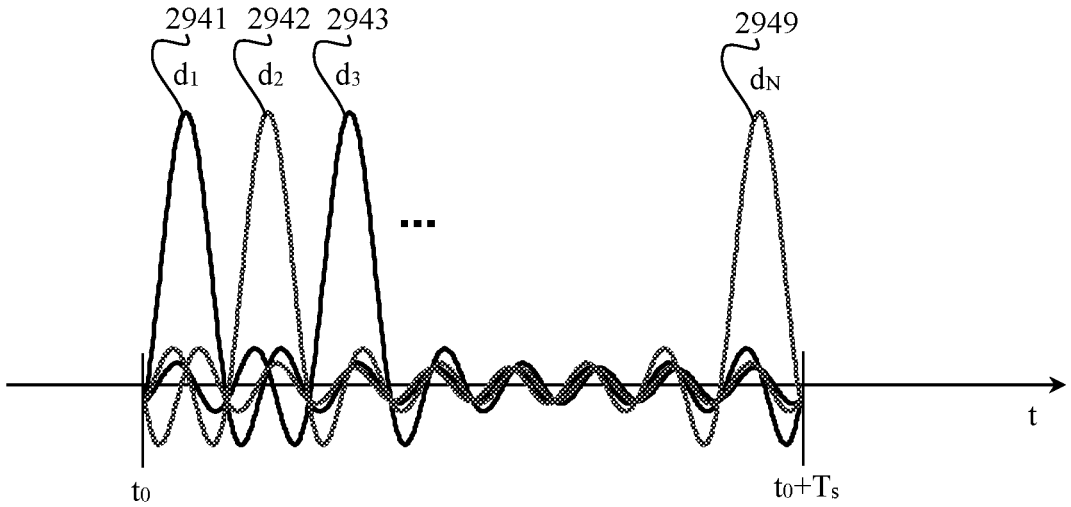


FIGURE 29A

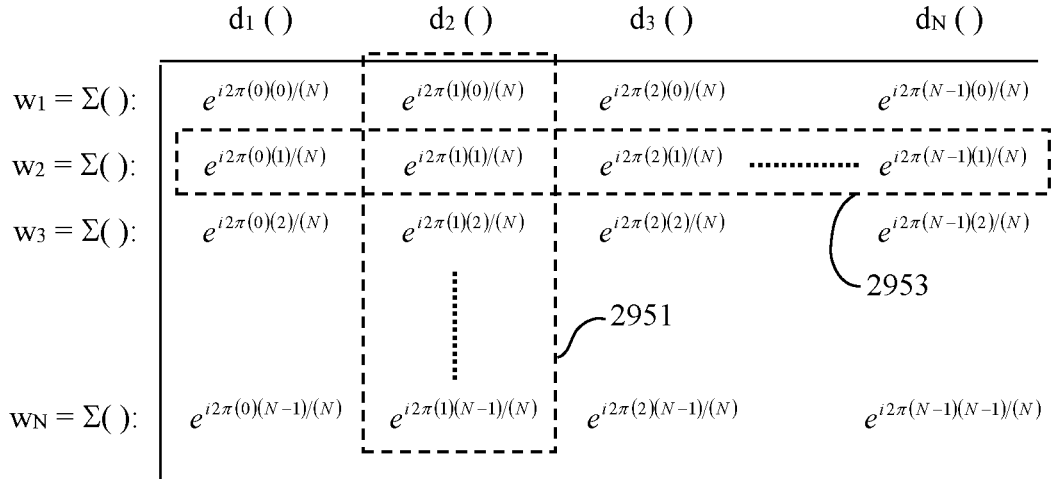


FIGURE 29B

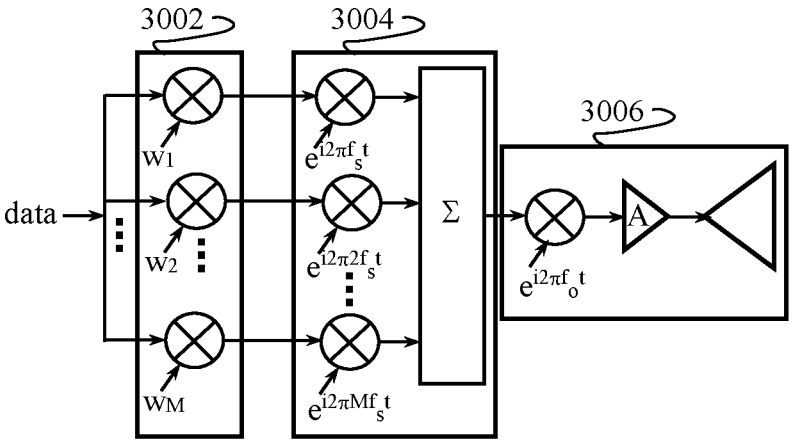


FIGURE 30A

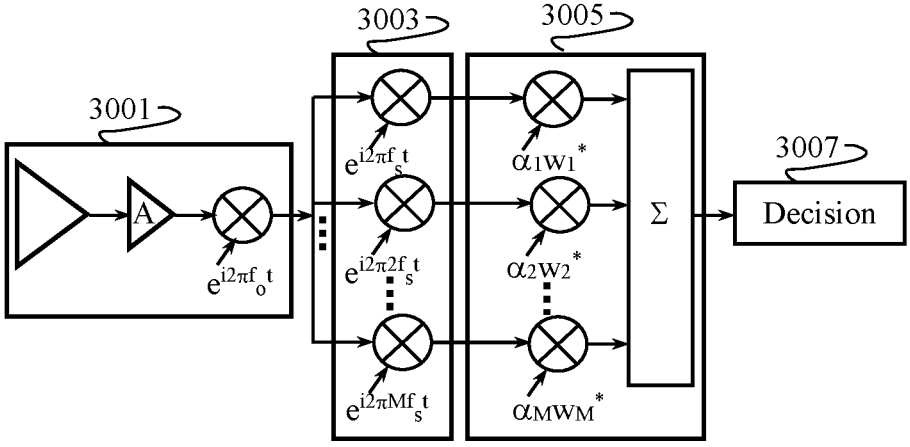


FIGURE 30B

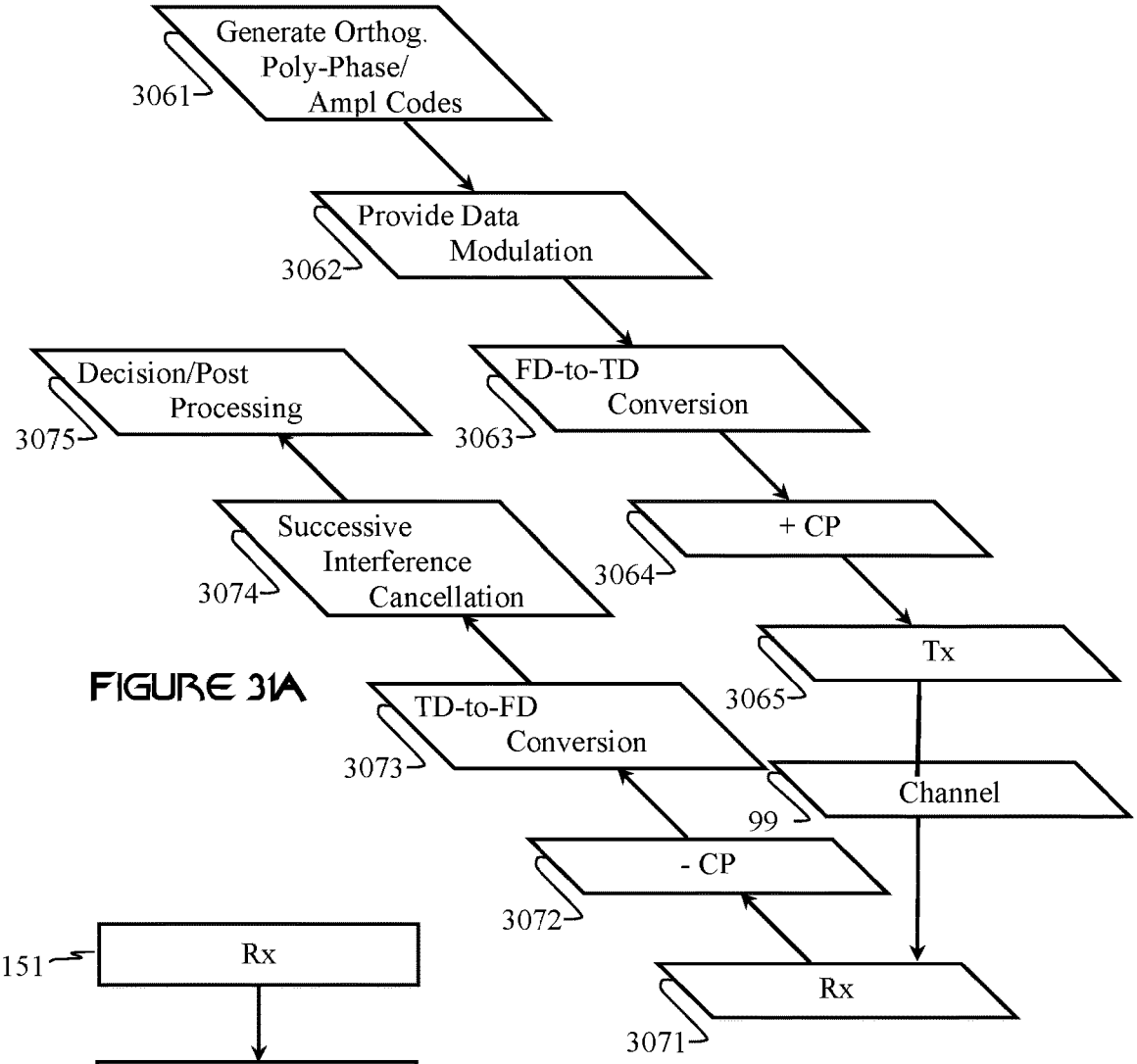


FIGURE 31A

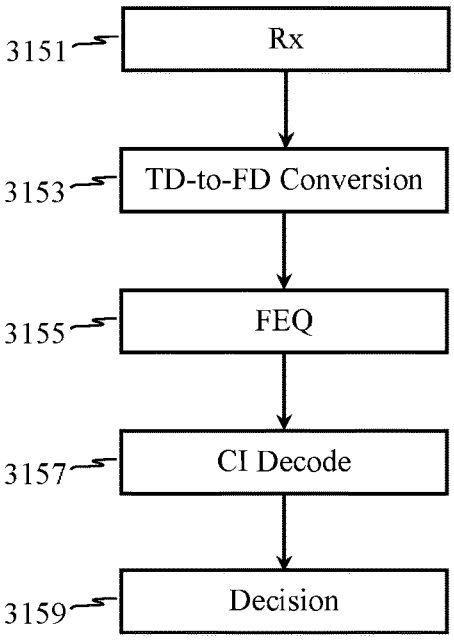


FIGURE 31B

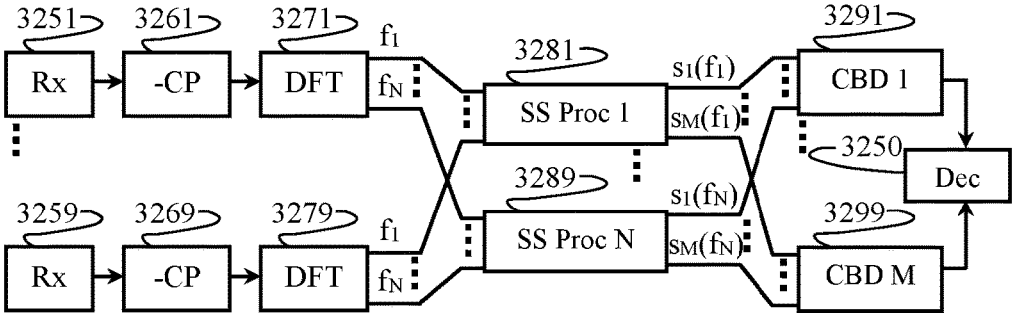


FIGURE 32

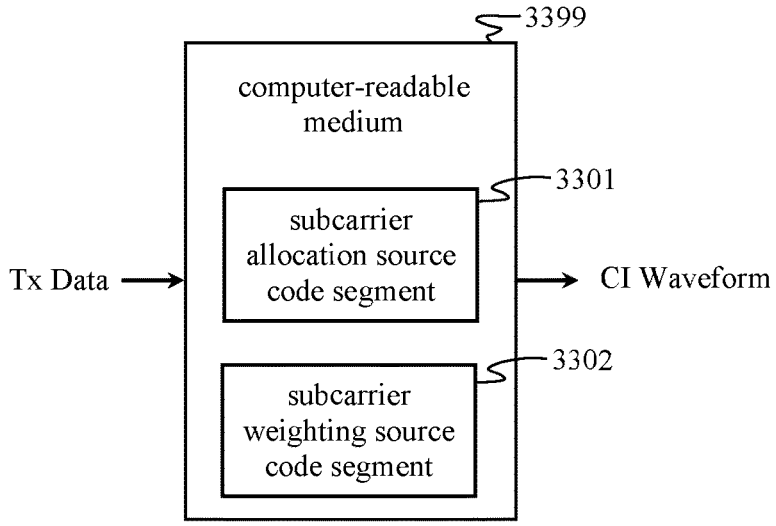


FIGURE 33A

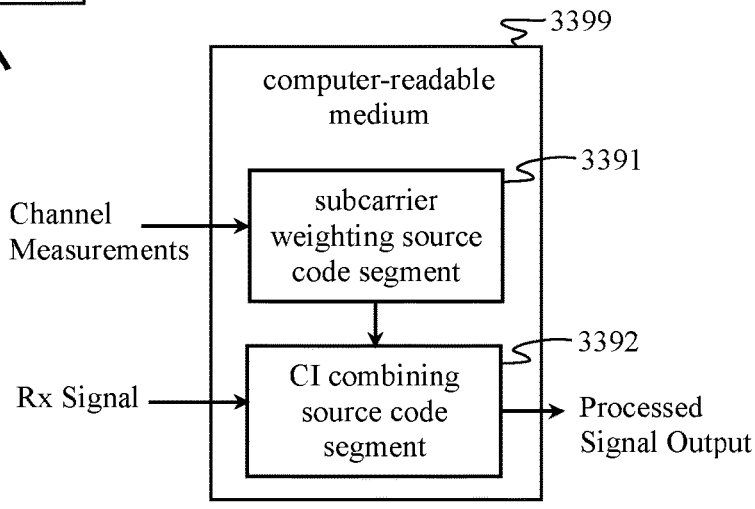


FIGURE 33B

TRANSMIT PRE-CODING

RELATED APPLICATIONS

This application is a Continuation of U.S. patent application Ser. No. 14/727,769, filed Jun. 1, 2015, which is a Continuation of U.S. patent application Ser. No. 14/276,309, filed May 13, 2014, now U.S. Pat. No. 9,048,897, which is a Continuation of U.S. patent application Ser. No. 12/545,572, filed Aug. 21, 2009, now U.S. Pat. No. 8,750,264, which is a Divisional of U.S. patent application Ser. No. 11/187,107, filed on Jul. 22, 2005, now U.S. Pat. No. 8,670,390, which claims priority to Provisional Appl. No. 60/598,187, filed Aug. 2, 2004, all of which are incorporated by reference in their entireties.

BACKGROUND

I. Field

Disclosed aspects relate generally to antenna-array processing and ad-hoc networking, and particularly to providing cooperative signal processing between a plurality of wireless terminal devices, such as to improve network access.

II. Description

Wireless data service is an emerging market with high growth potential. However, market growth requires higher bandwidth and better coverage than cellular technologies can provide. Furthermore, state-of-the-art wireless network technologies are mainly focused on the server side, rather than using mobile wireless terminals to extend the network infrastructure.

A peer-to-peer mode of communication is expected to offer distinct performance benefits over the conventional cellular model, including better spatial-reuse characteristics, lower energy consumption, and extended coverage areas. The key advantage of the peer-to-peer network model is the increase in spatial reuse due to its short-range transmissions. Although peer-to-peer networking shows some promise, there are significant drawbacks that prevent conventional peer-to-peer networks from being a technically and commercially viable solution.

Recent analyses of multi-hop networks compared to cellular networks have indicated that the spatial reuse improvement in the peer-to-peer network model does not translate into greater throughput. Rather, the throughput is lower than that observed in the cellular network model. This observation is explained in three parts:

- Multi-hop Routes: Although the spatial reuse is increased, since a flow traverses multiple hops in the peer-to-peer network model, the end-to-end throughput of a flow, while directly proportional to the spatial reuse, is also inversely proportional to the hop-length. Moreover, since the expected hop-length in a dense network is of the order of $O(\sqrt{n})$, a tighter bound on the expected per-flow throughput is $O(1/\sqrt{n})$. While this bound is still higher than that of the dense cellular network model ($O(1/n)$), the following two reasons degrade the performance even more.
- Base-Station Bottleneck: The degree of spatial reuse and expected per-flow throughput of the peer-to-peer network model is valid for a network where all flows have destinations within the same cell. In this case, the base station is the destination for all flows (e.g., it is the destination of the wireless path). Thus, any increase in spatial reuse cannot be fully realized as the channel around the base-station becomes a bottleneck and has to be shared by all the flows in the network. Note that this is not an artifact of the single-channel model. As long as the resources around the base-station are shared by all the flows in the network (irrespective of the number of channels), the performance of the flows will be limited to that of the cellular network model.
- Protocol Inefficiencies: The protocols used in the cellular network model are both simple and centralized, with the base station performing most of the coordination. Cellular protocols operate over a single hop, leading to very minimal performance degradation because of protocol inefficiencies. However, in the peer-to-peer network model, the protocols (such as IEEE 802.11 and DSR) are distributed, and they operate over multiple hops. The multi-hop path results in more variation in latency, losses, and throughput for TCP. These inefficiencies (which arise because of the distributed operation of the medium access and routing layers) and the multi-hop operation at the transport layer translate into a further degraded performance.

Similarly, antenna-array processing has demonstrated impressive improvements in coverage and spatial reuse. Array-processing systems typically employ multiple antennas at base stations to focus transmitted and received radio energy and thereby improve signal quality. In cellular communications, improvements in signal quality lead to system-wide benefits with respect to coverage, service quality and, ultimately, the economics of cellular service. Furthermore, the implementation of antenna arrays at both ends of a communication link can greatly increase the capacity and performance benefits via Multiple Input Multiple Output (MIMO) processing. However, power, cost, and size constraints typically make the implementation of antenna arrays on mobile wireless terminals, such as handsets or PDAs, impractical.

In cooperative diversity, each wireless terminal is assigned an orthogonal signal space relative to the other terminals for transmission and/or reception. In particular, both multiplexing and multiple access in cooperative diversity are orthogonal. In antenna-array processing, either or both multiplexing and multiple access are non-orthogonal. Specifically, some form of interference cancellation is required to separate signals in an array-processing system because transmitted and/or received information occupies the same signal space.

Applications and embodiments relate to ad-hoc networking and antenna-array processing. Embodiments may address general and/or specific needs that are not adequately serviced by the prior art, including (but not limited to) improving network access (e.g., enhancing range, coverage, throughput, connectivity, and/or reliability). Applications of certain embodiments may include tactical, emergency response, and consumer wireless communications. Due to the breadth and scope of the present invention, embodiments may be provided for achieving a large number of objectives and applications, which are too numerous to list herein. Therefore, only some of the objects and advantages of specific embodiments of the present invention are discussed in the Summary and in the Detailed Description.

SUMMARY

Some of the exemplary embodiments of the disclosure are summarized as follows. Embodiments include beam-forming systems configured to enable spatially separated wireless terminals (WTs) to perform beam-forming operations in a

wireless wide area network (WWAN). A wireless local area network (WLAN) couples together the WTs, which may be configured to share WWAN data, access, and control information. A beam-forming system may comprise the WTs, which function as elements of an antenna array. WWAN network access functions (such as monitoring control channels and exchanging control messages with the WWAN) may be provided in a centralized or a distributed manner with respect to the WTs.

Embodiments also include systems and methods configured for allocating network resources among the WTs, load balancing, distributed computing, antenna-switching diversity, WWAN diversity, interference mitigation, hand off, power control, authentication, session management, ad-hoc network control, error correction coding, and interference mitigation. Other embodiments and variations thereof are described in the Detailed Description.

In one embodiment, a computer program comprises a beam-forming weight calculation source code segment adapted to calculate at least one set of beam-forming weights for signaling between at least one group of WTs and at least one WWAN, and a WLAN information-distribution source code segment adapted to distribute at least one of a set of signals between the at least one group of WTs, the set of signals including a plurality of received WWAN signals, a plurality of WWAN transmission data, and the at least one set of beam-forming weights.

In another embodiment. a computer program comprises a beam-forming weight source code segment adapted to calculate at least one set of beam-forming weights for signaling between at least one group of WTs and at least one WWAN, and a MIMO combining source code segment adapted to combine a plurality of weighted received WWAN signals, at least one of the beam-forming weight source code segment and the MIMO combining source code segment including WLAN information-distribution source code adapted to distribute at least one of a set of signals between the at least one group of wireless terminals, the set of signals including a plurality of received WWAN signals, a plurality of WWAN transmission data, at least one channel estimate, and the at least one set of beam-forming weights.

A receiver embodiment of the invention comprises a plurality of WWAN interfaces, wherein each WWAN interface is adapted to receive at least one transmitted WWAN signal; a plurality of baseband processors wherein each baseband processor is coupled to at least one WWAN interface in the plurality of WWAN interfaces, the plurality of baseband processors adapted to generate a plurality of WWAN baseband signals; at least one WLAN coupled to the plurality of baseband processors; and at least one MIMO combiner adapted to receive at least one WWAN baseband signal from the WLAN, the at least one MIMO combiner adapted to perform MIMO combining of a plurality of WWAN baseband signals.

A transmitter embodiment of the invention comprises a plurality of WWAN interfaces wherein each WWAN interface is adapted to transmit at least one WWAN signal; at least one data source adapted to generate at least one data signal for transmission into at least one WWAN; at least one WLAN adapted to couple the at least one data signal to the plurality of WWAN interfaces for generating a plurality of WWAN data signals; and at least one MIMO processor adapted to generate a plurality of complex weights for weighting the plurality of WWAN data signals.

A wireless terminal according to one aspect of the invention comprises at least one WWAN interface; at least one WLAN interface; and at least one cooperative beam-forming system coupled between the WWAN interface and the WLAN interface and adapted to perform beamforming with information received from the WLAN interface.

Receivers and cancellation systems described herein may be employed in subscriber-side devices (e.g., cellular handsets, wireless modems, and consumer premises equipment) and/or server-side devices (e.g., cellular base stations, wireless access points, wireless routers, wireless relays, and repeaters). Chipsets for subscriber-side and/or server-side devices may be configured to perform at least some of the receiver and/or cancellation functionality of the embodiments described herein.

Additional embodiments, objects, and advantages are described and inferred from the following detailed descriptions and figures. Although particular embodiments are described herein, many variations and permutations of these embodiments fall within the scope and spirit of the invention. Although some benefits and advantages of the preferred embodiments are mentioned, the scope of the invention is not intended to be limited to particular benefits, uses, or objectives. Rather, embodiments of the invention are intended to be broadly applicable to different wireless technologies, system configurations, networks, and transmission protocols, some of which are illustrated by way of example in the figures and in the following detailed description. The detailed description and drawings are merely illustrative of the invention rather than limiting, the scope of the invention being defined by the appended claims and equivalents thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A illustrates an application of various embodiments of the invention to a cellular network.

FIG. **1**B illustrates an embodiment of the invention in which transmitted and/or received data between a WLAN group and a WWAN terminal occupies parallel, redundant channels c_n.

FIG. **1**C illustrates an embodiment of the invention in which a WLAN group comprising a plurality of Wireless Terminals (WTs) is adapted to communicate with at least one WWAN node.

FIG. **1**D illustrates an embodiment of the invention in which communications between a WWAN node and a plurality of WTs are characterized by different, yet complementary, code spaces c_1, c_2, and c_3.

FIG. **1**E illustrates an embodiment of the invention in which a first WLAN group is adapted to communicate with a second WLAN group via at least one WWAN channel or network.

FIG. **1**F shows an embodiment of the invention wherein a WLAN group includes a plurality of WWAN-active WTs and at least one WWAN-inactive WT.

FIG. **1**G illustrates a cooperative beam-forming embodiment of the invention that functions in the presence of a desired WWAN terminal and a jamming source.

FIG. **1**H illustrates a cooperative beam-forming embodiment of the invention that functions in the presence of a plurality of desired WWAN terminals.

FIG. **1**I illustrates an embodiment of the invention adapted to provide a plurality of WTs in a WLAN group with access to a plurality of WWAN services.

FIG. **1**J illustrates an embodiment of the invention in which a WLAN group includes at least one WWAN terminal.

FIG. **2**A illustrates a functional receiver embodiment of the invention that may be realized in both method and apparatus embodiments.

FIG. **2**B illustrates a functional receiver embodiment of the invention that may be realized in both method and apparatus embodiments.

FIG. **3**A illustrates an embodiment of the invention in which a WLAN controller for a WLAN group allocates processing resources based on WWAN-link performance.

FIG. **3**B illustrates an alternative embodiment of the invention in which a WLAN controller for a WLAN group allocates processing resources based on WWAN-link performance.

FIG. **4**A illustrates a MIMO receiver embodiment of the invention.

FIG. **4**B illustrates a functional embodiment of the invention in which MIMO processing operations are distributed over two or more WTs.

FIG. **4**C illustrates a functional embodiment of the invention for transmission and reception of WWAN signals in a distributed network of WTs.

FIG. **4**D illustrates a functional embodiment of the invention adapted to perform cooperative beamforming.

FIG. **5**A illustrates a receiver embodiment of the invention that may be implemented by hardware and/or software.

FIG. **5**B illustrates an alternative receiver embodiment of the invention.

FIG. **6**A illustrates functional and apparatus embodiments of the present invention pertaining to one or more WTs coupled to at least one WWAN and at least one WLAN.

FIG. **6**B illustrates a preferred embodiment of the invention that may be employed as either or both apparatus and functional embodiments of one or more WTs.

FIG. **7**A illustrates a functional embodiment of the invention related to calculating MIMO weights in a cooperative-beamforming network.

FIG. **7**B illustrates a functional embodiment of the invention adapted to calculate transmitted data symbols received by a cooperative-beamforming network.

FIG. **8**A illustrates a preferred transmitter embodiment of the invention.

FIG. **8**B illustrates a preferred receiver embodiment of the invention.

FIG. **8**C illustrates an embodiment of the invention in which a plurality of WTs is adapted to perform time-domain processing.

FIG. **9**A illustrates an optional transmission embodiment of the present invention.

FIG. **9**B illustrates a functional flow chart that pertains to transmitter apparatus and method embodiments of the invention.

FIG. **10**A illustrates software components of a transmission embodiment of the invention residing on a computer-readable memory.

FIG. **10**B illustrates software components of a receiver embodiment of the invention residing on a computer-readable memory.

FIG. **11** shows a WWAN comprising a WWAN access point (e.g., a base station) and a local group comprising a plurality of wireless terminals communicatively coupled together via a WLAN. A network-management operator is configured to handle WWAN-control operations within the local group.

FIG. **12** is a block diagram of a communication system comprising a WLAN for communicatively coupling a plurality of mobile wireless terminals to a WLAN controller, and a network-management operator for cooperatively processing WWAN-control messages for the mobile wireless terminals.

FIG. **13** is a block diagram of a mobile wireless terminal in accordance with an aspect of the invention in which a WWAN network management operator module is communicatively coupled to at least one other mobile wireless terminal via a WLAN and communicatively coupled to the WWAN.

FIG. **14** illustrates a method in accordance with an aspect of the invention in which WWAN communications for a group of wireless terminals are cooperatively processed.

FIG. **15** is a plot of a plurality of CI carriers and a superposition of the carriers.

FIG. **16**A is a plot of the relative frequency-versus-amplitude profile of a plurality of CI carriers that are combined to produce a time-domain pulse train, such as a DS-CDMA chip sequence.

FIG. **16**B is a time-domain representation of a modulated pulse train produced by providing time offsets to a plurality of modulated pulses, or equivalently, from a superposition of the CI carriers represented in FIG. **2**A.

FIG. **17**A illustrates a plurality of CI pulse waveforms modulated with code and/or information symbols .beta.sub.n and positioned orthogonally in time.

FIG. **17**B illustrates a CI pulse train of orthogonally time-offset pulses.

FIG. **18**A illustrates CI signal generation.

FIG. **18**B illustrates a CI transmitter.

FIGS. **19** and **20** each illustrates a system and method of generating CI signals.

FIG. **21** illustrates basic components of CI signal generation software residing on a computer-readable medium.

FIG. **22**A is a time-domain plot of a plurality of pulses generated from a superposition of equally spaced carriers, and shows a set of carrier phases corresponding to each of the pulses.

FIG. **22**B represents basic components and characteristics of a CI waveform.

FIG. **23**A is a functional flow chart of a CI receiver.

FIG. **23**B illustrates a CI receiver method and apparatus including a phase-space decoder.

FIG. **24**A shows an embodiment of a CI receiver.

FIG. **24**B shows an alternative embodiment of a CI receiver.

FIG. **25**A illustrates an aspect of a CI reception method and apparatus.

FIG. **25**B illustrates a CI receiver method and system of the present invention.

FIG. **26**A illustrates a CI receiver apparatus and method of the invention.

FIG. **26**B is a flow diagram for a receiver that receives a CI signal and samples the signal in multiple phase spaces.

FIG. **26**C illustrates basic components of a computer program on a computer-readable medium adapted to control a receiver and optimize performance.

FIG. **27**A illustrates a CI receiver configured as a multi-element receiver. Such receiver configurations may be employed in multiple-input, multiple-output (MIMO) communications.

FIG. **27**B illustrates three pulse-waveform blocks wherein each block includes four pulse waveforms of duration T.sub.s.

FIG. **28**A illustrates a CI transmitter.

FIG. **28**B illustrates a CI reception method and apparatus.

FIG. **28**C shows a CI receiver adapted to project a received signal onto at least one orthonormal basis, such as an orthonormal basis corresponding to at least one transmitted signal.

FIG. **29**A illustrates a block waveform including a set of orthogonal CI pulse waveforms.

FIG. **29**B illustrates a method for generating sub-carrier weights from a set of data symbols and a CI code matrix.

FIG. **30**A illustrates a transmitter apparatus and method configured to generate multiple transmission waveforms.

FIG. **30**B shows a receiver apparatus and method adapted to process a wide range of single-carrier and/or multi-carrier transmissions.

FIG. **31**A illustrates a communication method.

FIG. **31**B shows CI processing of received single-carrier and/or multi-carrier signals.

FIG. **32** illustrates a sub-space/sub-carrier processor receiver.

FIG. **33**A illustrates basic components of CI signal generation software residing on a computer-readable medium.

FIG. **33**B illustrates basic components of CI receiver software residing on a computer-readable medium.

DESCRIPTION

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the exemplary embodiments are not intended to limit the invention to the particular forms disclosed. Instead, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

FIG. **1**A illustrates how some embodiments of the invention may be employed in a cellular network. Each wireless terminal (WT) of a plurality of WTs **101-103** is in radio contact with at least one wireless wide area network (WWAN) terminal, which may also be referred to as a WWAN node, such as cellular base station **119**. The cellular base station **119** may include one or more antennas (e.g., an antenna array). WWAN signals transmitted between the base station **119** and the WTs **101-103** propagate through a WWAN channel **99**, which is typically characterized by AWGN, multipath effects, and may include external interference.

The WTs **101-103** represent a wireless local area network (WLAN) group **110** (or local group) if they are currently connected or are capable of being connected via a WLAN **109**. Accordingly, the WTs may be adapted to connect to at least one WWAN and to at least one WLAN. The WLAN group **110** may consist of two or more WTs in close enough proximity to each other to maintain WLAN communications. A given WWAN may include one or more WLAN groups, such as WLAN group **110**.

In an exemplary embodiment of the present invention, the WTs **101-103** may be configured to transmit data $d_t(n)$ over a WWAN channel to the base station **119**. The WTs **101-103** may also be configured to receive data $d_r(n)$ on a WWAN channel from the base station **119**. The received data $d_r(n)$ is shared by the WTs **101-103** via the WLAN **109**. Similarly, the transmitted data $d_t(n)$ may be distributed to the WTs **101-103** via the WLAN **109**. The WLAN **109** typically comprises the wireless-communication resource between the WTs **101-103** and the associated physical-layer interface hardware. The WLAN **109** is differentiated from a WWAN by its relatively shorter range. For example, a Bluetooth or UWB system functioning within an IEEE 802.11 network would be referred to as a WLAN, whereas the 802.11 network would be referred to as a WWAN. A WLAN may operate in a different frequency band than the WWAN. Alternatively, other orthogonalizing techniques may be employed for separating WLAN and WWAN signals from each other. WLANs and WWANs, as defined herein, may employ any type of free-space transmissions, including, but not limited to, ultra-low frequency, RF, microwave, infrared, optical, and acoustic transmissions. WLANs and WWANs may employ any type of transmission modality, including, but not limited to, wideband, UWB, spread-spectrum, multi-band, narrowband, or dynamic-spectrum communications.

The WLAN **109** may also comprise the WLAN network-control functionality commonly associated with a WLAN, and the WWAN-access control functionality required to distribute necessary WWAN-access parameters (e.g., node addresses, multiple-access codes, channel assignments, authentication codes, etc.) between active WTs **101-103**. The distribution of WWAN-access parameters between multiple WTs **101-103** enables each WT **101-103** to be responsive to transmissions intended for a particular WT in the local group and/or it enables a plurality of WTs **101-103** to function as a single WT when transmitting signals into the WWAN channel **99**.

Particular embodiments of the invention provide for adapting either or both the transmitted data $d_t(n)$ and the received data $d_r(n)$ in order to perform beamforming. Specifically, the group of WTs **110** may be adapted to perform antenna-array processing by linking the individual WTs together via WLAN links **109** and employing appropriate antenna-array processing on the transmitted and/or the received data, $d_t(n)$ and $d_r(n)$, respectively.

Ad-hoc wireless networks (e.g., multi-hop and peer-to-peer networks) may employ intermediate relay nodes to convey transmissions from a source to a destination. Relays reduce the transmission power requirements for sending information over a given distance. This indirectly increases the spatial-reuse factor, thus enhancing system-wide bandwidth efficiency. For this reason, ad-hoc wireless networking works particularly well with unlicensed spectrum, which is characterized by restrictive power limitations and high path loss compared to cellular bands. Similarly, for certain embodiments of the invention, it may be preferable to employ high-loss (e.g., high-frequency) channels for the WLAN connections **109**.

The capacity of wireless ad-hoc networks is constrained by interference caused by the neighboring nodes, such as shown in P. Gupta and P. R. Kumar, "The Capacity of Wireless Networks," IEEE Trans. Info. Theory, vol. IT-46, no. 2, March 2000, pp. 388-404 and in A. Agarwal and P. R. Kumar, "Improved capacity bounds for wireless networks." Wireless Communications and Mobile Computing, vol. 4, pp. 251-261, 2004, both of which are incorporated by reference herein. Using directional antennas (such as antenna arrays) reduces the interference area caused by each node, which increases the capacity of the network. However, the use of directional antennas and antenna arrays on the WTs **101-103** is often not feasible, especially when there are size constraints, power restrictions, cost constraints, and/or mobility needs. Thus, some embodiments of the present invention may provide for enabling WTs to form groups that cooperate in network-access functions. This provides each member of a given WLAN group with greater network access, as well as other benefits.

Antenna-array processing is generally categorized as multiple-input, single-output (MISO), single-input, multiple-

output (SIMO) or multiple input, multiple output (MIMO). Array processing often employs beam forming in at least one predetermined signal space or signal sub-space. For example, phased-array processing involves coherent beam-forming of at least one transmitted signal frequency. Sub-space processing often employs some form of baseband interference cancellation or multi-user detection. Other variations of phased-array and sub-space processing also exist and may be implemented in embodiments of the present invention.

Sub-space processing is commonly employed via space-time processing (e.g., Rake receivers are employed in a frequency-selective channel) and/or space-frequency processing (e.g., frequency-domain processing is employed to provide for multiple flat-fading channels). Similarly, sub-space processing may employ other diversity parameters and combinations thereof, including (but not limited to) polarization processing and code-space processing.

MIMO systems have been shown to significantly increase the bandwidth efficiency while retaining the same transmit power budget and bit-error-rate (BER) performance relative to a single input, single output (SISO) system. Similarly, for a given throughput requirement, MIMO systems require less transmission power than SISO systems. MIMO technology is useful for enabling exceptionally high bandwidth efficiency. However, many spatial-multiplexing techniques require rich scattering. Increased path loss and poor scattering are major problems for MIMO systems operating above 2.4 GHz. For these reasons, lower (e.g., cellular) frequencies are often preferred for MIMO applications. However, some MIMO benefits can also be achieved at higher frequencies.

FIG. **1**B illustrates an embodiment of the present invention in which transmitted and/or received data between the WLAN group **110** and the WWAN terminal **119** occupies parallel, redundant channels c_n. This approach is distinct from typical cooperative-diversity implementations in which WWAN data transmissions are conveyed over a plurality of orthogonal channels. Rather, each of the WTs **101-103** transmits and/or receives on a common channel c_n. This enables many well-known types of array processing to be performed.

The WLAN group **110** may function as either or both a transmitting array and a receiving array. The signal received at an antenna array is a noisy superposition of the n transmitted signals:

$$y(n) = \sqrt{\frac{E_s}{M_t}}\, Hs(n) + v(n)$$

where $\{s(n)\}_{n=0}^{N-1}$ is a sequence of transmitted vectors, E_s corresponds to the transmit energy assuming that $E_{sn}\|s_n\|=1$ for n=1, . . . , M_t, v(n) represents AWGN with zero mean and variance, and H is an $M_r \times M_t$ matrix channel (where M_r is the number of receiver elements and M_t is the number of transmitter elements), which is assumed constant over N symbol periods. The nominal rank of a rational matrix H is the order of the largest minor of H that is not identically zero, such as shown in T. Kailath, Linear Systems, Prentice-Hall, Inc., 1980, (especially Sec. 6.5), which is incorporated by reference.

Channel characterization involves finding a set of channel realizations (e.g., functions) that indicate channel quality with respect to some performance metric (e.g., error probability or asymptotic criteria). In the MIMO channel, several variables contribute to the channel quality (and thus, to the optimization of channel quality), including the choice of space-time codes, receiver-terminal selection, and receiver algorithm(s) employed.

In one embodiment of the invention, a subset of WTs in a WLAN group may be selected such as to provide optimal WWAN transmission and/or reception within at least one predetermined constraint, such as an optimal or maximum number of active WWAN transceivers within the WLAN group. Such predetermined constraints may be established to optimize some combination of WWAN link performance and resource use within the WLAN group. In one embodiment, WTs experiencing the best WWAN channel conditions may be selected. Techniques employing antenna selection, such as may be used for diversity processing with antenna arrays, may be used in embodiments of the present invention. In one aspect of the invention, resource conservation may focus on WT battery power, MIMO processing complexity, and/or WLAN bandwidth.

Certain embodiments of the invention may distinguish between circuit power (e.g., power used to perform signal processing) versus transmission power. Other embodiments of the invention may provide consideration for the total battery power (e.g., processing power plus transmission power) budget, such as to provide power (e.g., battery usage) load balancing between WTs. Thus, embodiments of the invention may optimize a balance of signaling parameters, including (but not limited to) transmission power, channel-coding (and decoding) complexity, modulation, signal processing and the complexity associated with cooperative array processing parameters (e.g., number of active array elements, number of channels, number of WTs employed to perform signal processing, number of WTs in a WLAN group, type of array-processing operations, etc.).

Any combination of various channel-characterization functions may be employed as a measure of link performance. Example functions including, but not limited to, the following may be employed. Possible functions include the average signal strength:

$$P(H) = \frac{1}{N}\sum_{n=0}^{N-1} \|H^{(n)}\|_F^2$$

the average mutual information:

$$I(H) = \frac{1}{N}\sum_{n=0}^{N-1} \log\det\left(I_{M_r} + \frac{E_s}{N_o M_t} H^{(n)} H^{(n)H}\right)$$

and the normalized average mutual information:

$$I(H) = \frac{1}{N}\sum_{n=0}^{N-1} \log\det\left(I_{M_r} + \frac{E_s}{N_o}\frac{1}{\alpha} H^{(n)} H^{(n)H}\right)$$

$$\text{where } \alpha = \frac{1}{NM_tM_r}\sum_{n=0}^{N-1} \|H^{(n)}\|_F^2$$

is an estimate of the path loss.

Theoretical capacity in a MIMO channel is typically expressed as:

$$C=\log_2 \det[I_{M_r}+\rho/M_t HH^*]$$

where ρ is the average SNR.

A preferred embodiment of the invention may employ error-correcting codes to add structured redundancy to the information bits. This can be done to provide diversity, such as temporal diversity, spatial diversity, and/or frequency diversity. Embodiments of the invention may employ spreading codes, which are well known in the art. In addition to collaborative MIMO operations, the WTs may engage in collaborative decoding. In particular, a WLAN group may be provided with functionality that directs the WTs to coordinate WWAN information exchange and decoding via the WLAN.

In yet another embodiment of the invention, a WWAN terminal may be adapted to receive channel information (and/or even received data) from WTs, perform array-processing (e.g., MIMO) computations, and then upload the resulting array-processing weights to the WTs. The WTs may simply apply the weights to their transmitted and/or received WWAN signals, and perform any other related operations, such as combining.

FIG. **1**C illustrates a WLAN group **110** comprising a plurality of WTs **101-103** adapted to communicate with at least one WWAN node **119**. A WWAN channel **99** expresses distortions, interference, and noise that affect WWAN transmissions between the WTs **101-103** and the WWAN node **119**. Channel estimation characterizes propagation characteristics (e.g., multipath, shadowing, path loss, noise, and interference) in the WWAN channel.

In one embodiment of the invention, a given WWAN transmission is separated into spectral components (such as denoted by f_1, f_2, and f_3) by the WLAN group **110**. For example, each of the WTs **101-103** may be adapted to receive predetermined spectral components f_1, f_2, and f_3 of a given transmission intended for a particular WT. Alternatively, each of the WTs **101-103** may be adapted to transmit one or more associated predetermined spectral components to the WWAN node **119**.

The selection of spectral components f_1, f_2, and f_3 and their association with particular WTs **101-103** is typically performed to optimize WWAN system performance relative to the current WWAN channel **99**. For example, since the frequency-dependent fading profile in a scattering-rich environment tends to be unique for each spatially separated WT **101-103** channel, the spectral components f_1, f_2, and f_3 are preferably selected to minimize the effects of deep fades and/or interference. Spectral-component selection may be selected and/or adapted to optimize one or more WWAN link-performance metrics, including, but not limited to, SNR, BER, PER, and throughput. Spectral-component selection may be performed to achieve other objectives, such as to distribute processing loads across the WLAN group **110**.

The spectral components f_1, f_2, and f_3 may be characterized by overlapping or non-overlapping frequency bands. Spectral components f_1, f_2, and f_3 may each include continuous or discontinuous (e.g., frequency interleaved) frequency-band components. Spectral components f_1, f_2, and f_3 may comprise similar or different bandwidths. Furthermore, the spectral components f_1, f_2, and f_3 may include gaps or notches, such as to notch out interference or deep fades. Accordingly, an aggregate signal derived from combining the spectral components f_1, f_2, and f_3 may include gaps or notches.

WWAN communication signals may include multicarrier (e.g., OFDM) or single-carrier signals. In the case of single-carrier signals, the WTs **101-103** can be adapted to perform frequency-domain synthesis and/or decomposition, such as described in published patent appl. nos. 20040086027 and 20030147655, which are hereby incorporated by reference in their entireties.

FIG. **1**D illustrates a similar communication-system embodiment to that shown in FIG. **1**C, except that the transmissions between the WWAN node **119** and the WTs **101-103** are characterized by different, yet complementary, code spaces c_1, c_2, and c_3. In this case, the term complementary means that the coded transmissions corresponding to the code spaces c_1, c_2, and c_3 can sum to produce at least one predetermined WWAN coded data sequence. This may be a weighted sum due to the given channel conditions. A predetermined WWAN coded data sequence may employ a code that would ordinarily (in view of the prior art) be employed in whole. That is, it would not ordinarily be partitioned into sub-codes to be transmitted by different transmitters or received by different receivers.

In one embodiment of the invention, the code spaces c_1, c_2, and c_3 correspond to direct-sequence codes, such as may be used to provide for spreading and/or multiple access. A superposition of signals transmitted across the code spaces c_1, c_2, and c_3 may provide at least one predetermined WWAN coded data sequence received by at least one WWAN node **119**. Similarly, a superposition of signals received by the WTs **101-103** and mapped onto the code spaces c_1, c_2, and c_3 may provide at least one predetermined WWAN coded data sequence that would ordinarily (in view of the prior art) be intended for a single WT. Preferred embodiments of the invention may provide for channel corrections (e.g., pre-distortion and/or receiver-side channel compensation) by either or both the WLAN group **110** and the WWAN node **119**. Accordingly, the code spaces c_1, c_2, and c_3 may be adapted to account for channel conditions.

In another embodiment of the invention, the code spaces c_1, c_2, and c_3 may correspond to direct-sequence codes having predetermined spectral characteristics. It is well known that different time-domain data sequences may be characterized by different spectral distributions. Accordingly, embodiments of the invention may provide for selecting complementary codes c_1, c_2, and c_3 having predetermined spectral characteristics with respect to WWAN channel conditions affecting the links between the WTs **101-103** and the WWAN node **119**. Thus, the codes c_1, c_2, and c_3 may be selected according to the same criteria employed for selecting the spectral components f_1, f_2, and f_3.

FIG. **1**E illustrates an embodiment of the invention in which a first WLAN group **110** (such as comprising WTs **101-103** connected via WLAN **109**) is adapted to communicate with a second WLAN group **120** (such as comprising WTs **111-113** connected via WLAN **118**) via WWAN channel **99**. Applications of this embodiment may be directed toward peer-to-peer and multi-hop networks. Specifically, antenna-array processing (e.g., MIMO operations) may be performed by both WLAN groups **110** and **120**. Each WLAN group (such as WLAN groups **110** and **120**) may function as a single node in an ad-hoc network, a peer-to-peer network, or a multi-hop network. For example, any communication addressed to (or routed through) a particular node (such as one of the WTs **101-103**) may be advantageously processed by one or more of the WTs **101-103** in the WLAN group **110**. In one embodiment, each active WT **101-103** in the WLAN group **110** may be responsive to communications addressed to itself and to at least one other WT **101-103** in the WLAN group **110**.

The WLAN **109** may be used to inform individual WTs **101-103** which node address(es) (or multiple-access channel assignments) to be responsive to. Similarly, the WLAN **109**

may convey information to WTs **101-103** in order to spoof node addresses and/or multiple-access information and otherwise help WTs **101-103** assume channelization information related to a particular WT identity prior to transmitting signals into the WWAN. Thus, the WLAN **109** can be used to assist in synchronizing WT interactions with the WWAN. The functionality of providing for sharing WWAN-access information between WTs **101-103** may be coordinated and controlled with respect to cooperative-array (e.g., MIMO) processing.

FIG. **1**F shows an embodiment of the invention wherein a WLAN group **110** includes a plurality of WWAN-active WTs **101-103** and at least one WWAN-inactive WT, such as WTs **104-106**. The WWAN-active WTs **101-103** may be configured to directly transmit and/or receive WWAN communication signals **129**. WWAN-inactive WTs **104-106** are defined as WLAN-connected terminals that do not directly communicate with the WWAN. Rather, the WWAN-inactive WTs **104-106** may be in a sleep or standby mode.

In a preferred embodiment of the invention, signals routed to and from a particular WT **101-103** may be provided with beam-forming weights that allow for phased-array and/or sub-space processing. Calculation of the weights may be facilitated via distributed computing (e.g., as a load-balancing measure) across a plurality of the WTs (**101-106**). This allows the WLAN group **110** to scale the effective throughput of the WWAN link and coordinate system throughput with local area load balancing. In particular, the efficiency of the WWAN link is proportional to the smaller of the number of array elements at the WWAN terminal (not shown) and the number of WWAN-active transceiver antennas linked by the WLAN **109**. When an equal number N of antennas is employed on both sides of the link, up to an N-fold increase in the link throughput is possible. Channel coding can be employed to exchange this increase for improved probability-of-error performance, increased range, and/or lower transmission power.

Although the capacity of a MIMO channel increases with the number of antennas employed at both ends of the link, the complexity of the transmission and reception algorithms increases accordingly. For example, the sphere decoder has a typical complexity of $O(M_T^6)$, where M_T is the number of transmitting antennas, and V-Blast has a typical complexity of $O((M_R M_T)^3)$, where M_R and M_T are respectively the number of receiving and transmitting antennas. However, the computational power increases only linearly with respect to the number of WTs (assuming each WT has identical processing capability). Thus, the aggregate processing power of the WTs may determine the maximum number of active antennas that a WLAN group **110** can support.

One solution to the disparity between required processing power and the number of WT processors in a given WLAN group **110** is to ensure that the total number of WTs exceeds the number of MIMO channels in the group **110**. This approach enables at least two significant processing advantages:

1) The processing load may be spread over a larger number of mobile-terminal processors, and
2) A form of antenna-switching diversity can be used to optimize performance and throughput in the MIMO channel.

Antenna switching is a well-known technique that switches between various antennas and selects ones having the best signal outputs. This can be done to reduce correlation between antennas, thereby improving MIMO performance. Antenna switching is described in G. J. Foschini, M. J. Gans, "On limits of wireless communication in a fading environment when using multiple antennas," *Wireless Personal Communications*, vol. 6, no. 3, pp. 311-335, March 1998, which is incorporated by reference. In some embodiments of the invention, WTs having the most favorable WWAN channel characteristics may be selected to improve MIMO performance without any increase in processing complexity.

In some embodiments of the invention, one or more WWAN-inactive WTs **104-106** may be employed for WLAN-based functions, such as (but not limited to) WLAN network control, distributed-computing applications, and WWAN-interface control. For example, WLAN network control may include any of the well-known network-control functions, such as terminal identification, authentication, error correction, routing, synchronization, multiple-access control, resource allocation, load balancing, power control, terminal-state management, hand-offs, etc.

The WLAN **109** may employ distributed computing across a plurality of the WTs. Distributed computing may be employed simply to achieve increased processing power. Alternatively, distributed computing may include other objectives, such as balancing computational processing loads or balancing power consumption across the WTs **101-106** in the WLAN group **110**. Computational loads on the WLAN group can potentially include any WWAN-related computations, such as WWAN channel estimation, WWAN channel compensation, diversity combining, WWAN channel coding/decoding, and cooperative array processing (e.g., MIMO weight calculation, interference cancellation, multi-user detection, matrix operations, and other smart antenna array processing operations).

WWAN-interface control may include distributing WWAN data and control information between the WTs **101-106**. In one exemplary embodiment of the invention, at least one of the WTs **101-106** comprises a data source that distributes its data to at least one other WT **101-106** for transmission into the WWAN. In a similar embodiment of the invention, received WWAN signals intended for a particular WT **101-106** are received by a plurality of WWAN-active WTs **101-103**. The received WWAN signals may optionally be processed by one or more WTs **101-106** prior to being routed to the intended WT **101-106**. Accordingly, WWAN channel-access information may be routed to a plurality of WWAN-active WTs **101-103** such that they function together as a single WT **101-106**.

The determination of which WTs **101-106** are active is typically performed by decision processing within the WLAN group **110** that determines which WTs **101-106** have the highest quality WWAN channel(s). The number of WWAN-active WTs (such as WTs **101-103**) may be determined by one or more factors, including WT channel quality, array-processing complexity, available computational resources within the WLAN group **110**, load balancing, and information-bandwidth requirements. In an alternative embodiment of the invention, the WWAN assigns cooperative channel-access information to the WTs **101-103** and may optionally determine which WTs **101-106** are active.

Some embodiments of the invention may take into consideration not only the MIMO complexity at the WTs, but also the added complexity associated with distributing the computational loads over WTs in a given WLAN group. Both MIMO and distributed computing overheads can be characterized as a function of the number of WTs in a WLAN group. Furthermore, the information bandwidth of a given WLAN channel limits the rate of information exchange between WTs. Accordingly, local channel conditions within the WLAN may affect throughput and range, and thus limit the number of WTs within the WLAN group.

Either the WLAN capacity or the computational capability of each WT may set a practical limit on the number of WTs in a WLAN group and the overall frequency-reuse factor.

Another important factor that can impact the WLAN group size is the channel rate-of-change, which may be due to motion of the WTs and/or other objects in the WWAN environment. In particular, rapidly changing channel conditions may necessitate frequent updates to the MIMO computations, thus increasing the computational load on WLAN group and potentially increasing the required data transfer across the WLAN. Similarly, local channel conditions may dictate the flow of data if distributed computing is employed.

MIMO systems experience substantial degradation in data transfer rates in mobile channels. Time-varying multipath-fading profiles commonly experienced in a mobile wireless network exhibit deep fades that often exceed 30 dB. Commercial viability of some embodiments of the present invention requires the ability to tolerate a rapidly changing channel. A promising approach to this problem is to employ diversity to reduce the channel rate-of-change. In a wideband system, or equivalently, in a system comprised of a number of narrowband subcarriers distributed (e.g., interleaved) over a wide frequency band, deep fades affect only a portion of the total channel bandwidth. Therefore, frequency and/or spatial diversity may be employed to reduce the likelihood of deep fades in a multipath environment. Similarly, alternative forms of diversity may be employed. In a mobile environment, this translates into reducing the channel rate-of-change.

FIG. **1**G illustrates a cooperative beam-forming embodiment of the invention that functions in the presence of a desired WWAN terminal **119** and an external interference source (or jammer) **118**. WTs **101-103** in a WLAN group **110** may coordinate their received aggregate beam pattern(s) to null out a jamming signal **115**. Array-processing operations performed on signals received from the WTs **101-103** may take the form of phased-array processing, which minimizes the array's sensitivity to signals arriving from one or more angles. Alternatively, array processing may employ baseband (or intermediate-frequency) interference cancellation. Similarly, beam-forming operations may be employed to cancel emissions transmitted toward one or more terminals (such as jammer **118**).

FIG. **1**H illustrates a cooperative beam-forming embodiment of the invention configured to function in the presence of a plurality of desired WWAN terminals **119** and **127**. In one embodiment of the invention, the WWAN terminals **119** and **127** may be common to a particular WWAN, and the configuration illustrated in FIG. **1**H may include a soft hand-off in which redundant transmissions are transmitted between the WLAN group **110** and the WWAN terminals **119** and **127**. In this case, the WLAN group may be distributed geographically over a plurality of WWAN sectors or cells. In one aspect of the invention, the WLAN group **110** may adapt its connectivity with the WWAN to transition to the cell or sector offering the optimal aggregate WWAN channel quality. Accordingly, the WLAN group may adapt its selection of WWAN-active WTs in response to a hand off.

In another embodiment of the invention, the WLAN group **110** may employ a first WWAN connection (such as illustrated by a connection between WTs **101** and **102**, and WWAN terminal **119**) and a second WWAN connection (such as illustrated by a connection between WT **103** and WWAN terminal **127**) to transmit and/or receive one or more data streams. The WLAN group **110** may employ a plurality of WWAN user channels in a given WWAN. Similarly, the WLAN group **110** may employ connections to a plurality of different WWANs.

FIG. **1**I illustrates an embodiment of the invention that provides a plurality of WTs **101-106** in a WLAN group **110** with access to a plurality of WWAN services (i.e., WWANs). For example, WT **101** is provided with a communication link with an IEEE 802.16 access-point terminal **116** in an IEEE 802.16 network, WT **102** maintains access capabilities to a 3G-cellular terminal **119**, and WT **103** has connectivity to an IEEE 802.11 access point **117**. WLAN connectivity **109** is adapted to enable any of the WTs **101-106** in the WLAN group **110** to access any of the plurality of WWAN (802.16, 3G, and 802.11) services.

The WLAN **109** may include a WWAN-access controller (not shown), which may take the form of WLAN-control software residing on a physical device, such as one or more WTs **101-106**. Connectivity of the WTs **101-106** to the available WWAN services may be performed with respect to a combination of technical rules and business rules. For example, WWAN access is typically managed using technical rules, such as network load balancing, power conservation, and minimizing computational processing loads. However, WWAN access can also be influenced by business rules, such as enabling a predetermined cost/service ratio for individual WTs **101-106**. For example, the WWAN-access controller (not shown) can anticipate the economic cost of particular WWAN services to the user, as well as user communication needs, when assigning WWAN access to individual WTs **101-106**. Each WT **101-106** may provide the WWAN-access controller (not shown) with a cost tolerance, which can be updated relative to the type of communication link desired. For example, high-priority communication needs (such as particular voice communications or bidding on an online auction) may include permissions to access more expensive WWAN connections in order to ensure better reliability.

The overall goal of WWAN access may be to achieve optimal connectivity with minimum cost. Accordingly, WWAN-access algorithms may include optimization techniques, including stochastic search algorithms (like multi-objective genetic algorithms). Multi-objective optimization are well known in the art, such as described in E. Zitzler and L. Thiele, "Multiobjective evolutionary algorithms: A comparative case study and the strength pareto approach," *IEEE Tran. on Evol. Comput.*, vol. 3, no. 4, November 1999, pp. 257-271 and J. D. Schaffer, "Multiple objective optimization with vector evaluated genetic algorithms," *Proceedings of 1st International Conference on Genetic Algorithms,* 1991, pp. 93-100, both of which are incorporated by reference.

A WWAN-access controller (not shown) preferably ensures an uninterrupted session when transitioning from one WWAN to another. In particular, the transition between different WWANs should be invisible to the user. This requires that the WWAN-access controller (not shown) be adapted to store user state information (e.g., save browser pages or buffer multimedia data streams). Furthermore, back-end systems may preferably be employed to manage cooperative WWAN access in order to consolidate different WWAN-access charges into a single bill for the user.

In FIG. **1**J, a plurality of WTs **101-106** in a WLAN group **110** includes at least one WWAN terminal **106**. The WTs **101-105** may contribute beam-forming capabilities to the WWAN terminal **106**, such as to increase range, increase spatial reuse, reduce transmission power, and/or achieve any of other various beamforming objectives.

In one embodiment of the invention the WTs **101-105** function as lens for WWAN signals transmitted and received

by the WWAN terminal **106**. For example, the WTs **101-106** may collect received WWAN signals and then focus retransmitted WWAN signals at the WWAN terminal **106**. Similarly, the WTs **101-105** may assist in the transmission of WWAN signals from the WWAN terminal **106** to one or more remote sources. In essence, the WTs **101-105** may function like a radio relay, but with directionality and focusing capabilities. In this embodiment, the WLAN connectivity of WTs **101-105** with the WWAN terminal **106** may not be necessary.

In another embodiment of the invention, one or more of the WTs **101-106**, such as WWAN terminal **106**, may be adapted to process the majority (or entirety) of necessary beam-forming computations. In this case, WT **106** is designated as a computer-processing terminal. The computer-processing terminal **106** is adapted to include specific computational resources for processing WWAN signals received by other WTs (such as WTs **101-103**), which are then relayed via the WLAN **109** to the computer-processing terminal **106**. Similarly, the computer-processing terminal **106** may be adapted to perform signal-processing operations associated with WWAN transmission. Computational operations associated with other WWAN signal-processing operations (e.g., coding, decoding, channel estimation, network-access control, etc.) may be provided by the computer-processing terminal **106**.

FIG. **2**A illustrates a functional embodiment of the invention that may be realized in both method and apparatus embodiments. A plurality M of WWAN Interfaces **1101.1-1101**.M is provided for coupling WWAN signals to and/or from at least one WWAN. In one functional embodiment, WWAN Interfaces **1101.1-1101**.M may include WWAN transceivers adapted to convert received WWAN signals into received baseband signals. A plurality of WWAN baseband processors **1102.1-1102**.M are optionally provided for performing baseband processing (such as, but not limited to, channel compensation, A/D conversion, frequency conversion, filtering, and demultiplexing) on the received baseband signals. Alternatively, the function of the WWAN baseband processors **1102.1-1102**.M may be performed by the WWAN Interfaces **1101.1-1101**.M.

Baseband outputs from the WWAN baseband processors **1102.1-1102**.M are coupled into a plurality of array processors, such as MIMO combiners **1103.1-1103**.M. In a MIMO channel, the received WWAN signals (and thus, the baseband outputs) are characterized by a plurality of overlapping (i.e., interfering) signals. Although MIMO combiners **1103.1-1103**.M are shown, any type of array processor may be employed. The number of array processors may be less than, equal to, or greater than the number M of WWAN Interfaces **1101.1-1101**.M. Baseband outputs may also be coupled into a WLAN **1105**, which is coupled to the plurality of MIMO combiners **1103.1-1103**.M. Each MIMO combiner **1103.1-1103**.M may be adapted to receive baseband outputs from two or more baseband processors **1102.1-1102**.M wherein at least one of those baseband outputs is coupled to the MIMO combiner **1103.1-1103**.M via the WLAN **1105**.

A particular m^{th} MIMO combiner **1103**.*m* need not process data from a corresponding (m^{th}) WWAN Interface **1101**.*m*. Rather, the mth MIMO combiner **1103**.*m* may process baseband signal outputs from a plurality of WWAN Interfaces **1101**.*p* {p=1, . . . , M, where p≠m}.

The WLAN **1105** comprises at least one WLAN channel between at least one baseband output (e.g., baseband processor **1102.1-1102**.M outputs) and at least one array processor, such as the MIMO combiners **1103.1-1103**.M. The WLAN **1105** may include WLAN interfaces (not shown) and associated WLAN-control hardware and/or software (not shown).

The MIMO combiners **1103.1-1103**.M may be adapted to separate the overlapping signals and output at least one desired transmission therefrom. Outputs of the MIMO combiners **1103.1-1103**.M are optionally processed by secondary data processors **1104.1-1104**.M, which may provide coupling into the WLAN **1105**. The secondary data processors **1104.1-1104**.M may be adapted to perform demodulation, error-correction decoding, data formatting, and/or other related baseband-processing functions.

In some embodiments of the invention, MIMO combiner **1103.1-1103**.M outputs may be coupled via the WLAN **1105** to other MIMO combiners **1103.1-1103**.M and/or secondary data processors **1104.1-1104**.M. For example, embodiments of the invention may employ an iterative cancellation process, such as successive interference cancellation (which is well-known in the art), involving the use of strongest-signal estimates, and then next-strongest-signal estimates to cancel known interference in weaker signals. Alternatively, embodiments may employ parallel cancellation.

FIG. **2**B illustrates an embodiment of the invention including a plurality M of WTs **1109.1-1109**.M, each comprising a corresponding combination of a WWAN Interface **1101.1-1101**.M, an optional WWAN baseband processor **1102.1-1102**.M, a combiner (such as a MIMO combiner **1103.1-1103**.M), and a secondary data processor **1104.1-1104**.M. The WTs **1109.1-1109**.M are coupled together by a WLAN **1105**, which is configured to convey data between the WTs **1109.1-1109**.M in order to enable cooperative antenna-array processing.

A WT, such as any of the WTs **1109.1-1109**.M, includes any system or device provided with communicative connectivity means to a WLAN **1105**. Two or more WTs **1109.1-1109**.M are preferably provided with WWAN interfaces, such as WWAN Interface **1101.1-1101**.M. A plurality of WTs **1109.1-1109**.M may share at least one WLAN **1105**. In one embodiment of the invention, individual WTs **1109.1-1109**.M may share the same WWAN service. This enables the WLAN group **110** to perform either or both transmit beam-forming and receive beam-forming (i.e., combining) operations.

In another embodiment of the invention, WTs **1109.1-1109**.M may have connections to different WWANs and/or WWAN services. This enables the WLAN group **110** to achieve WWAN-service diversity. One or more WTs **1109.1-1109**.M may optionally be capable of accessing multiple WWAN services. For example, many cellular handsets are provided with multi-mode capabilities, which give them the ability to access multiple WWANs. Some of the WTs **1109.1-1109**.M may have no WWAN service. For example, one or more WTs **1109.1-1109**.M may be out of range, in a WWAN dead spot, in an inactive WWAN state, or configured only to communicate via the WLAN **1105**. WTs **1109.1-1109**.M include, but are not limited to, cell phones, radio handsets, pagers, PDAs, wireless sensors, RFID devices, vehicle radio communication devices, laptop computers with wireless modems, wireless network access points, wireless routers, wireless switches, radio repeaters, transponders, and devices adapted to include satellite modems.

A WLAN group **110** may be adapted to perform any of various types and combinations of diversity and MIMO beam-forming. Three commonly used linear diversity-combining techniques include switched (or selection) combining, maximal ration combining (MRC), and equal gain

combining (EGC). Other combining techniques may be employed. The impact of using diversity may be expressed by a probability distribution p(γ) of the SNR γ at the output of a combining network. For switched diversity, wherein the combiner switches to the diversity branches (e.g., WTs) having the strongest signal, p(γ) is given by:

$$p(\gamma) = \frac{L}{\Gamma} e^{-\gamma/\Gamma}[1 - e^{-\gamma/\Gamma}]^{L-1}$$

where Γ is the average SNR for each diversity branch and L is the number of diversity branches. MRC weights branches (e.g., WT signals received from the WWAN) having better SNR more heavily (i.e., with greater-magnitude weights) than branches having poorer SNR. The p(γ) for MRC is given by:

$$p(\gamma) = \frac{\gamma^{l-1} e^{-\gamma/\Gamma}}{\Gamma^{L}(l-1)!}$$

For EGC, p(γ) is given by:

$$p(\gamma) = \frac{L}{a\Gamma} e^{-\gamma/a\Gamma}[1 - e^{-\gamma/a\Gamma}]^{L-1} \text{ where } a = \sqrt{L/1.25} \text{ for } L \geq 2,$$

and 1 otherwise.

These diversity techniques provide the greatest improvements when the branches are uncorrelated.

Adaptive arrays (or smart antennas) may include antenna systems that automatically adjust to achieve some predetermined performance criterion, such as maximizing the signal to interference (S/I) ratio, SINR, or link margin. Adaptive antenna techniques include switched beam, beam steering, and optimum combining (e.g., a linear spatial filtering approach that employs adaptation to closely match an output signal with a reference signal). A filtering process typically suppresses any artifacts that are not part of the desired incoming signal, including noise and interference.

In an optimum combining system, signals from each WT are down converted to baseband and converted to digital signals in an ADC. Noise associated with the front end of the down converter and other sources is naturally added to the signal. The resulting signal $x_m(k)$ is multiplied by a complex weighting function $w_m(k)$ and summed with similar signals from other WT antenna elements. The resulting sum signal $\Sigma w_m(k)x_m(k)$ is compared with a previously derived (and updated) reference signal (e.g., a training sequence). An error signal e(k) is generated and used to adjust the weight values in order to minimize e(k). The objective is to derive the weighting function $w_m(k)$ that enables the best match between an estimated received signal and the actual transmitted signal. Alternatively, an adaptive WT array may be configured as an analog array wherein amplitude and phase adjustments (i.e., weighting functions) are performed at RF or IF.

In a MIMO communication system, signals transmitted from M_T transmit sources interfere with each other at a receiver comprising the WTs **1109.1-1109**.M. Thus, interference cancellation (such as matrix inversion, channel transfer function inversion, and adaptive filtering) may be employed by one or more MIMO combiners **1103.1-1103**.M to separate the signals. The received signal is expressed by:

$$y = Hx + n$$

Where the Received Signal, y, is a Vector with M_R Terms (y_i, i=1, . . . , N_R) Corresponding to signals received by M_R (where M_R may have a value of 2 to M) receiver elements (i.e., WTs); x represents the transmitted signal, which is a vector having M_T terms $\{x_i, i=1, \ldots, M_T\}$ corresponding to signals transmitted by M_T transmitter elements; H is an $M_R \times M_T$ channel-response matrix that characterizes the complex gains (i.e., transfer function, or spatial gain distribution) from the M_T transmission elements to the M_R receive elements; and n represents AWGN having zero mean and zero variance.

In the case where the channel is characterized by flat fading, such as when a narrowband signal is employed (e.g., a sub-carrier of a multi-carrier signal), the elements in matrix H are scalars. The channel-response matrix H may be diagonalized by performing an eigenvalue decomposition of the $M_T \times M_T$ correlation matrix R, where $R = H^H H$. Eigenvalue decomposition is expressed by:

$$R = EDE^H$$

where E is an $M_T \times M_T$ unitary matrix with columns corresponding to the eigenvectors e_i of R, and D is an $M_T \times M_T$ diagonal matrix wherein the diagonal elements are eigenvalues λ_i of R. The diagonal elements of D indicate the channel gain for each of the independent MIMO channels. Alternatively, other eigenvalue-decomposition approaches, such as singular value decomposition, may be employed.

The process for diagonalizing the MIMO channel response is initiated by multiplying a data vector d with the unitary matrix E to produce the transmitted vector x: x=Es. This requires the transmitter to have some information corresponding to the channel-response matrix H, or related information thereof. The received vector y is then multiplied with $E^H H^H$ to provide an estimate of data vectors, which is expressed by:

$$\hat{s} = E^H H^H y = E^H H^H HEs + E^H H^H n = Ds + \hat{n}$$

where $\hat{n}$ is AWGN having a mean vector of 0 and a covariance matrix of $\Lambda_n = \sigma^2 D$.

The data vector s is transformed by an effective channel response represented by the diagonal matrix D. Thus, there are N_s non-interfering subchannels wherein each subchannel i has a power gain of λ_i^2 and a noise power of $\sigma^2\lambda_i$.

In the case where MIMO processing is performed on a multicarrier signal, or some other wideband signal that is spectrally decomposed into narrowband components, eigenmode decomposition may be performed for each frequency bin f_n.

If multicarrier spreading codes are employed (e.g., orthogonal DFT, or CI, codes), the channel-response matrix H can cause inter-symbol interference between spread data symbols, even in a SISO arrangement. Accordingly, the eigenmode decomposition technique described previously is applicable to multicarrier spreading and despreading. In one embodiment of the invention, eigenmode decomposition may be applied across two or more dimensions (e.g., both spatial and frequency dimensions). In another embodiment of the invention, eigenmode decomposition may be applied across a single dimension (e.g., spatial or frequency dimensions). For example, multicarrier spreading codes (for example, orthogonal codes for data multiplexing in a given multiple-access channel) may be generated and processed via eigenmode decomposition.

Any of various water-filling or water-pouring schemes may be employed to optimally distribute the total transmission power over the available transmission channels, such as

to maximize spectral efficiency. For example, water-filling can be used to adapt individual WT transmission powers such that channels with higher SNRs are provided with correspondingly greater portions of the total transmit power. A transmission channel, as defined herein, may include a spatial (e.g., a sub-space) channel, a space-frequency channel, or some other channel defined by a set of orthogonalizing properties. Similarly, water filling may be used at a physically connected (i.e., wired) antenna array. The transmit power allocated to a particular transmission channel is typically determined by some predetermined channel-quality measurement, such as SNR, SINR, BER, packet error rate, frame error rate, probability of error, etc. However, different or additional criteria may be employed with respect to power allocation, including, but not limited to, WT battery life, load balancing, spatial reuse, power-control instructions, and near-far interference.

In conventional water filling, power allocation is performed such that the total transmission power P_T is some predetermined constant:

$$P_T = \sum_{j \in K} \sum_{k \in L} P_j(k)$$

where $L=\{1, \ldots, N_s\}$ signifies the available subspaces and $K=\{1, \ldots, N_f\}$ represents the available sub-carrier frequencies f_n. The received SNR (expressed by $\psi_j(k)$) for each transmission channel is expressed by:

$$\psi_j(k) = \frac{P_j(k)\lambda_j(k)}{\sigma^2}, \text{ for } j = \{1, \ldots, N_s\} \text{ and } k = \{1, \ldots, N_f\}$$

The aggregate spectral efficiency for the N_sN_f transmission channels is expressed by:

$$C = \sum_{j=1}^{N_s} \sum_{k=1}^{N_f} \log_2(1 + \psi_j(k))$$

The modulation and channel coding for each transmission channel may be adapted with respect to the corresponding SNR. Alternatively, transmission channels may be grouped with respect to their data-carrying capability. Thus, groups of transmission channels may share common modulation/coding characteristics. Furthermore, transmission channels having particular SNRs may be used for particular communication needs. For example, voice communications may be allocated to channels having low SNRs, and thus, data-carrying capabilities. In some cases, transmission channels that fail to achieve a predetermined threshold SNR may be eliminated. In one embodiment of the invention, water filling is employed such that the total transmission power is distributed over selected transmission channels such that the received SNR is approximately equal for all of the selected channels.

An embodiment of the invention may employ reliability assessment for determining required processing and virtual-array size (i.e., the number of active WTs functioning as WWAN receiver elements). Received bits or symbols that have low reliability need more processing. Bits or symbols with high reliability may be processed with fewer elements (WTs) or provided with lower processing requirements. More information typically needs to be combined for data streams having less reliability and less information may need to be combined for data streams having more reliability. Also, nodes (WTs) with good channel quality may share more information via the WLAN than nodes having poor channel quality. Optimization algorithms, such as water-filling algorithms may be employed in the reliability domain.

FIG. **3**A illustrates an embodiment of the invention in which a WLAN controller for a WLAN group of WTs first identifies received data streams that have the least reliability (e.g., reliability that is below a predetermined threshold) **301**. Then the WLAN controller increases allocated processing (e.g., increases the number of receiver nodes, increases the number of processing nodes, employs a processing approach having higher computational complexity, etc.) **302** to those data streams. Data symbols may be combined from the smallest number of nodes such that the reliability of the sum is maximized, or at least exceeds a predetermined threshold reliability. The processes **301** and **302** may be repeated **303** until a predetermined result is achieved or until there is no more data left for processing.

FIG. **3**B illustrates an embodiment of the invention in which a WLAN controller identifies received data streams that have the most reliability, or data streams having reliability that exceeds a predetermined reliability threshold **311**. The WLAN controller may decrease allocated processing (e.g., decrease the number of receiver nodes, decrease the number of processing nodes, employ a processing approach having lower computational complexity, etc.) **312** to those data streams. The processes **301** and **302** may be repeated **303** until a predetermined result is achieved or until there is no more data left for processing. Embodiments of the invention may provide for encoding information across channels having a wide range of reliability.

Embodiments of the invention may be configured to perform blind signal separation (BSS), such as independent component analysis. For example, A. Jourjine, S. Rickard, and O. Yilmaz, "Blind Separation of Disjoint Orthogonal Signals: Demixing N Sources from 2 Mixtures," in *Proceedings of the* 2000 *IEEE International Conference on Acoustics, Speech, and Signal Processing*, Istanbul, Turkey, June 2000, vol. 5, pp. 2985-88, which is included herein by reference, describes a blind source separation technique that allows the separation of an arbitrary number of sources from just two mixtures, provided the time-frequency representations of the sources do not overlap. The key observation in the technique is that for mixtures of such sources, each time-frequency point depends on at most one source and its associated mixing parameters.

In multi-user wireless communication systems that employ multiple transmit and receive antennas, the transmission of user information through a dispersive channel produces an instantaneous mixture between user transmissions. BSS may be used in such instances to separate received transmissions, particularly when training sequences and channel estimation are absent. In an exemplary embodiment of the invention, an OFDM-MIMO protocol may be provided across multiple independent WTs. Multiple transmissions are provided on at least one frequency channel, and frequency-domain techniques of BSS may be employed to recover received signals.

In one embodiment of the invention, at least one data transmission source may be adapted to convey its data across the WLAN to a plurality of WTs for transmission into the WWAN. In another embodiment of the invention, a plurality of WTs are adapted to receive data transmissions

from a WWAN and couple said received data transmissions into a WLAN (with or without baseband processing) wherein centralized or distributed signal-processing means are provided for separating the data transmissions. Said signal-processing means includes any MIMO-processing techniques, including multi-user detection, space-time processing, space-frequency processing, phased-array processing, optimal combining, and blind source separation, as well as others.

In one embodiment of the invention, a vector of binary data symbols $b_i(n)$ are encoded with a convolutional encoder to produce a coded signal:

$$s_i(n)=b_i(n)*c(n)$$

where c(n) represents a convolutional code of length L'. A cluster of N coded symbols corresponding to an ith user, data source, or data stream is represented by:

$$s_{n,i}=[s_i(n), \ldots, s_i(n+N-1)]^T$$

The transmit signal is generated by performing an N-point IDFT to $s_{n,i}$ to produce:

$$S_{n,i} = [S_i(n, 0), \ldots, S_i(n, N-1)]^T$$

where

$$S_i(n, k) = \sum_{m=0}^{N-1} s_i(n+m)e^{i2\pi km/N}$$

The values $S_i(n,k)$ are transmitted via at least one of N_t transmit antennas. On the receive side, N_r receive antennas (typically, $N_r \geq N_t$) are employed. The signal received by j^{th} antenna is expressed by:

$$R_j(n) = \sum_{i=1}^{N_t} S_i(n) * h_{ij} + n_j(n)$$

where $n_j(n)$ represents the zero-mean AWGN introduced by the channel, and h_{ij} is the channel impulse-response of the ith transmit antenna to the jth receive antenna. The received signal can be interpreted as a convolutive mixture of the coded signals, where the channel matrix h represents the mixing system. An N-point DFT is applied to the received signals $R_j(n)$ to produce:

$$r_j = [r_j(n), \ldots, r_j(n+N-1)]^T$$

where

$$r_j(n) = \sum_{m=0}^{N-1} R_j(n+m)e^{-i2\pi km/N}$$

Typically, a sufficient guard interval or cyclic prefix is employed to eliminate inter-symbol interference.

The signals from the N_r receiver antennas are grouped with respect to frequency bin. An observation at a kth frequency bin are expressed by:

$$r_n(k) = [r_1(n+k), r_2(n+k), \ldots, r_{N_r}(n+k))]^T = H(k)s(k) + n(k)$$

Thus, the observations $r_n(k)$ (k=0, . . . , N−1) can be interpreted as an instantaneous mixture of the transmitted signals s(k), where H(k) represents the mixing system.

There are many approaches for estimating the transmitted signals s(k) from the received signals $r_n(k)$ that may be employed by the current invention. An exemplary embodiment of the invention employs BSS techniques. One class of BSS produces an output vector having the following form:

$$y(k)=W^H(k)r_n(k)$$

where W(k) is an $N_r \times N_t$ matrix that groups the coefficients of the separating system. The output y(k) can also be expressed by:

$$y(k)=G(k)s(k)+W^{\gamma H}(k)n(k)$$

where $G(k)=W^H(k)H(k)$ represents the mixing/separating system. The goal of the separation process is to calculate the matrices W(k) so that the G(k) matrices are diagonal and the effects of noise $W^H(k)n(k)$ are minimized. Many different approaches are applicable for achieving these goals.

A BSS algorithm (such as the one described in J. F. Cardoso, A. Souloumiac, "Blind Beamforming for non-Gaussian Signals," *IEEE-Proceedings-F*, vol. 140, no. 6, pp. 362-370, December 1993, which is incorporated by reference herein) may be employed to separate the instantaneous mixture in each frequency bin. Each output at frequency bin k' can be regarded as corresponding to a single source at bin k' multiplied by a particular gain introduce by the algorithm. The outputs y(k') are then used as reference signals in order to recover the sources at frequencies k'±1. For example, the separation matrices W(k) are determined by minimizing the mean-square error between the outputs $y(k)=W^H(k)r^n(k)$ and reference signals y(k'). For a given frequency bin k:

$$W_o(k)=\arg\min_{W(k)} E\lfloor |y(k)-\alpha y(k')|^2 \rfloor$$

where α is a real constant, which is selected with respect to the convolutional code:

$$\alpha = \frac{\sum_{p=0}^{L-1} c^2(p)}{\sum_{p=0}^{L-2} c(p)c(p+1)}$$

This is done to ensure G(k)=G(k'). The solution to the optimization problem is given by:

$$W_o(k) = \alpha R_{r_n}^{-1}(k)R_{r_n y}(k, k')$$

where

$$R_{r_n}(k) = E[r_n(k)x^H(k)] \text{ and}$$

$$R_{r_n y}(k, k') = E[r_n(k)y^H(k')]$$

FIG. **4**A illustrates an embodiment of the invention wherein a plurality M of WTs **1109**.**1**-**1109**.M is coupled to a MIMO processor **1103** via a WLAN **1105**. In this particular embodiment, a computer-processing terminal **1119** may include the MIMO processor **1103**. The computer processing terminal **1119** may be provided with WLAN-interface functionality, and may optionally include WWAN-interface functionality.

The computer-processing terminal **1119** may include any of a plurality WLAN-connected devices with signal-processing capability. For example, the computer-processing

terminal **1119** may include one of the WTs **1109.1-1109**.M. In one aspect of the invention, the computer-processing terminal **1119** comprises a WLAN controller. In another aspect of the invention, the computer processing terminal **1119** comprises a network gateway, router, or access point including a CPU adapted to process signals received from the plurality of WTs **1109.1-1109**.M. Applications of embodiments of the invention include (but are not limited to) sensor networks, micro-networks, RFID systems, cellular networks, and satellite networks.

Each WT **1109.1-1109**.M may include a baseband processor **1102.1-1102**.M adapted to provide WWAN baseband (or IF) signals to the MIMO processor **1103** via the WLAN **1105**. The MIMO processor **1103** may be configured to separate interfering WWAN data symbols in the WWAN baseband signals. The separated WWAN data symbols are then coupled back to data processors **1104.1-1104**.M in the WTs **1109.1-1109**.M.

FIG. **4**B illustrates a functional embodiment of the invention in which MIMO processing operations (represented by MIMO processors **1103.1-1103**.M) may be distributed over two or more WTs **1109.1-1109**.M. Baseband processors **1102.1-1102**.M provide WWAN baseband signals to a WLAN controller **1106**, which may distribute the signals (and signal-processing instructions) to the MIMO processors **1103.1-1103**.M. The separated WWAN data symbols are then coupled back to data processors **1104.1-1104**.M.

FIG. **4**C represents a functional embodiment of the invention. At least one WT may provide WWAN access information **1140** to a WLAN controller. The WWAN access information typically includes necessary information (such as at least one WWAN channel assignment, authentication codes, etc.) to access at least one particular WWAN channel. The WWAN access information may optionally include performance information, such as WWAN channel estimates, link-bandwidth demand, link priority, and/or WWAN channel-quality measurements (e.g., SNR, SINR, BER, PER, latency etc.). This information is typically provided to the WLAN controller by one or more WTs.

The WLAN controller determines which WTs to activate **1141** for a particular WWAN communication link. This may be performed for either or both transmission and reception. The determination of which WTs will be active **1141** in a given WWAN link typically depends on a combination of factors, including (but not limited to) the number M of WTs required to achieve predetermined channel characteristics or access parameters, which WTs have the best WWAN channel quality, load balancing, power-consumption balancing, computational overhead, latency, and WLAN-access capabilities. Accordingly, the WLAN controller may send control information via the WLAN to the WTs that includes state information (e.g., operating-mode assignments, such as active, standby, sleep, and awake).

The WLAN controller may convey WWAN information to the active WTs **1142**. The WWAN information may be derived from the WWAN access information and provided to the WTs to establish and/or maintain at least one WWAN link. Accordingly, the WWAN information may include WWAN channel assignments. The WWAN information may include beam-forming weights and/or space-time codes. Accordingly, the step of conveying WWAN information to the WTs **1142** may optionally include a preliminary signal-processing step (not shown), such as blind adaptive or deterministic weight calculation. This preliminary signal-processing step (not shown) may be distributed among a plurality of the WTs, or it may be performed in a centralized mode, such as by a single computing terminal. A distributed-computing mode may take various forms. In one mode, each of a plurality of WTs takes its turn functioning as a computing terminal. In another mode, multiple WTs function as computing terminals simultaneously.

Communications in the WWAN link are coordinated between the WTs in order to synchronize the transmitted and/or received WWAN signals **1143**. A receiver embodiment of the invention may provide for synchronizing the received WWAN signals, such as to provide for coherent combining. A transmitter embodiment of the invention may provide for synchronizing the transmitted WWAN signals from the WTs such as to enable coherent combining at some predetermined WWAN terminal.

An optional transmitter embodiment of the invention may employ synchronization to deliberately time-offset signals arriving at one or more WWAN terminals in order to provide for transmit diversity by the WTs. In such embodiments, one or more of the WT transmissions may be provided with time-varying complex weights (e.g., amplitudes and/or phases), such as described in S. A. Zekavat, C. R. Nassar and S. Shattil, "Combined Directionality and Transmit Diversity via Smart Antenna Spatial Sweeping," proceedings of 38th *Annual Allerton Conference on Communication, Control, and Computing, University of Illinois in Urbana-Champaign*, pp. 203-211, Urbana-Champaign, Ill., USA, October 2000, S. A. Zekavat, C. R. Nassar and S. Shattil, "Smart antenna spatial sweeping for combined directionality and transmit diversity," *Journal of Communications and Networks* (*JCN*), *Special Issue on Adaptive Antennas for Wireless Communications*, Vol. 2, No. 4, pp. 325-330, December 2000, and S. A. Zekavat, C. R. Nassar and S. Shattil, "Merging multi-carrier CDMA and oscillating-beam smart antenna arrays: Exploiting directionality, transmit diversity and frequency diversity," *IEEE Transactions on Communications*, Vol. 52, No. 1, pp. 110-119, January 2004, which are incorporated by reference herein.

In an alternative embodiment of the invention, providing WWAN access information **1140** may include providing WWAN channel-performance information from the WTs to at least one WWAN terminal. Thus, conveying WWAN information to the WTs **1142** may be performed by at least one WWAN terminal. An optional embodiment of the invention may provide for at least one WWAN terminal determining which WTs in a WLAN group will operate in a given WWAN link and conveying that WWAN information **1142** to the WLAN group. Embodiments of the invention may provide capabilities to WWAN terminals to set up and adapt the formation of WLAN groups and determine which WTs are assigned to which WLAN groups. Such control capabilities may employ GPS positions of WTs to assist in assigning WTs to a WLAN group. Some embodiments of the invention may provide for collaboration between a WWAN and a WLAN group for activating WTs and/or assigning WTs to the WLAN group.

In one embodiment of the invention, step **1142** may include a preliminary signal-processing step (not shown) in which at least one WWAN terminal calculates cooperative-beamforming weights for the WTs based on channel-performance information provided by the WTs. Accordingly, the WWAN information may include cooperative-beamforming weights derived by at least one WWAN terminal and conveyed to at least one WT. Synchronization **1143** of the transmitted and/or received WWAN signals by the WTs may optionally be performed by at least one WWAN terminal. Similarly, embodiments of the invention may provide for applying time-varying weights to WWAN-terminal transmissions (such as described previously).

FIG. **4**D illustrates a functional embodiment of the invention adapted to perform cooperative beamforming. WWAN channel information is provided **1144** for assigning subchannels **1145** and calculating cooperative beamforming (i.e., WT) weights **1146**. The beamforming weights are then distributed to the appropriate WTs **1147**.

Sub-channel assignments **1145** are typically performed with respect to a predetermined subchannel-quality threshold, such as SNR, SINR, or BER. Subchannels having the required minimum performance may be assigned for transmission and/or reception. Sub-channel assignments **1145** may also provide for bit loading. Alternatively, sub-channel assignments **1145** may be performed without regard to sub-channel quality. In such cases, spreading or channel coding may be performed to mitigate the effects of lost and compromised subchannels.

Weight calculations **1146** may be achieved by either deterministic or blind adaptive techniques. The calculations may be performed by one or more WTs, or alternatively, by at least one WWAN terminal. Cooperative beamforming weights may be provided to achieve at least one form of array processing benefit, including diversity combining, interference cancellation, and spatial reuse.

FIG. **5**A illustrates a functional embodiment of the invention that may be implemented by hardware and/or software. A plurality of transmitted WWAN signals are received **1150** by a plurality of WTs. Baseband (or IF) WWAN information is derived **1151** from the received WWAN signals. For example, in an OFDM system, a baseband WWAN signal s_k received by a kth WT can be represented by a linear superposition of up to M transmitted data symbols d_i {i=1, . . . , M} weighted by complex channel weights α_{ik}:

$$s_k = \sum_{i=1}^{M} \alpha_{ik} d_i + \eta_k$$

Baseband WWAN signals (which typically include the complex channel weights α_{ik}), are optionally transmitted **1158** into a WLAN for distribution to one or more other WTs. Accordingly, data (including baseband WWAN signals s_k, complex channel weights α_{ik}, and/or MIMO weights β_{il}) from the one or more other WTs is received **1152** from the WLAN. MIMO processing **1153** may be performed to produce at least one set of MIMO weights β_{il} and/or estimated transmitted data symbols d_i, which may optionally be transmitted **1159** to at least one other WT via the WLAN. Baseband information recovery **1154** may optionally be performed on the estimated transmitted data symbols d_i. For example, baseband operations may include despreading, demodulation, error correction (e.g., channel decoding), demultiplexing, de-interleaving, data formatting, etc.

FIG. **5**B illustrates an alternative functional embodiment of the invention that may be implemented by hardware and/or software. In this case, WWAN baseband information that does not include MIMO weights may be received **1155** from at least one other WT via the WLAN. Thus, MIMO processing **1153** includes generating MIMO weights, which may be transmitted **1159** to one or more WTs via the WLAN. The functional embodiment illustrated in FIG. **5**B is particularly applicable to a WT functioning as a computer-processing terminal in a WLAN group. In the case where the subject WT functions as the only MIMO-processing terminal in a given WLAN group, the functional embodiment may be characterized solely by steps **1155**, **1153**, **1154**, and optional step **1159**. Furthermore, the functional embodiments described herein may be adapted to perform other array-processing operations in addition to, or instead of, MIMO.

FIG. **6**A illustrates functional and apparatus embodiments of the present invention pertaining to one or more WTs, such as WT **1109**. In particular, a WWAN interface **1161** may be coupled to a beam-forming system **1162**, which is coupled to a WLAN interface **1163**. The beam-forming system **1162** may employ data received from the WLAN interface **1163** (and optionally, from data received from the WWAN interface **1161**) to perform beam-forming operations. The WLAN interface **1163** is adapted to provide WLAN data communications with at least one other WT (not shown). The beam-forming system **1162** may be adapted to provide either or both WWAN transmission beam-forming and reception beam-forming operations.

FIG. **6**B illustrates a preferred embodiment of the invention that may be employed as either or both apparatus and functional embodiments. A WWAN interface **1161** includes an RF front-end **1611**, a DAC/ADC module **1612**, a pulse-shaping filter **1613**, a modulator/demodulator module **1614**, an equalizer modulator **1615** that optionally employs pre-equalization means, a multiplexer/demultiplexer module **1616**, and a baseband-processing module **1617**. The WWAN interface may also include a network-control module **1618** that may be responsive to both WWAN control signaling and WLAN-control signals configured to convey WWAN control information to the WWAN interface **1161**.

A WLAN interface **1163** includes an RF front-end **1631**, a DAC/ADC module **1632**, a pulse-shaping filter **1633**, a modulator/demodulator module **1634**, an equalizer modulator **1635** that optionally employs pre-equalization means, a multiplexer/demultiplexer module **1636**, and a baseband-processing module **1637**. A beam-forming module **1162** is adapted to process signals from either or both baseband modules **1617** and **1637**. The beam-forming module **1162** may be adapted to process local data symbols generated by a local data source **1160**.

As described previously, the beam-forming module **1162** may be adapted to perform beam-forming operations on baseband WWAN signals received from either or both the WWAN interface **1161** and the WLAN interface **1163**. Specifically, the beam-forming module **1162** may be adapted to perform beam forming by utilizing baseband WWAN signals, channel weights (or other channel-characterization information), beam-forming weights (such as MIMO weights), and/or baseband data symbols. Baseband data symbols may be received from the local data source **1160**, from local data sources on other WTs, and/or from estimated data generated by one or more external beam-forming modules (e.g., beam-forming modules on other WTs). Optionally, the beam-forming module **1162** may be configured to adjust equalization and/or pre-equalization **1615**.

In an exemplary embodiment of the invention, the beam-forming module **1162** is configured to process baseband WWAN signals received from the baseband-processing module **1617** and the WLAN interface **1163**. Information output from the beam-forming module **1162** is conveyed to at least one of the WLAN interface **1163** and a local data sink **1169**. Estimated WWAN data symbols output by the beam-forming module **1162** may optionally be processed by the baseband-processing module **1617** or the local data sink **1169**. For example, the baseband-processing module **1617** may be configured to perform various types of signal processing, including error correction (such as Viterbi decoding), constellation mapping, and data formatting on

data output by the beam-forming module **1162**. The resulting processed data may then be coupled to the local data sink **1169** and/or the WLAN interface **1163**. Alternatively, the local data sink **1169** may perform the previously described signal-processing types.

Beam forming is performed cooperatively with other WTs to provide predetermined WWAN spatial processing for transmitted and/or received WWAN signals. Thus, a network-function adapter **1165** may be employed to provide WWAN channel-access information to one or more WTs. For example, some embodiments of the invention require multiple WTs to function as a single WT. In this case, each WT is provided with WWAN-access information corresponding to the single WT it is configured to spoof. The network function adapter **1165** may be configured to generate WWAN-access information to be distributed to at least one other WT and/or it may be configured to receive WWAN-access information from the WLAN interface **1163** and convey it to the network-control module **1618** in the WWAN interface **1161**.

WWAN-access information typically includes channelization (or some other form of multiple access) information used to transmit and/or receive data from the WWAN. For example, WWAN-access information may take the form of user identification sequences, assigned time slots, frequency band assignments, and/or multiple-access code assignment.

In some embodiments of the invention, a particular WT may be required to function as multiple WTs. In this case, WWAN-access information is conveyed to the network-control module **1618** and data is configured to be appropriately multiplexed and/or demultiplexed relative to a plurality of multiple-access channels.

The network-function adapter **1165** may be used to convey other WWAN control information to WTs, including (but not limited to) power-control commands, timing and synchronization information, key-exchange messages, WWAN routing tables, acknowledgements, requests for retransmission, probing signals, and paging messages.

The network-function adapted **1165** may be configured to alter or adapt the WWAN-control information that it receives from either or both the WWAN interface **1161** and the WLAN interface **1163**. For example, WWAN power-control commands received by one or more WTs may be adapted by the network-function adapter **1165** prior to being conveyed to network-control modules (such as network-control module **1618**) on multiple WTs. Power control may be adapted by one or more network-function adapters **1165** for particular WTs depending on their WWAN channel quality and power. Alternatively, the network-function adapter **1165** may adapt the number Mof WTs servicing a given link in response to WWAN control information.

In some embodiments of the invention, it may be advantageous to employ a single decision system for network-function adaptation **1165**. In one mode of operation, the network-function adapter **1165** of only one of a plurality of WTs assigned to a particular WWAN channel is adapted to convey WWAN control information to the other WTs. In each of the other WTs, the associated network-function adapter **1165** identifies the WWAN control information received from the WLAN and couples it to the network-control module **1618**. Thus, the network-function adapter **1165** may instruct the network-control module **1618** to disregard one or more types of WWAN control information received from the WWAN interface **1161**. One or more network-function adapters (such as network-function adapter **1165**) may synchronize WT responses to WWAN control information.

In another embodiment of the invention, each WT may be responsive to WWAN control information that it receives. In yet another embodiment, each of a plurality of WWAN multiple-access channels is preferably controlled by a separate network-function adapter **1165**. These and other adaptations and permutations of network function may be embodied by functional aspects of the network-function adapter **1165**.

One embodiment of the invention employs the functionality of a group of WTs corresponding to FIG. **1**C with respect to the transceiver embodiment shown in FIG. **6**B. In a transmission configuration, a serial data stream s(n) from the local data source **1160** of a particular WT is channel coded to produce coded data stream u(n), which is grouped in blocks of size N: $u(i)=[u(iN), u(iN+1), \ldots, u(iN+N-1)]^T$. In this case, Nis chosen to equal the number M of WTs employed as antenna elements. The N−1 coded data symbols u(n) are distributed to the other N−1 WTs via the WLAN interface **1163**.

At each WT's Mux/DeMux block **1615**, a particular data symbol u(n) is mapped into a frequency bin vector. In one aspect of the invention, each data symbol u(n) is provided with both a unique frequency bin and a unique WT, such as to achieve optimal diversity benefits. This takes the form of a frequency-bin vector having all zeros except for one bin corresponding to u(n). This scheme can be used to achieve low transmitted PAPR, as well as other benefits. In other embodiments, alternative WT/frequency-bin combinations may be employed. For example, multiple serial data streams s(n) may be provided to the frequency-bin vector. Redundant symbols may be provided. Alternatively, the data s(n) may be spread across frequencies and/or WTs.

At each Mod/DeMod block **1614**, an IFFT is applied to each data block to produce:

$$\tilde{u}(i)=F^H U(i)$$

where F is the N×N FFT matrix with $F_{nm}=N^{-1/2}\exp(-j2\pi nm/N)$. A cyclic prefix of length N_{CP} may be inserted in ũ(i) to produce $\tilde{u}_{CP}(i)\beta T_{CP}\tilde{u}(i)$, which has length $N_T=N+N_{CP}$. The term $T_{CP}=[I_{CP}{}^T I_N{}^T]^T$ represents the cyclic prefix insertion in which the last N_{CP} rows of the N×N identity matrix I_N (denoted by I_{CP}) are concatenated with identity matrix I_N. The term β is the power loss factor, $\beta=\sqrt{N/N_T}$.

The block $\tilde{u}_{CP}(i)$ is serialized to yield $\tilde{u}_{CP}(n)$, which is then pulse shaped **1613**, carrier modulated **1612**, amplified, and transmitted **1611** via multiple antenna elements through a channel. The channel impulse response h(n) includes the effects of pulse shaping, channel effects, receiver filtering, and sampling.

In a receiver configuration of the invention, each of a plurality of WTs is adapted to receive a different transmitted symbol on a different orthogonal carrier frequency. For a WT employing a square-root Nyquist receive filter, the received samples are expressed by:

$$x(n)=\tilde{u}_{CP}(n)*h(n)+v(n)$$

where v(n) is additive white Gaussian noise (AWGN). The received samples are grouped into blocks of size N_T: $x_{CP}(i)=[x(iN_T), x(iN_T+1), \ldots, x(iN_T+N_T-1)]^T$. The first N_{CP} values of $x_{CP}(i)$ corresponding to the cyclic prefix are discarded, which leaves N-length blocks expressed by: $x(i)=[x(iN_T+N_{CP}), x(iN_T+N_{CP}+1), \ldots, x(iN_T+N_T-1)]^T$. H is defined as an N×N circulant matrix with $\tilde{H}_{n,m}=h((n-m)_{mod\ N})$. The block input-output relationship is expressed as: $\tilde{x}(i)=\beta\tilde{H}\tilde{u}(i)+\tilde{n}(i)$, where $\tilde{n}(i)=[v(iN_T+N_{CP}), v(iN_T+N_{CP}+1), \ldots, v(iN_T+N_T-1)]^T$ is the AWGN block. Applying the FFT to $\acute{x}(i)$ yields:

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$$x(i) = F\tilde{x}(i) = \beta F\tilde{H}F^H u(i) + \tilde{\eta}(i) = \beta D_H u(i) + \eta(i)$$

where

$$D_H = \text{diag}\left[H\left(e^{j0}\right), H\left(e^{j(2\pi/N)}\right), \ldots H\left(e^{j(2\pi(N-1)/N)}\right)\right] = F\tilde{H}F^H$$

and $H(e^{j2\pi f})$ is the frequency response of the ISI channel;

$$H(e^{j2\pi f}) = \sum_{n=0}^{N_{CP}} h(n)e^{-j2\pi fn}.$$

An equalizer followed by a decoder uses x(i) to estimate the data symbols encoded on u(i).

Preferred embodiment of the invention may employ Spread-OFDM, which involves multiplying each data block s(n) by a spreading matrix A:

$$u(n)=As(n)$$

In the case where CI spreading codes are employed, A_{nm}=exp(−j2 πnm/N). This maps the data symbols to pulse waveforms positioned orthogonally in time. This choice of spreading codes also gives the appearance of reversing the IFFT. However, the resulting set of pulse waveforms is a block, rather than a sequence, wherein each waveform represents a cyclic shift within the block duration T_s, such as described in U.S. Pat. Appl. Pubs. 20030147655 and 20040086027, which are both incorporated by reference.

FIG. **7**A illustrates a functional embodiment of the invention related to calculating MIMO weights in a cooperative-beamforming network. A plurality of WTs provide received baseband information from a WWAN channel **1701** that includes a training sequence and/or a data sequence having a predetermined constellation of values. WWAN MIMO processing is performed **1702** on the received baseband information to derive a plurality of array-processing weights β_i, which are then distributed **1703** via the WLAN to a predetermined plurality of WTs.

FIG. **7**B illustrates a functional embodiment of the invention adapted to calculate transmitted data symbols received by a cooperative-beamforming network. A plurality of WTs provide received baseband information from a WWAN channel **1701** that includes a data sequence having a predetermined constellation of values. WWAN MIMO processing may be performed **1704** on the received baseband information to derive a plurality of estimated data symbols d_i, which are then conveyed **1705** via the WLAN to at least one destination WT. The WWAN MIMO processing **1704** may optionally include providing for any of a set of signal-processing operations, including filtering, demodulation, demultiplexing, error correction, and data formatting.

FIG. **8**A illustrates a functional embodiment for a method and apparatus of the invention. Specifically, a data source **1800** is adapted to distribute a plurality of data symbols via a WLAN channel **199** to a plurality N_t of WTs **1806.1-1806**.N_t, which are adapted to transmit the data symbols into at least one WWAN channel **99**. Although the functional embodiment shown in FIG. **8**A is illustrated with respect to uplink WWAN functionality, the functional blocks may alternatively be inverted to provide for downlink WWAN functionality.

The data source and the WTs **1806.1-1806**.N_t include appropriate WLAN-interface equipment to support distribution of the data symbols to the WTs **1806.1-1806**.N_t. For example, the WTs **1806.1-1806**.N_t are shown including WLAN-interface modules **1801.1-1801**.N_t. The WLAN channel **199** may optionally include additional network devices that are not shown, such as routers, access points, bridges, switches, relays, gateways, and the like. Similarly, the data source **1800** and/or the WTs **1806.1-1806**.N_t may include one or more said additional network devices. The data source **1800** may include at least one of the WTs **1806.1-1806**.N_t.

A coder **1803.1-1803**.N_t in each of the WTs **1806.1-1806**.N_t is adapted to receive a baseband data sequence from the associated WLAN-interface module **1801.1-1801**.N_t and provide coding, such as channel coding, spreading, and/or multiple-access coding. A coded data sequence output from each coder **1803.1-1803**.N_t is mapped into frequency bins of multicarrier generators, such as IDFTs **1804.1-1804**N_t. This embodiment may be employed to produce multicarrier signals or to synthesis single-carrier signals from a plurality of spectral components. Alternatively, other types of multicarrier generators may be employed, such as quadrature-mirror filters or DSPs configured to perform other transform operations, including Hadamard transforms. The resulting multicarrier signals are coupled into the WWAN channel **99** by associated WWAN-interface modules **1805.1-1805**.N_t.

For each flat-fading subcarrier frequency channel, the WWAN channel may be characterized by channel responses **1890.1-1890**-N_t and **1899.1-1899**-N_t of a mixing system. The channel responses **1890.1-1890**-N_t and **1899.1-1899**-N_t represent elements of H, an $N_r \times N_t$ channel-response matrix that characterizes the complex gains (i.e., transfer function, or spatial gain distribution) from the N_t transmission elements to the N_r receive elements; and $n_t(n)$ represents an AWGN contribution having zero mean and zero variance.

There are N_r receiver elements comprising WWAN-interface modules **1815.1-1815**.N_r and filter banks, such as DFTs **1814.1-1814**.N_r, coupled to at least one MIMO combiner **1810**. The MIMO combiner **1810** is adapted to perform any number of signal-processing operations, including decoding received data symbols. In one embodiment of the invention, the MIMO combiner **1810** is adapted to perform diversity combining. In another embodiment of the invention, the MIMO combiner **1810** is adapted to perform spatial (e.g., sub-space) processing. Furthermore, many other applications and embodiments of the invention may be achieved using the functional description (or minor variations thereof) depicted in FIG. **8**A.

FIG. **8**B illustrates a functional embodiment of the invention that may be incorporated into specific apparatus and method embodiments. In particular, WWAN signals received from a WWAN channel **99** by a plurality N_r of WTs **1836.1-1836**.N_r are conveyed via a WLAN channel **199** to a MIMO combiner **1830**.

In this case, WWAN data symbols are encoded by one or more coders (such as coders **1821.1-1821**.N_t), impressed on a plurality of subcarriers by IDFTs **1822.1-1822**.N_t, and coupled into the WWAN channel **99** by a plurality of WWAN-interface modules **1825.1-1825**.N_t. Received WWAN signals may be coupled from the WWAN channel **99** by a plurality N_r of WTs **1836.1-1836**.N_r. Each WT **1836.1-1836**.N_r includes at least one WWAN-interface module (such as WWAN-interface modules **1831.1-1831**.N_r), a filter bank (such as DFTs **1834.1-1834**.N_r), and a WLAN-interface module (such as **1835.1-1835**.N_r).

WWAN signals received by each WT **1836.1-1836**.N_r are converted to a baseband data sequence, separated into frequency components (by the DFTs **1834.1-1834**.N_r), and then adapted for transmission into the WLAN channel **99**. A MIMO combiner **1830** may be configured to receive WLAN

transmissions, recover the frequency components, and perform MIMO processing to generate estimates of the transmitted WWAN data symbols. The MIMO combiner **1830** and/or the WTs **1836.1-1836**.N_r may be adapted to perform decoding. In one embodiment of the invention, the MIMO combiner **1830** may include one or more of the WTs **1836.1-1836**.N_r.

FIG. **8**C illustrates an embodiment of the invention in which WTs **1836.1-1836**.N_r are adapted to perform time-domain (e.g., Rake) processing. Specifically, each WT **1836.1-1836**.N_r includes a Rake receiver **1854.1-1854**.N_r. The embodiment illustrated in FIG. **8**C is particularly suited to performing MIMO operations on received direct-sequence signals, such as direct sequence CDMA (DS-CDMA) signals.

Particular embodiments of the invention may be directed toward transmitting and/or receiving any of the well-known types of spread signals. Spread signals include spread-spectrum signals in which a transmitted signal is spread over a frequency band much wider than the minimum bandwidth needed to transmit the information being sent. Spread spectrum includes direct-sequence modulation commonly used in CDMA systems (e.g., cdmaOne, cdma2000, 1×RTT, cdma 1×EV-DO, cdma 1×EV-DV, cdma2000 3×, W-CDMA, Broadband CDMA, and GPS), as well as frequency-domain spreading techniques, such as spread-OFDM, multi-carrier CDMA, and multi-tone CDMA.

In a DS-CDMA system, a kth WWAN transmission signal $s^k(t)$ that includes N code bits $\{b^k[n]\}_{n=1}^{N}$ is given by:

$$s^k(t)=\sum_{n=0}^{N-1} b^k[n]g_{T_b}(t-nT_b)g_\tau(t)a^k(t-iT_b)\cos(2\pi f_c t)$$

where

$$a^k(t)=\sum_{i=0}^{G-1} C_i^k g_{T_c}(t-iT_c),\ C_i^k\in\{-1,1\}$$

is the DS spreading signal, G represents processing gain, T_c is the chip duration, T_b is the bit duration, and $g_{T_c}(t)$, $g_{T_b}(t)$, and $g_\tau(t)$ represent the chip, bit, and transmitted pulse shapes, respectively.

A plurality M of WTs linked together by a WLAN comprises elements of an M-element antenna array capable of receiving K≤M transmission channels. In a frequency-selective channel, the received signal at the array is:

$$r(t)=\sum_{k=1}^{K}\sum_{l=0}^{L^k-1}\sum_{n=0}^{N-1}\alpha_l^k\vec{V}(\vartheta_l^k)b_k[n]g(t-\tau_l^k-nT_b)\cos(2\pi f_c t+\varphi_l^k)+\upsilon(t)$$

where $\vec{V}(\vartheta)$ is an array-response vector, K is the number of received transmission channels, L^k is the number of distinct fading paths corresponding to the kth user, α_l^k is the fade amplitude associated with path l and user k, $\varphi_l^k=U[0,2\pi]$ represents the associated fade phase, Σ_l^k is the path time-delay (which occurs below a predetermined duration threshold T_{max}), and ϑ_l^k denotes angle of arrival. The array response vector $\vec{V}(\vartheta)$ is expressed by:

$$\vec{V}(\varepsilon)=[1\ e^{-2\pi d1\cos\theta/\lambda}\ \ldots\ e^{-2\pi dM\text{-}1\cos\theta/\lambda}]$$

where d_m is the antenna separation, and X is the wavelength corresponding to carrier frequency f_c. For a jth user's l^{th} path, the nth bit at the beamformer output is given by:

$$z_l^j[n]=W^H(\vartheta_l^k)\int_{+(n-1)T_b}^{+nT_b} r(t)\cos(2\pi f_c t+\varphi_l^j)a^j(t-\tau_l^j-(n-1)T_b)dt$$

where $W(\vartheta_l^k)$

is the weighting vector of the beamforming system. $z_l^k[n]$ can be expressed by four components:

$$z_l^k[n]=S_i^j[n]+ISI_i^j[n]+IXI_i^j[n]+\upsilon_i^j[n]$$

where S is the desired signal, ISI is inter-symbol interference, IXI is cross interference (i.e., multiple-access interference), and ν is the AWGN contribution. These components can be expressed as follows:

$$S_l^j[n]=\alpha_l^j W^H(\vartheta_l^j)\vec{V}(\vartheta_l^j)b^j[n]G$$

$$ISI_i^j[n]=\sum_{\substack{h=0\\h\neq l}}^{L^k-1}\sum_{n=0}^{N-1}\alpha_l^k W^H(\vartheta_h^j)\vec{V}(\vartheta_l^k)b^j[n]\cos(\varphi_h^j-\varphi_l^j)R_{jj}(\tau_h^j-\tau_l^j-nT_b)$$

$$IXI_i^j[n]=\sum_{\substack{k=1\\k\neq j}}^{K}\sum_{\substack{h=0\\h\neq l}}^{L^k-1}\sum_{n=0}^{N-1}\alpha_l^k W^H(\vartheta_h^k)\vec{V}(\vartheta_l^j)b^j[n]\cos(\varphi_h^k-\varphi_l^j)R_{kj}(\tau_l^j-\tau_h^k-nT_b)$$

$$\upsilon_l^j[n]=\int_{+(n-1)T_b}^{+nT_b} W^H(\vartheta_l^j)n(t)a^j(t-\tau_l^j)\cos(2\pi f_c t+\varphi_l^j)dt$$

where $W^H(\vartheta_l^j)\vec{V}(\vartheta_l^j)$

represents the spatial correlation, φ_l^j and Σ_l^j are the random phase and time delay for the jth user's l^{th} path, G is the processing gain, and R_{ij} and R_{kj} are the partial auto-correlation and cross-correlation of the direct sequence code(s):

$$R_{kj}(\tau)=\int_\tau^T a^k(t)a^j(t-\tau)dt$$

Maximal ratio combining produces an output:

$$z^j[n]=\sum_{l=0}^{L-1}\alpha_l^j z_l^j[n]$$

which can be processed by a decision processor. In this case, the BER is given by:

$$P_e=\int_0^\infty Q(2r_o)f(r_o\mid\bar{r}_o)dr_o$$

where $\bar{r}_o$ is the mean value of the instantaneous SINR, r_o, and Q( ) represents the complementary error function.

It should be appreciated that the WTs may be adapted to perform either or both time-domain (e.g., Rake) or frequency-domain processing as part of a receiver operation. Signals received by a plurality of WTs may be combined with respect to any combining technique, including EGC, MRC, Minimum Mean Squared Error Combining, other

types of optimal combining, Successive Interference Cancellation, and other matrix-reduction/matrix diagonalization techniques. Array-processing operations may include combinations of local and global processing. For example, diversity combining may be performed at each multi-element WT. Then signals from each WT may be combined (e.g., in a central processor) to perform sub-space (e.g., directional) processing. Other combinations of local and global processing may be employed. Similarly, combinations of sub-space processing (i.e., capacity enhancement) and diversity combining (i.e., signal-quality enhancement) may be performed. It should also be appreciated that the WTs may be adapted to perform either or both time-domain and frequency-domain processing for transmission. Thus, appropriate delays or complex weights may be provided to WT transmissions to produce a coherent phase front that converges at a predetermined WWAN destination node.

FIG. **9**A illustrates an optional transmission embodiment of the present invention. That is, method and apparatus configurations can be inferred from the following descriptions. A data source **1900** is adapted to provide data for processing by an array processor, such as MIMO processor **1902**. Optionally, other types of array processors may be provided. A physical (e.g., wired) connection **1902** and/or a wireless connection **1901** couple the data between the data source **1900** and the MIMO processor **1902**. The wireless connection **1901** is enabled by a WLAN **1999**. The MIMO processor **1902** is adapted to provide MIMO processing to the data, such as providing complex channel weights, providing spreading weights, and/or providing channel coding.

In one exemplary embodiment of the invention, MIMO processor **1902** provides convolutional or block channel coding to the data, which effectively spreads each data bit over multiple coded data bits. The resulting coded data bits are then grouped in serial blocks by the MIMO processor **1902**. Signal-block outputs from the MIMO processor **1902** are provided with serial-to-parallel conversion by the WLAN **1999** (which is denoted by S/P **1914**) and distributed to a plurality of WTs **1906**.**1**-**1906**.M.

Each WT **1906**.**1**-**1906**.M has a WLAN interface **1907**.**1**-**1907**.M adapted to receive and demodulate the data received from the MIMO processor **1902**. The MIMO processor **1902** is accordingly equipped with a WLAN interface that is not shown. The MIMO processor **1902** is typically comprised of one or more WTs **1906**.**1**-**1906**.M. In some embodiments of the invention, MIMO processor **1902** may include at least one computer-processing terminal that does have a WWAN interface.

Data received from the MIMO processor **1902** is then modulated **1908**.**1**-**1908**.M by each WT **1906**.**1**-**1906**.M for transmission into a WWAN channel by a corresponding WWAN interface **1909**.**1**-**1909**.M. Modulation **1908**.**1**-**1908**.M typically includes mapping blocks of data bits to data symbols, which are then mapped to a modulation constellation. Modulation **1908**.**1**-**1908**.M may also include channel coding and/or data interleaving. In an exemplary embodiment of the invention, modulation **1908**.**1**-**1908**.M includes the application of complex WWAN channel weights. Such channel weights may optionally be provided by the MIMO processor **1902**. In alternative embodiment of the invention, modulators **1908**.**1**-**1908**.M provide a predetermined delay profile (provided by the MIMO processor **1902**) to the data to be transmitted into the WWAN channel.

FIG. **9**B illustrates a functional flow chart that pertains to transmitter apparatus and method embodiments of the invention. One or more data sources **1920**.**1**-**1920**.K are coupled via a WLAN **1999** to a plurality M of WTs **1926**.**1**-**1926**.M. Each WT **1926**.**1**-**1926**.M includes a WLAN interface **1927**.**1**-**1927**.M, an array processor (such as a MIMO processor **1926**.**1**-**1926**.M), and a WWAN interface **1929**.**1**-**1929**.M.

The data sources **1920**.**1**-**1920**.K optionally include baseband-processing capabilities, such as channel coding, interleaving, spreading, multiplexing, multiple-access processing, etc. The data sources **1920**.**1**-**1920**.K include WLAN interfaces (not shown). The data sources **1920**.**1**-**1920**.K may include one or more WTs **1926**.**1**-**1926**.M.

The WLAN interfaces **1927**.**1**-**1927**.M include apparatus and means for converting received signals that were formatted for transmission in the WLAN **1999** into baseband data signals. The MIMO processors **1926**.**1**-**1926**.M are adapted to provide for frequency-domain and/or time-domain MIMO operations on the baseband data signals received from the WLAN interfaces **1927**.**1**-**1927**.M. Alternatively, the MIMO processors **1926**.**1**-**1926**.M may be adapted to perform phase operations at WWAN carrier frequencies transmitted by the WWAN interfaces **1929**.**1**-**1929**.M. The WWAN interfaces **1929**.**1**-**1929**.M provide any necessary baseband, IF, and RF operations necessary for transmitting data in a WWAN channel.

FIG. **10**A illustrates software components of a transmission embodiment of the invention residing on a computer-readable memory **1950**. An array-processing weighting source-code segment **1951** is adapted to generate a plurality of array-element weights for an antenna array comprised of a plurality of WTs coupled to at least one WWAN. The array-element weights may include at least one of frequency-domain weights (e.g., complex sub-carrier weights) and time-domain weights (e.g., weighted Rake taps). The array-processing weighting source-code segment **1951** is adapted to accept as input at least one of a set of information inputs, including data signals for transmission into the WWAN, training signals (e.g., known transmission symbols) received from the WWAN, data signals (e.g., unknown transmission symbols) received from the WWAN, WWAN channel estimates, and WWAN-control information.

The array-processing weighting source-code segment **1951** is adapted to provide as output at least one of a set of information signals, including WWAN weights and weighted data for transmission into the WWAN (i.e., weighted WWAN data). A WLAN distribution source code segment **1952** is provided for distributing either or both WWAN weights and weighted WWAN data received from source-code segment **1951** to a plurality of WTs via at least one WLAN. The WLAN distribution source code segment **1952** may optionally function to couple at least one of a set of information inputs to the source-code segment **1951**, including data signals for transmission into the WWAN (such as generated by other WTs), training signals received from the WWAN, data signals received from the WWAN, WWAN channel estimates, and WWAN-control information.

FIG. **10**B illustrates software components of a receiver embodiment of the invention residing on a computer-readable memory **1960**. An array-processing weighting source-code segment **1961** is adapted to generate a plurality of array-element weights for an antenna array comprised of a plurality of WTs coupled to at least one WWAN. The array-element weights may include at least one of frequency-domain weights (e.g., complex sub-carrier weights) and time-domain weights (e.g., weighted Rake taps). The array-processing weighting source-code segment **1961** is adapted to accept as input at least one of a set of information inputs, including training signals (e.g., known transmission

symbols) received from the WWAN, data signals (e.g., unknown transmission symbols) received from the WWAN, WWAN channel estimates, and WWAN-control information.

The array-processing weighting source-code segment **1961** is adapted to provide as output at least one of a set of information signals, including WWAN weights, weighted received WWAN data for transmission into the WLAN (i.e., weighted received WWAN data), weighted WWAN data received from a plurality of WTs connected by the WLAN and then combined (i.e., combined weighted WWAN data), and estimates of said combined weighted WWAN data. A WLAN distribution source code segment **1962** is provided for distributing at least one of a set of signals (including the WWAN weights, the weighted received WWAN data, the combined weighted WWAN data, and the estimates said combined weighted WWAN data) to a plurality of WTs via at least one WLAN. The WLAN distribution source code segment **1962** may optionally function to couple at least one of a set of information inputs to the source-code segment **1961**, including WWAN data signals received by other WTs, training signals received from the WWAN by other WTs, WWAN channel estimates (either of both locally generated and received from other WTs), WWAN-control information, weights received from at least one other WT, and weighted WWAN data received from at least one other WT.

Since software embodiments of the invention may reside on one or more computer-readable memories, the term computer-readable memory is meant to include more than one memory residing on more than one WT. Thus, embodiments of the invention may employ one or more distributed-computing methods. In one embodiment of the invention, the computer-readable memory **1950** and/or **1960** further includes a distributed-computing source-code segment (not shown). It will be appreciated that many different types of distributed computing, which are well known in the art, may be performed. The WLAN distribution source code segment **1952** and/or **1962** may be adapted to provide for synchronizing transmitted and/or received WWAN signals.

Embodiments of the invention described herein disclose array-processing methods (including software implementations) and apparatus embodiments employed in a WWAN and coordinated between a plurality of WTs connected via at least one WWAN. WTs in a WLAN group typically share the same WWAN access. However, some embodiments of the invention provide for WTs with access to different WWANs. Furthermore, one or more WTs may have access to a plurality of WWANs and WWAN services. In some cases, one or more WTs may not be configured to access any WWAN.

In some embodiments of the invention, the computer-readable memory **1950** and/or **1960** further includes a WLAN setup source-code segment (not shown) capable of establishing and/or dynamically reconfiguring at least one WLAN group. For example, WTs may convey location information (e.g., GPS) and/or signal-strength information (e.g., in response to a WLAN probing signal) to the WLAN setup source-code segment (not shown). The WLAN setup source-code segment (not shown) may reside on one or more of the WTs and/or at least one WWAN terminal, such as a cellular base station.

The WLAN setup source-code segment (not shown) may provide one or more WLAN group configuration functions, including determining the number of WWAN-enabled WTs, the total number of WTs in the WLAN group, which WTs are active (and inactive), which WTs are in the WLAN group, and selecting which WT(s) has (have) network-control functionality. The WLAN setup source-code segment (not shown) may be adapted to perform WWAN channel quality analysis functions, including determining WWAN link performance (relative to one or more WTs) from training sequences or pilot signals, performing WWAN-channel estimation, receiving link performance or channel estimates from the WWAN, and performing channel-quality calculations (e.g., SNR, BER, PER, etc.).

The WLAN setup source-code segment (not shown) may select which WTs are WWAN-enabled based on one or more criteria points, including WWAN link performance, WLAN link performance, required transmission and/or reception needs (e.g., the number of WLAN-group WTs requesting WWAN services, the types of WWAN services required, individual and total throughput, required signal-quality threshold, and WWAN bandwidth available to the WLAN group), computational load, WLAN capacity, power-consumption load, diversity gain, and interference mitigation.

The WLAN distribution source code segments **1952** and **1962** may be adapted to route WWAN channel-access information to the WTs. For example, WWAN channel-access information can include multiple-access information (e.g., multiple-access codes, frequency bands, time slots, spatial (or sub-space) channels, etc.), power control commands, timing and synchronization information, channel coding, modulation, channel pre-coding, and/or spread-spectrum coding.

FIG. **11** shows a WWAN comprising a WWAN access point (e.g., a base station) **2120** and a local group **2100** comprising a plurality of wireless terminals (WTs) **2101-2104** communicatively coupled together via a WLAN **2105**. A network-management operator **2106** is configured to handle WWAN-control operations within the local group **2100**. In an exemplary embodiment, the network-management operator **2106** is coupled to at least one of the WTs **2101-2104** (e.g., WT **2103**). One or more of the WTs **2101-2104** may be configured to transmit and/or receive WWAN communication signals, such as WWAN traffic channels **2110** and WWAN control messages **2111**. Signals in the WWAN traffic channels **2110** may be processed by one or more of the WTs **2101-2104**, which may include at least one local area network controller (e.g., **2103**). The WWAN control messages **2111** are processed by the network-management operator **2106**.

In an exemplary embodiment of the invention, a target WT (e.g., WT **2104**) communicates with one or more WTs in the local group **2100** via the WLAN **2105**, and the local group **2100** is configured to communicate with the base station **2120** via the WWAN. More specifically, one or more of the WTs **2101-2104** may be configured to participate in WWAN communications at any particular time. The target WT **2104** may communicate with the network controller (e.g., WT **2103**), which is configured to communicate with other WTs in the local group **2100**. The network controller **2103** typically oversees network control functions in the local area network. Alternatively, the target WT **2104** may function as a local area network controller. A particular WT may determine which WTs to use for transmitting and/or receiving signals in the WWAN based on local area network criteria, as well as WWAN-related criteria. Local area network control and/or WWAN control functionality may be distributed between one or more WTs in the local group.

In FIG. **12**, a communication system comprises a plurality M of WTs **2209.1-2209.M** communicatively coupled together in a WLAN, which comprises a WLAN controller **2206**. A WWAN network-management operator **2210** is communicatively coupled to the WLAN controller **2206**.

WWAN network-management operator **2210** is configured for cooperatively processing WWAN-control messages for the WTs **2209**.1-**2209**.M, each of which comprises at least one WWAN interface **2201**.1-**2201**.M, respectively.

According to one aspect of the invention, the WWAN interfaces **2201**.1-**2201**.M receive WWAN control messages from the WLAN that were processed by the WWAN network-management operator **2210** and transmit those messages into the WWAN.

According to another aspect of the invention, the WWAN interfaces **2201**.1-**2201**.M receive WWAN control messages from the WWAN and couple those messages through the WLAN to the WWAN network-management operator **2210**. According to yet another aspect of the invention, one or more WTs functions as the WWAN network-management operator **2210**. Thus, the WWAN network-management operator **2210** may comprise one or more WWAN interfaces and be configured to transmit WWAN control messages into the WWAN.

For the purpose of the present disclosure, a WWAN comprising a plurality of wireless terminals communicatively coupled together via a WLAN may be defined as one or more of the following system configurations:

A plurality of WTs in a local group configured to receive from a base station a signal intended for at least one WT.

A plurality of WTs in a local group configured to receive from a base station a plurality of signals modulated on interfering (e.g., common) channels and intended for at least one WT.

A plurality of WTs in a local group configured to receive from a base station a plurality of signals modulated on different non-interfering channels and intended for at least one WT.

A plurality of WTs in a local group configured to receive from a plurality of base stations a signal modulated on a common channel intended for at least one WT.

A plurality of WTs in a local group configured to receive from a plurality of base stations a signal redundantly modulated on a plurality of different channels intended for at least one WT.

A plurality of WTs in a local group configured to receive from a plurality of base stations a plurality of signals modulated on interfering channels and intended for at least one WT.

A plurality of WTs in a local group configured to receive from a plurality of base stations a plurality of signals modulated on different non-interfering channels and intended for at least one WT.

A plurality of WTs in a local group configured to transmit to a base station a signal originating from at least one WT.

A plurality of WTs in a local group configured to transmit to a base station a plurality of signals modulated on interfering (e.g., common) channels originating from at least one WT.

A plurality of WTs in a local group configured to transmit to a base station a plurality of signals modulated on different non-interfering channels originating from at least one WT.

A plurality of WTs in a local group configured to transmit to a plurality of base stations a signal modulated on a common channel originating from at least one WT.

A plurality of WTs in a local group configured to transmit to a plurality of base stations a signal redundantly modulated on a plurality of different channels originating from at least one WT.

A plurality of WTs in a local group configured to transmit to a plurality of base stations a plurality of signals modulated on interfering channels originating from at least one WT.

A plurality of WTs in a local group configured to transmit to a plurality of base stations a plurality of signals modulated on different non-interfering channels and originating from at least one WT.

A plurality of WTs in a first local group configured to receive from a second local group a signal intended for at least one WT in the first local group.

A plurality of WTs in a first local group configured to receive from a second local group a plurality of signals modulated on interfering channels and intended for at least one WT in the first local group.

A plurality of WTs in a first local group configured to receive from second local group a plurality of signals modulated on different non-interfering channels and intended for at least one WT in the first local group.

A plurality of WTs in a first local group configured to transmit to a second local group a signal originating from at least one WT in the first local group.

A plurality of WTs in a first local group configured to transmit to a second local group a plurality of signals modulated on interfering channels and originating from at least one WT in the first local group.

A plurality of WTs in a first local group configured to transmit to a second local group a plurality of signals modulated on different non-interfering channels and originating from at least one WT in the first local group.

A base station comprising a plurality of WTs in a base station local group configured to transmit a signal intended for at least one subscriber WT not in the base station local group.

A base station comprising a plurality of WTs in a base station local group configured to transmit a plurality of signals modulated on interfering (e.g., common) channels and intended for at least one subscriber WT not in the base station local group.

A base station comprising a plurality of WTs in a base station local group configured to transmit a plurality of signals modulated on different non-interfering channels and intended for at least one subscriber WT not in the base station local group.

Multiple base stations comprising at least one base station local group configured to transmit a signal modulated on a common channel intended for at least one WT.

Multiple base stations comprising at least one base station local group configured to transmit to a plurality of WTs a signal redundantly modulated on a plurality of different channels intended for at least one WT.

Multiple base stations comprising at least one base station local group configured to transmit to a plurality of WTs a plurality of signals modulated on interfering channels and intended for at least one WT.

Multiple base stations comprising at least one base station local group configured to transmit to a plurality of WTs a plurality of signals modulated on different non-interfering channels and intended for at least one WT.

A base station comprising a plurality of WTs in a base station local group configured to receive a signal originating from at least one WT.

A base station comprising a plurality of WTs in a base station local group configured to receive a plurality of signals originating from at least one WT and modulated on interfering channels.

A base station comprising a plurality of WTs in a base station local group configured to receive a plurality of signals modulated on different non-interfering channels and originating from at least one WT.

Multiple base stations comprising at least one base station local group configured to receive a signal modulated on a common channel originating from at least one WT.

Multiple base stations comprising at least one base station local group configured to receive a signal redundantly modulated on a plurality of different channels originating from at least one WT.

Multiple base stations comprising at least one base station local group configured to receive a plurality of signals modulated on interfering channels and originating from at least one WT.

Multiple base stations comprising at least one base station local group configured to receive a plurality of signals modulated on different non-interfering channels and originating from at least one WT.

A WWAN network-management operator may include a single WT or a plurality of WTs. In one embodiment, the WWAN network-management operator includes a single WT communicatively coupled to the WWAN and configured to perform WWAN-control operations for one or more WTs in the local group. For example, a block diagram of a WT **2300** shown in FIG. **13** comprises a WWAN network-management operator module **2302** communicatively coupled to a WWAN interface **2301** and a WLAN interface **2303**. In another embodiment, the WWAN network-management operator may comprise WWAN network-management operator modules residing in a plurality of WTs. Thus, the WWAN network-management operator may be configured to transmit and/or receive WWAN-control parameters in the WWAN on behalf of one or more WTs in the local group. A local area network controller may also include a WWAN network-management operator module and may perform WWAN network management for one or more WTs in the group.

Each WT may function as its own network-management operator. For example, a WT functioning as its own network-management operator may be communicatively coupled to the WWAN and configured to transmit and receive WWAN control information directly with the WWAN, whereas traffic-channel processing may be performed in cooperation with one or more other WTs in the local group. In another exemplary configuration, WWAN control information may be coupled from a target WT (e.g., a source or destination WT relative to the subject information, i.e., the WWAN control information) to a relay WT communicatively coupled to the WWAN and configured to transmit and receive the target WT's WWAN control information. While the target WT functions as its own network-management operator, it may employ other WTs in the local group to transmit and receive WWAN control messages. Thus, the relay WT may merely function as a pass through having optional added physical-layer adjustments for the WWAN control information. The physical-layer adjustments may be used to condition the WWAN control messages for the WWAN channel and/or the WLAN channel. Similarly, a WT functioning as a network-management operator for itself and/or at least one other WT may employ one or more WTs in the local group for transmitting and receiving WWAN control messages in the WWAN.

In another embodiment, a WT may function as a network-management operator for one or more other WTs. For example, a network controller may function as a network-management operator for at least one other WT. In another embodiment, at least one WT that is neither a network controller nor a target WT may function as the network-management operator. For example, a WT having the best WWAN channel (such as may be determined by any of a variety of signal quality criteria that are well known in the art) may be selected as the network-management operator. Various criteria for selecting WTs for network-management operator responsibilities may be implemented, including load balancing.

In another embodiment of the invention, a plurality of WTs in a local group may simultaneously function as a network-management operator. The network-management operator may comprise multiple WTs including a target WT, multiple WTs including a network controller, multiple WTs not including a network controller, or multiple WTs not including a target WT. A plurality of WTs may redundantly process WWAN control messages. Alternatively, each of a plurality of WTs configured to perform WWAN-control operations may be configured to perform a predetermined subset of the WWAN-control operations.

A network-management operator may participate in any combination of various WWAN-control operations, including power control, data-rate control, session control, authentication, key exchange, paging, control-channel monitoring, traffic channel request, channel assignment, error detection, acknowledgement, request for retransmission, identification, reconnects, synchronization, flow control, request for service from a particular sector or access point, hand-off.

FIG. **14** is a flow diagram of a communication method configured in accordance with an aspect of the invention. A WLAN is employed for sharing WWAN control information between a group of WTs **2401**. WWAN control information is coordinated between the group of WTs and the WWAN **2402**, and WWAN control information is cooperatively processed by the group **2403**.

The Open Systems Interconnection Reference Model (OSI Reference Model) may be used to describe the function of a WWAN comprising a local group of a plurality of WTs communicatively coupled together via a WLAN.

In the Application Layer, each WT typically employs its own user applications for accessing network services (e.g., login, data upload, data download, multi-media processing). Thus, each WT handles its own application-layer network access, flow control, and error processing. Each WT controls its own user interface for access to services that support user applications. These applications typically are not subject to cooperative access (e.g., sharing). However, certain network resources (e.g., printers, faxes) may be shared. Some applications, such as computational processing applications, may provide for distributed computing processes between WTs in a network. However, such distributed-computing applications have not been employed in the prior art for receiving and decoding wireless communications.

In the Presentation Layer, each WT may translate data from an application format to a network format and vice-versa. Different data formats from different applications are processed to produce a common data format. Each WT may manage its own protocol conversion, character conversion, data encryption/decryption, and data compression/expansion. Alternatively, a network controller that serves multiple WT may perform one or more presentation-layer functions. For example, data-processing intelligence may be handled by a network controller, and individual WTs may function as dumb terminals. In some multimedia applications, a network controller may function essentially as a media server configured to deliver predetermined data formats to each WT functioning as a media device. Furthermore, there are vari-

ous degrees of how presentation-layer processing may be shared between WTs and a network controller.

In the Session Layer, each WT may be responsible for identification so only designated parties can participate in a session. Session setup, reconnects, and synchronization processes may be managed by the target WT (e.g., a subscriber, an access point, or a base station), which functions as its own network-management operator for session-layer processing. Alternatively, a network controller may manage session-layer activities for each of one or more WTs in the local group. The network controller may store identities for each WT and manage sessions and the flow of information for each WT.

In another embodiment, multiple WTs may participate in session management. Some centralized decision-processing (such as by the target WT or a network controller) may be employed to direct one or more WTs to perform specific session-layer activities. Multiple responsibilities may be divided among the WTs. For example, one WT may conduct synchronization processes and another WT may perform session setup. The WTs assigned to perform particular functions may change with respect to signal quality with the WWAN, load balancing criteria, and/or other considerations.

In the Transport Layer, each WT may convert data streams into packets or predetermined segments. Each WT may also process received packets to reassemble messages. Thus, each WT may perform its own error handling, flow control, acknowledgement, and request for retransmission.

Alternatively, a network controller may manage transport-layer operations for each of one or more WTs in a local group. The network controller may be configured to convert data streams received from the WTs into packets. Similarly, the WT may convert data packets received from the WWAN into data streams that are routed to the appropriate WTs. The network controller may perform common network-management operator functions, including error handling, flow control, acknowledgement, and request for retransmission for each of the WTs.

In yet another embodiment, multiple WTs may be used to convert data streams into packets and/or process received packets to reassemble messages for a particular target WT. Each of a plurality of WTs may process only a portion of the received data stream and perform error handling, flow control, acknowledgement, and request for retransmission for the data it processes. Alternatively, multiple WTs may handle the same data. For example, redundant transport-layer processing may be performed by different WTs having uncorrelated WWAN channels in order to reduce errors, and thus, requests for retransmission. In another embodiment, only one WT may handle transport-layer processing at any given time. For example, a particular WT may be assigned to handle transport-layer processing if it has favorable WWAN-channel conditions. Other criteria, such as load balancing, may be used to select and transfer transport-layer processing responsibilities between WTs.

In the Network Layer, WTs may perform their own network-layer processing, such as addressing and routing. A WT, such as a router, a base station, a switch, or a relay may perform network-layer processes, including managing data congestion, adjusting data frames, packet switching, and routing. In addition to managing network-layer control within its local group, a network controller may perform network-layer processes for the WWAN.

The Data Link layer includes a Media Access Control (MAC) sub-layer and the Logical Link Control (LLC) sub-layer. Each WT may perform Data-link processing, such as converting received raw data bits into packets and managing error detection for other WTs. Similarly, each WT may convert data packets into raw data bits for one or more other WTs. In one embodiment, a target WT may perform its own data-link processing. Alternatively, a network controller may perform data-link processing for one or more WTs.

A Physical layer embodiment may provide for performing all physical-layer processes by a target WT. For example, a target WT distributes spread, scrambled baseband data to the other WTs, which then up convert and transmit the target's transmission signal as specified by the target WT. Similarly, each WT may receive and down convert WWAN transmissions and direct the down-converted signal via the WLAN for processing (e.g., descrambling and despreading) by a target WT.

In one embodiment, physical-layer processes may be divided between a target WT and other WTs in a local group. For example, the target WT may convey baseband data and control parameters to other WTs, which then spread and scramble the baseband data with respect to the control parameters. Additional control parameters, such as power control, and data rate control may be specified. Similarly, WTs in a local group may descramble and despread received data for further processing by a target WT. WTs may monitor control channels for signals addressed to any of a plurality of WTs in a local group.

In yet another embodiment, a network controller may perform some or all physical-layer processes corresponding to a target WT. A network controller may perform all physical-layer processes for a target WT (and other WTs in the corresponding local group if it performs higher-layer processes for the target WT). Alternatively, some of the higher-layer processes may be performed by the network controller and/or other WTs as part of a distributed computing procedure regardless of how the physical-layer processes are performed.

Several aspects of physical-layer processing include WWAN-control operations. Other WWAN-control operations may fall within any of a plurality of the OSI reference model layers. Embodiments and interpretations of the invention should not be constrained to the limitations of the OSI reference model. The OSI reference model is a generalization that may not be suitable for expressing the implementation of all WWAN-control operations.

In one aspect of the invention, a cellular base station may transmit a probe signal (e.g., a predetermined signal that is ramped in signal power) to a plurality of subscriber WTs. A network-management operator in a local group of WTs may be responsive to the probe signal for indicating a signal power level capable of being received from the base station. Similarly, the signal power level may be used as an indicator for transmit power and/or data rate.

Functions of the network-management operator may be distributed over a plurality of WTs in the local group, and network-management responsibilities may be shared by more than one WT and/or dynamically assigned to particular WTs. For example, a WT that first detects the probe signal may be assigned subsequent network-management responsibilities, such as predicting forward-link SINR and an associated achievable data rate, sending an acknowledgement to the base station, or requesting a particular data rate (e.g., sending a dynamic rate control signal to the base station). In another embodiment of the invention, WWAN signals received by a group of WTs may be combined before being processed by a network-management operator.

In one embodiment of the invention, a network-management operator in a local group performs open loop estimation to adjust reverse link (i.e., local group) transmit power.

Alternatively, closed-loop power corrections may involve both the network-management operator and the base station. The network-management operator may send an access probe sequence and wait for an acknowledgement from a base station. Initial probe power is typically determined via power control.

A WT in the local group is typically denoted as being in an inactive state relative to the WWAN when it is not assigned a forward traffic channel. However, the network-management operator may assign one or more WWAN traffic channels to WTs that the WWAN considers inactive. In such cases, inactive WTs may help transmit and/or receive WWAN communications intended for active WTs in the local group. Similarly, active WTs may be assigned additional traffic channels by the network-management operator for transmitting and/or receiving WWAN communications intended for other active WTs in the group. Such assignments may be invisible to the WWAN, since so-called inactive WTs are used for connecting active WTs to the WWAN. In other embodiments of the invention, complex assignments, including sharing traffic channels between WTs, may be implemented.

A network-management operator may service one or more WTs in a variable-rate state. For example, a forward traffic channel is transmitted at a variable rate determined by the network-management operator's data rate control value. The network-management operator may determine the maximum data rate using any of a variety of well-known techniques. The network-management operator uses a data rate control channel to instruct the WWAN what data rate to serve to a particular WT in the local group. In response, the base station selects modulation, channel coding, power and/or number of multiple-access slots.

The network-management operator may direct its instructions to the best base station (i.e., the base station having the best channel relative to the local group) in its active set via addressing (e.g., a covering code). Alternatively, the network-management operator may instruct multiple base stations to serve the local group. This may occur when WTs can access more than one WWAN. This may also occur when some WTs are better served by one base station or sector while other WTs in the same local group are better served by a different base station or sector.

A WT enters a fixed-rate state when its network-management operator signals a request for a specific fixed rate from a base station or sector. The WT may transition to a variable rate if it cannot receive packets at the previously requested fixed rate. A network-management operator may select a fixed rate if there is an imbalance (e.g., different channel conditions) between the forward and reverse links.

In one aspect of the invention, a network-management operator is configured to perform connection-layer protocols that are typically conducted between a target WT and the base station. For example, the network-management operator may participate in acquisition and initialization state protocols, air link management protocols, connection state protocols, route updates, and/or idle state protocols.

A WT in an inactive state typically awakes from a sleep state periodically to monitor a control channel to receive overhead parameter messages and paging messages. In one aspect of the invention, a network-management operator may wait for an activate command from a default air link management protocol. A network-management operator may monitor a WWAN control channel for multiple WTs in a local group. In an alternative embodiment, WTs in the local group may take turns monitoring the WWAN control channel. In this case, responsibilities of the network-management operator are transferred betweens WTs in the local group. In another embodiment, a plurality of WTs may monitor the WWAN control channel, wherein each WT is configured to monitor the channel for only a subset of WTs in the local group.

In a network determination state, the network-management operator selects a channel on which to acquire a base station for a WT in the local group. After selecting a channel, the network-management operator enters a pilot acquisition state in which the network-management operator tunes to a particular channel and searches for the strongest pilot signal. Upon acquiring a pilot, the network-management operator enters a synchronization state. At this point, the network-management operator may transfer synchronization responsibilities to the target WT. If the network-management operator (or the target WT) is unable to obtain a pilot, it reverts back to the network determination state.

In the synchronization state, the network-management operator or the target WT looks for a sync message on the control channel and sets its clock to the time specified in the sync message. Failure to receive the sync message or similar failures may result in returning to the network determination state.

The base station undergoes various state transitions in the process of serving the WTs. In an initialization state, the base station activates an initialization state protocol, overhead message protocol, and a control channel MAC protocol. A network-management operator may selectively route certain messages through WTs in a local group comprising the base station while reserving other messages for WWAN transmission only by the base station.

An idle state occurs after the network is acquired, but before an open connection is established. The base station initiates an idle state protocol, overhead messages protocol, route update protocol, control channel MAC protocol, access channel MAC protocol, and forward and reverse channel MAC protocols. In the connected state, base station and the target WT have an open connection until the connection is closed (i.e., goes to the idle state) or network redirection (goes to the initialization state). The base station activates a connected state protocol, overhead messages protocol, route update, control channel MAC protocol, and forward and reverse channel MAC protocols.

A network-management operator may be configured to direct hand offs between WWAN sectors, base stations, and/or networks. In one embodiment, a network-management operator in a local group may measure the SINR on each pilot in an active set (e.g., a set of base stations that actively serve the local group) and request data from the sector having the highest SINR. The network-management operator predicts the SINR for the next packet and request a higher data rate if it can decode it at that SINR. The rate request (which may include data rate, format, and modulation type) is sent by the network-management operator to the appropriate sector using a data rate control channel.

Generally, the network-management operator requests data from only one sector at a time. However, different WTs in a local group serving a particular target WT may request WWAN channels from multiple sectors at a time on identical or different WWAN channels. The network-management operator may coordinate requests for channels from different sectors. Multiple sectors (or base stations) may be configured to serve the same WWAN channel simultaneously. Alternatively, multiple WWAN channels may be used to serve one WT in the group. Although the target WT may have a better connection with a particular base station, the local group as a whole may have a better connection with a

different base station. Thus, the network-management operator may dictate that the link be established and maintained relative to the group's connection rather than the target WT's connection.

A base-station scheduler may allocate physical channels for WTs. However, a network-management operator in a local group may provide logical channel assignments to the WTs that are invisible to the physical channel operation of the WWAN. Multiple WTs in a local group may utilize a single WT channel, such as for packet switched data communications. Each WT may utilize multiple physical channels, such as when higher data rates are required. The network-management operator may assign logical channels to various physical WWAN channels, and thus, effectively hand off those data channels to other sectors, base stations, or WWAN networks serving those physical WWAN channels.

Data rates requested by WTs may follow a channel fading process, wherein higher data requests occur when channel conditions are favorable and lower rates are requested as the channel degrades. It is well known that when a base station serves a large number of WTs, that diversity of multiple units can mitigate system-wide variations in data rate due to changing channel conditions. Multi-user diversity teaches that the opportunity for serving good channels increases with the number of users, which increases total network throughput.

One embodiment of the invention may provide for a network-management operator that dynamically selects one WT in a local group to communicate with a WWAN at a particular time, even though one or more channels may be served between the base station and the local group. The selection of which WT in the group communicates with the WWAN may change with changing channel conditions between the local group and the base station(s). Thus, the update rate for the dynamic selection may be based on the rate of change of WWAN channel conditions. This embodiment may be adapted for simultaneous communication by multiple WTs and/or the use of multiple base stations and/or WWANs. In another exemplary embodiment, the network-management operator may interleave communications (e.g., packets) across multiple WWAN channels undergoing uncorrelated channel distortions. Similarly, a WWAN specifically configured to interact with a local group may interleave messages across multiple WWAN channels transmitted to the local group. Different WWAN channels may be transmitted and received by one base station or a plurality of base stations. This type of interleaving (at either the local group and the base station) may be determined by a network-management operator.

In another embodiment, a network-management operator may be configured to redundantly transmit data symbols over multiple slots or physical channels to reduce transmission power or to allocate more power to data.

A network-management operator may employ an authentication protocol to authenticate traffic between a base station and a MT. For example, a network-management operator may identify a particular WT in a local group to a base station. The base station may then verify that the WT has a legitimate subscription record with a service provider that utilizes the WWAN. Upon verification, the base station allows access to the air interface and the network-management operator (whose responsibilities may be transferred to the WT) signs access channel packets to prove it is the true owner of the session. In one exemplary embodiment of the invention, the WT and/or the network-management operator may use IS-856 Air Interface Authentication.

In one embodiment of the invention, a target WT includes a network-management operator that employs other WTs in its local group to interact with a WWAN. In this case, authentication may be performed only with the target WT. In an alternative embodiment, the network-management operator resides in at least one other WT, such as a network controller. Thus, authentication may be performed with a network-management operator in a single terminal that is configured to perform authentication for more than one WT.

A network-management operator may employ a key exchange protocol (e.g., a Diffie-Hellman algorithm) for exchanging security keys between a WT and a WWAN for authentication and encryption. Typically, there is some predetermined key exchange algorithm used within a particular WWAN. Public values are exchanged and then messages are exchanged between the WT and the WWAN to indicate that the session keys have been correctly calculated. The keys may be used by the WT and the WWAN in an encryption protocol to encrypt traffic.

In one embodiment of the invention, a network-management operator resides on a target WT that accesses the WWAN via multiple WTs in a local group. The network-management operator may be configured to encrypt and decrypt WWAN traffic for the target WT without vital security information being made available to WTs other than the target WT. In another embodiment, the network-management operator may reside in a network controller. In this case, the network-management operator may be configured to engage in security protocols for more than one WT in the local group. Network-management operators according to various embodiments of the invention may be configured to participate in security protocols used to provide crypto sync, time stamps, and other elements used in authentication and encryption protocols.

Some aspects provide a multicarrier protocol that controls interference relationships between the carriers. This control enables time domain signal shaping, which provides for low PAPR and adaptability to single-carrier waveforms. Disclosed aspects include Carrier Interferometry (CI).

In CI, subcarrier frequencies are selected to provide a predetermined spectral response. Polyphase codes are applied to each subcarrier to control the time-domain characteristics of the superposition signal, as well as provide for orthogonality between data symbols and/or users. In one aspect, a pulse (i.e., a constructive interference resulting from a zero-phase relationship between the subcarriers) is generated from a superposition of the coded signals. Time-offset replicas of the pulse are used to construct waveforms having a predetermined frequency-domain profile.

An objective may be to enable a communication protocol that provides frequency-diversity benefits of multicarrier modulation to single-carrier systems and provides the low-PAPR benefits of single-carrier modulation to multicarrier communication systems, and the ability to provide the benefits of both systems simultaneously.

FIG. **15** illustrates a CI pulse shape characterized by an in-phase alignment (e.g., mode locking) of harmonic subcarriers **1505** at a specific time t_1. A composite signal **1530** results from a superposition (i.e., summation) of the carriers **1505**. The composite signal **1530** shows a pulse envelope centered at a predetermined time instant t_1. In the case where there is no amplitude tapering (i.e., a rectangular window) and a plurality N of carriers have a uniform frequency separation fs, a composite CI signal is:

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$$e(t) = \sum_{n=1}^{N} e^{j[(\omega_c + n\omega_c)t + n\Delta\phi]}$$

which is characterized by an envelope-magnitude function:

$$|e(t)| = \left| \frac{\sin(N(\omega_s t + \Delta\phi)/2)}{\sin((\omega_s t + \Delta\phi)/2)} \right|$$

where ω_c is related to a carrier frequency f_c (or equivalently, an offset frequency $f_o=f_c$) by the relationship $\omega_c=2\pi f_c$. Similarly, ω_s is related to the separation frequency f_s by the relationship $\omega_s=2\pi f_s$.

The phase offsets $\Delta\phi$ typically correspond to any of N orthogonal time offsets corresponding to N orthogonal pulse positions. A kth bit or data symbol a_k in a user's transmission s(t) modulated onto a particular CI pulse, or phase space is expressed as:

$$s_k(t)=e(t-kT_b)$$

where T_b is a time offset corresponding to the particular CI pulse. Orthogonal pulses are centered at intervals of $T_b=T_s/N$. A burst of bits or symbols may be transmitted onto a contiguous train of pulses, such as shown in FIG. **16**B. In this case, a transmission corresponding to a particular user is characterized by the following relationship:

$$s(t) = \sum_{k=1}^{N} a_k e(t - kT_b)$$

The time-shifted pulses are orthogonal to each other even though the pulses overlap in time:

$$\int_0^{T_s} e(t - kT_b)e(t - nT_b)\delta t \ (k \neq n)$$

FIG. **16**A illustrates an amplitude distribution of the CI carriers corresponding to the pulse train shown in FIG. **16**B. In some applications of the invention, carriers may be provided with complex weights to generate superposition signals corresponding to a predetermined sequence of code chips or data symbols.

FIG. **17**A illustrates individual CI pulses provided with code chips or data symbols, such as symbols $\beta_0(k)$ to $\beta_{14}(k)$. A pulse train **1795** shown in FIG. **17**B corresponds to the modulated pulses shown in FIG. **17**A.

In time-division multiplexing (e.g., in TDMA), the symbols modulated onto the pulses are typically data symbols corresponding to a particular user. In frequency-division multiplexing (e.g., in OFDM), data symbols corresponding to a particular user are modulated onto a pulse train (such as the pulse train shown in FIG. **16**B) constructed from a predetermined set of carrier frequencies allocated to that user. In direct sequence code division multiplexing (e.g., DS-CDMA) or direct sequence spread spectrum, data-bearing code symbols are modulated onto the pulse train. In coded multicarrier spreading (e.g., MC-CDMA or Spread OFDM), data-bearing code symbols are modulated directly onto the carriers.

The function e(t) is also characterized by an in-phase carrier component $\cos(\omega_c t)$ and a quadrature-phase component $\sin(\omega_c t)$. The in-phase and quadrature-phase components can correspond to N orthogonal pulse positions (i.e., phase spaces) and N pseudo-orthogonal pulse positions, respectively.

The CI signals are periodic with period $T_s=1/f_s$ for an odd number of carriers N and with period $2/f_s$ for an even number of carriers N. In either case, data symbols of duration T_s are typically modulated onto the carriers (or pulses). The main lobe has duration $2/Nf_s$ and each of the N−2 side lobes has a duration $1/Nf_s$.

In FIG. **16**A, 20 carrier frequencies are allocated to a particular user and provided with complex weights to generate a train of CI pulse waveforms that convey information. FIG. **16**B shows 20 pulses orthogonally (and equally) positioned in time corresponding to data transmitted by (or to) that user. Each pulse waveform is a superposition of the 20 carriers provided with phases relative to the orthogonal positions in time. Predetermined sets of phase offsets are provided to the carriers to position the pulses orthogonally in time.

The cross correlation between the real parts of the pulse waveforms is illustrated by the following equation:

$$R_{k,j}(\tau) = \frac{1}{2f_s} \frac{\sin(2\pi N f_s \tau/2)}{\sin(2\pi f_s \tau/2)} \cos\left(\frac{(N-1)}{2} 2\pi f_s \tau\right)$$

N equally spaced zeros occur over the time interval $T_s=1/f_s$ as a result of the sinc-like term in the cross-correlation equation. This corresponds to each pulse waveform being centered at a particular time instant corresponding to a zero crossing (i.e., zero value) of all of the other orthogonal pulse waveforms.

The cross-correlation equation expresses the Nyquist zero inter-symbol interference criteria. The Nyquist zero inter-symbol interference criteria requires a waveform to have zero crossings corresponding to positions of the other waveforms.

The spacing of the pulse positions (i.e., time instants) corresponds to zeroes in the cross-correlation function. The pulses are centered at equally spaced time instants k/Nf_s, where k=0, 1, . . . , N−1, N is the number of carriers, and $f_s=1/T_s$ is the frequency separation between the carriers. Thus, the time instants are defined by 0, T_s/N, . . . , $T_s(N-1)/N$.

CI waveforms may be implemented with contiguous or non-contiguous carriers. Contiguous carriers are defined as carriers allocated to one or more users characterized by a frequency separation f_s and symbol duration $T_s=1/f_s$.

In the OFDM implementation of the invention, each user is provided with a unique set of carrier frequencies to eliminate multiple access interference (MAI). Similar frequency-division multiplexing may be provided to other CI-based transmission protocols to reduce or eliminate MAI. The real part of each user's OFDM transmission is expressed by

$$s(t) = \sum_{k=1}^{N} \sum_{i=1}^{N} a_k \cos(2\pi(f_c + if_s)t + mi2\pi/N)g(t)$$

where a_k is a kth data symbol (preferably a channel-coded data symbol) that is then spread over the N carriers allocated to the user. Since each data symbol is spread across all of the

carriers, the full frequency diversity benefits of the channel can be achieved. Time interleaving may also be provided.

In one aspect, a received CI-OFDM signal for at least one user is separated into its orthogonal frequency components. Channel compensation (e.g., equalization) and combining are performed to provide estimates of the transmitted symbols. Inter-bit interference may be compensated via any combination of equalization and multi-user detection.

Carrier mixers or a carrier generator, as described herein, includes any type of system, method, or combination thereof adapted to perform at least one of a plurality of functions, including carrier generation, carrier selection, carrier allocation, and modulation. Carrier mixers imply the existence of a carrier generator (e.g., a multicarrier generator). Thus, carrier mixers and carrier generator can be equivalent terms as used herein. A carrier generator may include a carrier-mixer circuit. A carrier mixer may include any type of mixer, modulator, or equivalent device adapted to provide carrier selection and/or modulation. Carrier mixers/carrier generators may include local oscillators, harmonic signal generators, digital filters, invertible transform algorithms, quadratic mirror filters, sine wave look-up tables, etc. Carrier mixers may be interpreted as performing frequency-domain processes.

Carrier mixers or carrier generators may employ digital signal processing systems, such as microprocessors, may be employed. Consequently, Fourier transforms, such as DFT-based systems may be employed. For example, an IFFT or IDFT may be employed with one or more weight vectors applied to the frequency bins of the transform. A carrier mixer (or carrier generator) may include a weight-vector selector adapted to select predetermined frequency bins. A weight vector may include zero and non-zero values, such as to provide for carrier selection/allocation. Carrier mixers may include one or more carrier-allocation circuits. A carrier mixer allocates one or more carriers to one or more users. A carrier mixer may provide for modulation of data symbols onto the carriers. A carrier mixer may include a plurality of modulators or a modulator adapted to modulate at least one data symbol onto a plurality of carriers.

In this case, the frequencies of the CI carriers are incrementally spaced by a shift frequency f_s. However, non-uniform spacing of the frequencies may also be used to achieve certain benefits. The carrier frequencies are typically chosen to be orthogonal to each other:

$$\int_0^{T_C} \cos(\omega_i t + \phi_i)\cos(\omega_j t + \phi_j)dt = 0$$

where T_c is the chip duration, ω_i and ω_j are the ith and j^{th} carrier frequencies, and ϕ_i and ϕ_j are arbitrary phases. A signal in the jth frequency band does not cause interference in the ith frequency band.

The term carrier, as used herein with respect to a multi-carrier signal or system, is equivalent to the terms subcarrier and tone. Orthogonal carriers may be characterized by constant-frequency carriers with orthogonal frequencies. Alternatively, orthogonal carriers may employ dynamically varying carrier frequencies, such as chirped or hopped carriers. For example, the frequency separation between a set of orthogonal carriers with dynamic frequencies may be constant or limited to integer multiples of an orthogonal frequency spacing f_s.

An input data source includes any input port adapted to receive data bits and/or data symbols, such as coded data bits and/or symbols. An input data source may include any apparatus and/or algorithm adapted to generate data, such as coded or uncoded data bits and/or symbols. An input data source may include at least one coder and/or coding algorithm. Channel coding may include any combination of well known channel coding techniques, such as trellis, block, convolutional, parity check (e.g., Gallagher coding or any other type of low-density parity check coding), and iterative soft-decision feedback (e.g., turbo) coding.

The phase of each CI signal is set with respect to at least one predetermined receiver time interval (i.e., phase space) in which the carriers constructively combine when received by a CI receiver. A set of incremental phase offsets $e^{in\Delta\Phi_k}$ corresponding to at least one pulse position is applied to the CI carriers by one of a plurality N of interval delay (i.e., phase) systems. Each pulse's phase space is a set of carrier phases corresponding to the time instant at which the pulse is centered. Thus, each set of phase offsets maps a data symbol to a pulse centered at a particular instant in time.

Interval delay systems, or equivalently, phase-shift systems, include any type of phase shift module, delay module, temporal mapping module, polyphase code module, polyphase filter, etc., adapted to map data symbols to pulse positions. A pulse position is an instant in time at which a CI pulse is centered. A pulse, as used herein, typically refers to a single-pulse waveform generated from a superposition of selected carriers. Pulse waveforms may include a plurality of pulses, such as a pulse train. Delay systems are systems, algorithms, and/or devices adapted to provide time offsets (i.e., phase shifts) to individual carriers to generate carrier superpositions (pulse waveforms). Delay systems may provide phase offsets and/or time offsets to carriers and/or data symbols.

A delay system is typically configured to receive as input at least one of a data sequence and a set of carriers. The delay system directly maps data on modulated carriers to particular instants in time. The delay system may align carriers to produce pulse waveforms centered at one or more time instants and then modulation may be provided to the pulse waveforms. An interval delay system may include a polyphase coder adapted to provide polyphase codes to data symbols and/or carriers. A delay system may provide polyphase codes to frequency bins of an invertible transform, such as an IDFT or IFFT.

Although the apparatus diagrams illustrated herein illustrate the generation of CI transmission signals as step-by-step procedures, a preferred embodiment for accomplishing these processes may use digital signal-processing techniques, such as Discreet Fourier Transforms. The order of some of these processes may be switched. For example, modulation of each carrier by the input data may be the final step before combining.

Disclosed aspects may provide for any of various forms of duplexing, such as frequency division duplexing, code division duplexing, and time division duplexing (TDD). TDD allows for a highly efficient and cost-effective architecture, since the same frequency is used for both transmission and reception and the channel characteristics in both directions are virtually identical. In array-processing applications, the beam-forming weights can be determined from a base station antenna array for the reverse link and the same weights can be used on the forward link without requiring multiple antennas at the remote unit. This allows the system to deliver the capacity and interference mitigation benefits of adaptive beam forming for both the uplink and the downlink while keeping the complexity and cost of the remote unit very low. Furthermore, the TDD approach eliminates expen-

sive diplexing filters and permits the use of a single RF chain, further reducing subscriber-unit costs.

FIG. **18**A is a functional diagram of a CI transmitter. An allocation step **1814** is performed by carrier mixers, which allocate a plurality of carrier frequencies (i.e., tones) to a particular user. A mapping step **1816** is performed by phase-shift/delay systems, which map each data symbol from data source **1812** to a particular pulse position. A pulse-generation step **1820'** is performed by a combiner, which receives the allocated carriers as inputs and generates CI pulses at predetermined pulse positions. The resulting data-bearing CI waveform may be an analog or digital signal. If it is an analog signal, the waveform may optionally be sampled **1821**.

The plurality of carrier mixers performs the allocation step that provides carrier frequencies used to generate at least one superposition signal for a particular user. The plurality of phase-shift/delay systems provides the mapping **1816** of each data symbol from the data source to a predetermined instant in time (i.e., pulse position). Each set of phase shifts applied to the information-modulated carriers by the phase-shift/delay system produces a phase alignment of the carriers (i.e., an interference pulse) at the predetermined instant in time. Thus, the combination of the phase-shift/delay systems and the data source produces a discrete signal of the mapped data symbols. The data symbols are typically provided with polyphase codes and modulated onto the individual CI carriers. Each polyphase code maps its associated data symbol to a particular instant in time.

A combining system, or combiner, as described herein, is any system, device or algorithm adapted to combine a plurality of allocated carriers (for transmission or reception) to produce a time-domain waveform. A combiner may be interpreted as a frequency-domain to time-domain converter. A combiner may be referred to as an interpolation circuit because it generates a time-domain waveform from a plurality of frequency-domain components. A combiner may include an inverse-Fourier transform, such as an IDFT or IFFT circuit or algorithm. Thus, one way to implement carrier generation and combining is to provide an IDFT. Consequently, carrier selection and data-symbol mapping may be performed by a polyphase coder adapted to generate a vector of frequency-bin weights.

The combining system (which may equivalently be an interpolation circuit) is adapted to perform pulse generation, as it combines the phase shifted carriers to produce one or more information-modulated pulses centered at the predetermined instants in time. A plurality of information-modulated pulses may be positioned contiguously in time (such as shown in FIGS. **16**B and **17**B) to provide a substantially uniform (low PAPR) signal over a predetermined interval (e.g., symbol period T_s or some multiple thereof). The pulse waveforms are functions that span the symbol duration T_s. In this case, a pulse waveform may be a digital or analog signal. The frequency response of the pulses includes sinusoids provided by the carrier mixers (i.e., allocation circuit).

FIG. **18**B illustrates a CI transmitter that includes a subcarrier allocation module **1814**, a mapping module **1816**, and an interpolation module **1820**. The subcarrier allocation module **1816** performs the function of carrier mixers. Subcarrier allocation assigns a predetermined number N of carriers to one or more users wherein the carrier frequency spacing f_s and data symbol period T_s are selected to ensure orthogonality between the carriers. Orthogonality may be provided between the allocated carriers and unallocated carriers (e.g., carriers assigned to other users). For a number N of carriers, there are N orthogonal phase spaces (i.e., pulse positions). Thus, the number of users in an orthogonal CI system is less than or equal to the number N of carriers.

The carriers corresponding to each user may include contiguous carrier frequencies or uniformly spaced frequencies distributed over a broad frequency band. Each user may be allocated a unique set of carriers, thus providing for orthogonal frequency division multiple access. Alternatively, two or more users may share at least one set of carrier frequencies. Thus, CI may employ other multiple-access schemes, including time division and code division.

The mapping module **1816** is equivalently a multicarrier phase-shift module. The mapping module **1816** maps each data symbol from a data source to a predetermined instant in time. Incremental phase offsets applied to a plurality of carriers are equivalent to a time offset (e.g., delay) applied to a superposition of the carriers. Each set of phase offsets produces a phase alignment of the carriers (i.e., an interference pulse) at a predetermined instant in time, thus, mapping each data symbol to an instant in time.

The carriers are provided by the subcarrier allocation module **1814** (e.g., a plurality of carrier mixers) and modulated with one or more data symbols. Modulation may be performed at the carrier mixers. The combination of the phase-shift/delay systems and the data source produces a discrete signal consisting of the mapped data symbols.

The interpolation module **1820** can be expressed by a combining system. The interpolation module **1820** combines the phase-shifted carriers to produce one or more information-modulated pulses centered at the predetermined instants in time. The subcarrier allocation module **1814** provides the carriers from which the pulses are produced. Thus, the frequency response of the pulses may include only the sinusoids allocated by the subcarrier allocation module **1814** to a particular user. Since each user may be assigned a unique set of carriers, the pulse waveforms produced by the communication system can include non-zero sinusoids allocated to a particular user and zero-valued (i.e., an absence of) sinusoids allocated to other users.

The CI transmitter components illustrated in FIG. **18**B, as well as other components in the transmitter, may be implemented as digital signal processing components. Consequently, the information-modulated pulses generated by a CI transmitter may be a digital signal sample vector.

Since the CI pulses are positioned orthogonally in time if the phase offsets are appropriately selected, signal characteristics (e.g., phase, amplitude, frequency, etc.) of each pulse at the pulse maxima conveys the data symbol value assigned to the corresponding phase space (i.e., instant in time at which the pulse is centered).

FIG. **19** illustrates a CI transmitter. A set of carrier mixers **1914** (which typically includes a multicarrier signal generator) is adapted to allocate a set of carriers to a particular user. Thus, the carrier mixers **1914** perform the same function as a Discreet Fourier Transform (DFT) circuit combined with a zero-insertion circuit. For example, carriers corresponding to other users are removed, avoided, or otherwise set to zero.

A phase-shift/delay system **1916** is adapted to map each of a plurality of data symbols from a data source **1912** to a predetermined instant in time. The data source **1912** provides data symbols to any of the transmitter modules **1914**, **1916**, and/or **1920**. Data symbols may be modulated directly onto individual carriers, data-bearing polyphase codes may be generated, or CI pulse waveforms may be modulated with data. The phase-shift/delay system **1916** applies sets of phase offsets to a plurality of carriers, which are provided by the carrier mixers **1914** and optionally modulated with one or more data symbols. Each set of phase offsets produces a

phase alignment of the carriers (i.e., an interference pulse) at a predetermined instant in time, and thus, maps each data symbol to an instant in time. The combination of the phase-shift/delay systems **1916** and the data source **1912** produces a discrete signal of the mapped data symbols.

A combining system **1920** combines the modulated, phase-shifted carriers to produce information-modulated pulse waveforms. These pulse waveforms are inverse Fourier transforms of the carriers represented in the frequency domain. Thus, the combining system **1920** performs the same function as an Inverse-DFT circuit. Although not shown, a gain adjustment module or system (e.g., a pulse-shaping filter) may optionally be included in the transmitter.

CI signal generator systems may include a transmission system, such as is known in the art with respect to single carrier and multicarrier communications. For example, a transmitter may include analog and/or digital components typically used to process a baseband signal for transmission into a communication channel.

FIG. **20** illustrates a specific embodiment of a CI transmitter. A carrier generator/mixer circuit **2014** includes a pulse generator **2001** and a carrier-selection filter **2002**. The pulse generator **2001** is adapted to generate pulse having a predetermined pulse-repetition frequency to provide a predetermined multicarrier output. Other pulse-generation parameters, such as pulse shape, may be selected and/or adapted to provide for desirable spectral characteristics.

A subcarrier processing module **2016** may be adapted to provide phase offsets to the selected carriers, provide polyphase coding to the carriers, modulate data (or coded data) symbols onto the carriers, and/or provide for carrier gain adjustments (e.g., pulse shaping, channel compensation, carrier selection, etc.). Accordingly, the subcarrier processing module **816** may include any combination of digital filters, modulators, coders, phase shifters, and channel-compensation circuits.

A combiner **2020** is optionally provided to generate a superposition of the carriers. A transmission module **2022** processes the baseband multicarrier signal and couples the processed signal into a communication channel. Although the combiner **2020** is shown coupled between the subcarrier processing module **816** and the transmission module **2022**, in-channel combining may be provided. Accordingly, transmitter components (not shown), such as amplifiers, frequency converters, and guard-interval modules may be provided separately to each subcarrier.

A data source **2012** is coupled to at least one of the modules **2014**, **2016**, and **2020**. The pulse generator **2014** may be modulated with data or otherwise adapted to generate information-modulated pulses. Alternatively, the subcarrier processing module **2016** may be adapted to modulate data onto the pulses or the selected individual carriers. In another embodiment of the invention, the combiner **2020** includes a modulator (not shown) adapted to modulate data symbols from data source **2012** onto the superposition signal.

Some aspects may employ any of a number of techniques for providing channel estimating. For many of these methods, a block of pilot chips, tones, or other known signals may be inserted into the transmitted waveform. Known symbols may be mapped to CI phase spaces. Training symbols may be provided to individual subcarriers. In other embodiments, various types of coded training symbols may be transmitted. Blind adaptive estimation and equalization may be employed.

FIG. **22**A illustrates a plurality of CI pulse waveforms **2201** to **2209** orthogonally positioned in time. A plurality N of equally spaced carriers f_1, f_2, . . . , f_N are combined to generate the pulses **2201** to **2209**. A set of carrier phases **2211**, **2212**, . . . , **2219** corresponds to each of the pulses **2201**, **2202**, . . . , **2209**, respectively. Each set of carrier phases **2211**, **2212**, . . . , **2219** is an orthogonal polyphase CI code (or phase space) applied to the carriers to center a given pulse waveform at a corresponding instant in time.

A complex-valued data symbol (not shown) impressed onto a pulse (such as pulse **2201**) may be characterized by an in-phase (e.g., real) part modulated onto pulse **2201** and a quadrature-phase (e.g., imaginary) part modulated onto a pulse waveform (not shown) centered equidistantly between pulses **2201** and **2202**. Similarly, a first set of N real data symbols may be impressed onto a first set of N 9 orthogonal pulses (such as the pulses **2201** to **2209**). A second set of real data symbols may be impressed onto a quadrature-phase set of orthogonal pulses (not shown) centered equidistantly between adjacent pairs of the pulses **2201** to **2209**.

Complex carrier weights corresponding to each of the carriers f_1, f_2, . . . , f_N, represent a sum of the phase spaces **2211**, **2212**, . . . , **2219** multiplied by their corresponding data symbols. In particular, an nth (n=1, 2, . . . , N) carrier's complex weight equals the sum of each complex data symbol in the nth row of each phase space **2211**, **2212**, . . . , **2219** multiplied by the data symbol value (not shown) associated with that phase space **2211**, **2212**, . . . , **2219** (i.e., pulse position **2201**, **2202**, . . . , **2209**).

FIG. **22**B represents a CI waveform of the present invention. A plurality N of subcarriers **2221** to **2229** (e.g., sinusoids, or tones) are characterized by at least one predetermined set of complex subcarrier weights **2210**. These weights **2210** align the sinusoids **2221** to **2229** to produce a train or sequence of information-modulated pulses **2201** to **2209** in the time domain. These pulses **2201** to **2209** may be generated by applying the subcarrier weights **2210** to subcarriers (such as subcarriers **2221** to **2229**) allocated to at least one user in a network.

A network may be characterized by various types of communication architectures having two or more users, or nodes, including point-to-point, point-to-multipoint, broadcast, multipoint-to-multipoint, multipoint-to-point, hierarchical, ad-hoc, peer-to-peer, multi-hop, and cellular. The invention is independent of the type of network. Accordingly, other network configurations may be employed. Similarly, the invention is independent of the propagation medium (i.e., communication channel) connecting the nodes.

Alternatively, multiple time-offset pulses are combined wherein each pulse **2201** to **2209** is generated from a superposition of predetermined subcarriers **2221** to **2229** and modulated with a corresponding data symbol. In some cases, time-domain waveforms are provided with frequency-domain processing (e.g., pulse-rate control, rise-time and roll-off control, pulse shaping, pulse-width control, frequency-selective filtering, windowing, and/or frequency masking) to generate pulse waveforms having predetermined spectral characteristics.

Variations of the disclosed pulse-generation techniques and/or multicarrier-generation techniques, as well as other techniques, may be employed in generating CI pulse waveforms. Pulse generators include circuits, systems, software, etc., adapted to generate pulse waveforms. Pulse generators can also include carrier-generation circuits, systems, software, etc. having some carrier-weighting apparatus or algorithm (e.g., CI coder, phase shifter, delay device, mode-locking system, etc.) adapted to produce a plurality of carriers having complex weights that shape a superposition

of the carriers into one or more pulse waveforms. Since there are many techniques for generating CI waveforms, the invention is not limited to any specific embodiment for generating CI waveforms disclosed herein. Other techniques for generating CI waveforms will be evident to persons skilled in the art.

CI waveforms are typically impressed onto one or more carriers. CI subcarriers may be impressed onto multiple transmission carrier signals, such as carriers corresponding to different frequency bands. CI waveforms may be conveyed as analog waveforms (such as generated by a D/A converter or a bank of oscillators). CI waveforms may be digital signals (such as a digital output generated by an IDFT or other transform). Digital CI waveforms may be generated from an A/D conversion of at least one analog CI waveform. Digital CI waveforms may be generated by appropriately weighting and summing a predetermined set of digital sinusoids that are dynamically generated or stored in memory. Digital CI waveforms may include binary or M-ary (i.e., higher order) signals. Digital CI signals may be expressed as discreet or continuous modulation symbols, including, but not limited to, QAM, PSK, CPM, FSK, AM, FM, PAM, and TOM. The digital signals may be transmitted in any order.

Various interleaving and/or channel-coding techniques may be employed in the transmission of digital signals associated with CI waveforms. In one aspect of the invention, coding (which is not necessarily limited to channel coding) and/or interleaving are applied to data symbols prior to generating the CI waveforms. In another aspect of the invention, coding and/or interleaving are applied to digitized CI signals. In yet another embodiment, modulation symbols may be interleaved.

The offset frequency f_o represents the carrier frequency. In some applications, CI waveforms may be conveyed in their baseband form (i.e., a carrier frequency, or offset frequency f_o, having zero frequency). For example, baseband CI waveforms may be conveyed inside a digital signal processor or equivalent device, between storage devices (physical and/or virtual memory) and signal-processing devices (e.g., DSPs, microprocessors, CPUs), inside transmitter components, inside receiver components, and/or between transmitter and receiver components. CI waveforms may be conveyed in an intermediate-frequency (IF) form. For example, the multi-carrier CI signal may be impressed on an IF carrier. Carriers having other frequencies, including optical, infra-red, and microwave, may be employed.

Complex subcarrier weights convey phase space (e.g., CI codes, phase-shift sets, carrier delays, pulse (time-) offset, or any other interpretation of carrier superposition signals resulting from carrier phase alignments at predetermined times) and information (e.g., data symbol) values. Complex subcarrier weights may be generated from a product of a vector or matrix of data symbols with a vector or matrix of phase space (i.e., CI code) values. Complex subcarrier weights may be generated from sums of information-modulated phase spaces. Complex subcarrier weights may be generated from a sum of products of each of a plurality of phase-shift sets corresponding to a particular phase space with data symbols corresponding to that particular phase space. Carrier weights may be generated by calculating or measuring subcarrier amplitudes and phases resulting from combining a plurality of information-modulated, time-offset pulse waveforms.

Subcarrier weights may optionally include channel compensation weights, array-processing weights, and/or coding (e.g., channel coding, multiple-access coding, spread-spectrum coding, etc.). The subcarrier weights may optionally provide for data interleaving.

In some aspects of the invention, subcarrier weights may be provided with at least one code (e.g., a complex-valued or real code) adapted to de-orthogonalize (e.g., provide time-domain spreading, and thus, overlapping of) the transmitted pulses. Upon reception, an appropriate derivative of the code (e.g., a complex-conjugate code) can be applied to the appropriate frequency-domain components to re-orthogonalize the pulse waveforms.

FIG. **21** illustrates basic components of CI signal generation software residing on a computer-readable medium **2199**. CI signal generation software is typically configured to control the function and transmission-signal output of a single carrier or multicarrier transmitter. In some cases, a CI transmission may be characterized as a single-carrier signal in the time domain having a plurality of predetermined frequency-domain (or spectral) components.

A subcarrier allocation source code segment **2191** is adapted to generate a plurality of subcarriers allocated to at least one user or allocate a plurality of input subcarriers (not shown) to a particular user. A subcarrier weighting source code segment **2192** is adapted to provide complex weights (e.g., CI codes) to a plurality of the allocated subcarriers. The weights are configured to map one or more input data symbols into one or more phase spaces.

The computer-readable medium **2199** may include any item of manufacture adapted to store or convey software and/or firmware. The source-code segments **2191** and **2192** may reside on a physical memory storage device, such as any magnetic, electrical, or optical device adapted to store data and/or computer command instructions. The source-code segments **2191** and **2192** may be implemented as gate configurations on a programmable or integrated circuit. Other means for arranging physical devices and/or electromagnetic phenomena may be employed to convey the function of the source-code segments **2191** and **2192**. Accordingly, the computer-readable medium **2199** may include any combination of FPGAs, ASICs, transient memory, and persistent memory.

Subcarrier allocation may include generating subcarriers, providing for receiving input subcarriers, retrieving subcarriers or superposition waveforms from memory (e.g., a look-up table), or selecting non-zero (or equivalently, zero) valued input bin weights of an invertible transform, such as a DFT. In some applications, subcarrier allocation can include pulse shaping, controlling symbol durations, and/or selecting subcarrier frequency spacing. Some frequencies may be selected or avoided relative to channel conditions, bandwidth requirements, and/or interference.

The subcarrier allocation source code segment **2191** and subcarrier weighting source code segment **2192** may be implemented in one program. Similarly, other processing operations typically performed in a communication system transmitter may be implemented in, or in addition to, the source-code segments **2191** and **2192**. It should be appreciated that subcarrier allocation, selection, and assignment can include providing subcarriers for system control and/or monitoring. Subcarrier allocation, as described throughout the specification may include providing for pilot tones, training sequences, and/or other subcarriers allocated to other system-control functions. Subcarrier weighting may include channel coding, source coding, spread-spectrum coding, formatting, multiple-access coding, multiplexing, encryption, array processing, and/or modulation. Systems and methods illustrated herein and described throughout the

specification may be implemented as source-code segments residing on one or more computer-readable mediums.

Network control in CI communications may be adapted to enable users to share network resources (e.g., bandwidth). For example, channel resources in the form of phase spaces and/or subcarriers may be allocated to each user relative to their level of service. Bandwidth may be allocated to users relative to any combination of individual throughput requirements, purchased level of service, and availability of bandwidth. Circuit-switched processes may be implemented with respect to subcarrier allocations. Packet-switched processes may be implemented with respect to phase spaces. CI communications provides for the concurrent implementation of circuit switching and packet switching.

FIG. **23**A is a functional flow chart of a CI receiver. A receiver process **2301** couples at least one transmitted signal from a communication channel and converts it to an IF or baseband signal. Multicarrier receivers typically include various combinations of signal-processing components, such as amplifiers, filters, down converters, A/D converters, cyclic prefix removers, beam forming circuits, as well as other components. The receiver process **2301** may generate analog or digital signals.

A filtering process **2302** performs a time-domain to frequency-domain conversion of the received signal to produce a plurality of frequency-domain components. Filtering may remove one or more frequency components, or otherwise provide frequency-domain constraints such that the resulting frequency-domain components correspond to components of at least one desired transmit signal. The frequency-domain components may include subcarriers or complex weights corresponding to the magnitude and phase of each subcarrier. Time-domain to frequency-domain processes and frequency-domain to time-domain processes are commonly performed using Fourier transforms or cosine transforms.

An optional frequency domain equalization (FEQ) step **2303** may be provided. The FEQ step **2303** typically involves applying complex channel-compensation weights to the frequency-domain components. An equalizer, as used herein, is a digital hardware/software apparatus adapted to correct for the inter-symbol interference, fading, and/or other distortions of the received digitally-encoded signals so that the initial data can be recovered. Typically, an equalizer compensates for inter-symbol interference via several processes, such as linear equalization or decision feedback equalization. In linear equalization, the incoming signals are multiplied by the inverse of the inter-symbol interference, generally removing inter-symbol interference from the incoming signals. A drawback of linear equalization is that noise inherent in the data transmission is undesirably simultaneously amplified. Decision feedback equalization avoids the noise amplification problems of linear equalization, but runs the risk of error propagation since any decision errors that are made are fed back. Other types of equalization that may be included in the invention include maximum likelihood sequence estimation, iterative equalization, inter-symbol interference cancellation, and/or turbo equalization.

A combining process **2304** combines the selected frequency-domain components to produce a time-domain signal (e.g., a superposition signal or a sequence of data symbols). Thus, the combining process **2304** is equivalent to other frequency-domain to time-domain conversion processes. Combining **2304** may be followed by an optional time-domain equalization (TEQ) step **2305** and/or an optional multi-user detection (MUD) step **2306**. A decision process **2307** is adapted to estimate the received data in order to recover transmitted data symbols. Various types of decision processing **2307** may be employed. An integration step (not shown) is typically provided with combining **2304** and/or decision processing **2307** to combine samples, or otherwise process the received signal, over one or more symbol durations T_s.

A decision system, as used herein, describes any combination of devices and/or algorithms adapted to process an input signal to provide at least one estimate of the input signal's value. Hard and/or soft decisions may be employed. A decision system may provide for various signal-processing techniques (e.g., decoding, feedback, as well as various adaptive routines), such as are typically associated with receivers and reception techniques. A decision system may employ some reference, such as a reference symbol constellation.

FIG. **23**B illustrates a receiver method and apparatus similar to that shown in FIG. **23**A with the addition of a CI phase space decoder step **2310**. A plurality of CI phase spaces (i.e., time intervals) can be selected by the same transversal filter described with respect to the TEQ **2305**. In this case, data symbols impressed onto different phase spaces are separated by applying the appropriate incremental delays (i.e., phase offsets) to the individual carriers prior to combining **2304**. If the components are complex values (e.g., output-bin values of a discreet Fourier transform), a complex conjugate of each CI code used to map a data symbol to a particular phase space may be employed to recover the corresponding mapped symbol.

FIG. **24**A shows an embodiment of a CI receiver that includes a receiving module **2301**, a filter bank **2302**, a delay system (or phase-shifter bank) **2310**, a combiner **2304**, and a decision module **2307**. Received signals are processed by the receiving module **2301** prior to processing at the filter bank **2302**. The filter bank **2302** may include a plurality of filters, such as a plurality of analysis filters. The filter bank **2302** is typically a complementary system with respect to a carrier synthesizer (not shown) employed on the transmit side to generate CI signals. Alternatively, the filter bank **2302** may include a transform operation that is complementary (e.g., inverted) relative to an associated transform function in a corresponding CI transmission process. For example, the filter bank **2302** may be adapted to perform a Fourier transform operation (e.g., a DFT implemented with a fast transform algorithm, such as a fast Fourier transform). Alternatively, the filter bank **2302** may be adapted to perform matched filtering. In any of these cases, the function of the filter bank **2302** is to convert an input time-domain signal into a plurality of frequency-domain components.

The delay system **2310** is adapted to provide incremental delays to a plurality of subcarrier waveforms generated by the filter bank **2302**. Equivalently, the delay system **2310** may provide incremental phase offsets to frequency-bin values or equivalent complex values corresponding to carrier magnitudes and phases. It is well known that there is a linear relationship between carrier time offsets t and carrier phase offsets ϕ related to a given carrier frequency f_n: $\phi=2\pi f_n\tau$. The delay system **2310** typically provides a complementary or inverse set of delays (or equivalently, phase shifts) to the component waveforms. Accordingly, the delay system **2310** is adapted to provide complementary phase offsets (or time offsets) that are complex conjugates of terms corresponding to each predetermined phase space, such as the phase spaces **2211**, **2212**, . . . , **2219** shown in FIG. **22**A.

The combiner **2304** is adapted to combine one or more sets of the delayed (or phase offset) carrier components. Combining may include equalization, such as frequency-

domain equalization. Similarly, some form of time-domain equalization and/or multi-user detection may be performed after combining. Consequently, the combiner **2304** may include at least one equalizer (not shown).

The combiner **2304** combines the frequency-domain components to generate a time-domain sequence, such as a reconstructed CI pulse waveform or a sequence of symbol values corresponding to the transmitted data. A CI pulse waveform typically includes a plurality of orthogonally positioned CI pulses (i.e., a pulse train, such as illustrated in FIGS. **16**B and **17**B) wherein each pulse conveys (e.g., is modulated with) a data symbol. Thus, the combiner **2304** generates signal values from data symbols that were mapped to predetermined instants in time (i.e., phase spaces, or pulse positions centered at equally spaced time instants) by at least one transmitter.

The decision module **2307** processes the signal values to generate estimated data symbols. Methods of formatting information symbols, such as mapping a constellation of data symbols to a constellation of modulation levels, and the reverse operation, are typically understood to be a process within a symbol-estimation step or decision step.

Such as in which information symbols are converted to waveform symbols at a transmitter and the reverse conversion is performed at a receiver. A decoder may perform symbol-to-bit mapping. Digital data may be mapped into a signal point sequence with respect to a predetermined code, and an inverse mapping produces an estimated data sequence from a received signal point sequence. An inverse-mapping device (not shown), which may be part of the decision module **2307**, produces an estimated data sequence from a received signal point sequence. Receivers may employ channel estimation. Channel estimation in multicarrier systems is typically regarded as part of an equalization process.

FIG. **24**B illustrates a CI receiver. A DFT **2302** functions as a filter bank. A delay system **2310** is implemented as a plurality M of phase-space modules **2310.1** to **2310**.M. Each phase-space module **2310.1** to **2310**.M, such as phase-space module **2310.1**, is adapted to generate a plurality N of phase offsets, such as **2310.11** to **2310.1**N corresponding to a particular phase space. Phase-shifted values or time-offset carriers generated by each phase-space module **2310.1** to **2310**.M are coupled to a corresponding combiner of a plurality M of combiners **2304.1** to **2304**.M. A decision module **2307** is adapted to process combined symbols or waveforms to generate at least one data estimate. A decision module or a delay system may include at least one decoder (not shown) adapted to perform any necessary decoding, such as channel decoding, multiple-access decoding, demultiplexing, de-spreading, decryption, etc.

FIG. **25**A illustrates a CI reception method and functional components of a CI receiver. A receiver module **2501** is adapted to process transmissions from a communication channel to generate one or more received signals for baseband or IF processing. A projection module **2502** is adapted to project the received signals onto at least one orthonormal basis corresponding to at least one user's transmissions. A combining module **2504** is adapted to combine the projections and optionally perform equalization. Combined signals are processed in a decision module **2507** adapted to generate one or more estimated data symbol values.

In particular, the steps of performing time-domain to frequency-domain conversion and filtering the frequency-domain signal may be achieved by projecting the received signal onto the orthonormal basis of the transmitted signals (such as indicated by the projection module **2502**). Projecting a received multicarrier signal onto an orthonormal basis of a particular user's transmitted signal produces frequency-domain signal components $r=(r_0, r_1, \ldots, r_{N-1})$ corresponding to that user's assigned carriers. Equivalently, the projection of a received signal onto an orthonormal basis excludes signals (e.g., carriers and/or phase spaces) that do not correspond to that orthonormal basis.

FIG. **25**B illustrates a CI receiver method and system. A receiver module **2501** is adapted to process and couple one or more transmitted signals from a communication channel to a matched filter **2502**. The receiver module **2501** is adapted to perform various types of signal processing (e.g., amplification, filtering, down conversion, A/D conversion, guard-interval removal, beam forming, and/or other types of signal processing) to modify a received signal into an appropriate format for baseband or IF signal processing. The modified signal may include an analog or digital signal.

The matched filter **2502** is typically matched to one or more signal characteristics (e.g., subcarriers, phase spaces, time intervals, codes, etc.) of at least one user or data stream. Different users and/or transmitted data symbols are typically characterized by at least one set of unique diversity parameter values, such as carrier frequencies, phase spaces, time intervals, codes, subspaces, polarizations, or combinations thereof. Other diversity parameters may be used to characterize different users and/or data streams. The matched filter **2502** may include one or more matched-filter elements.

The output(s) of the matched filter **2502** typically characterizes the degree of matching (e.g., correlation) of the filter **2502** with the received signal(s). Measured variations in the degree of matching can indicate the transmitted symbol values. Thus, these measurements may be mapped to a predetermined symbol constellation. The temporal characteristics (e.g., synchronization and duration) of these measurements are typically selected in an integrator **2504**. The integrator's **2504** function is typically optimized relative to the probability of error (or BER) of the symbol estimates generated by a decision module **2507**.

Integration represents combining in the time domain. Consequently, integration may be part of a combining process (not shown). Frequency-domain combining is typically performed in the matched filter **2502**. For example, matching of a particular phase space includes carrier selection, and accordingly, a combining of the appropriately phase-shifted carriers. Alternatively, the matched filter **2502** simply matches components of a signal space corresponding to a particular user or data channel. In this case, the integrator **2504** produces values corresponding to the components over a predetermined time interval, and the decision module **2507** combines the component values to generate symbol estimates. Thus, the matched filter **2502** may employ polyphase codes corresponding to CI phase spaces as part of its matching function. Similarly, the decision module **2507** may employ polyphase CI codes as part of a combining process.

The decision module **2507** may be adapted to perform any of various functions related to data-symbol processing. For example, the decision module **2507** may perform any combination of channel decoding, demodulation, spread-spectrum decoding, de-interleaving, demultiplexing, multiple-access decoding, and formatting. Equalization may be performed by one or more receiver modules **2502**, **2504**, and/or **2507**.

FIG. **26**A illustrates a CI receiver apparatus and method of the invention. A receiver module or system **2501** is adapted to receive and process at least one transmitted signal to provide a digital or analog time-domain signal to a first software module **2502**. The first software module **2502** is

adapted to project the received signal onto the orthonormal basis of the transmitted signals. This achieves a combined time-domain to frequency-domain transform and tone filtering.

The first software module **2502** includes a plurality N of multipliers **2511.1** to **2511**.N adapted to multiply the received signal by reference signals having orthogonal carrier frequencies $f_n=f_o+nf_s$ (n=0, . . . , N−1) and at least one predetermined phase relationship $n\Delta\Phi_k$. Software module **2502** also includes a plurality N of integrators **2504.1** to **2501**.N adapted to integrate the products over each symbol interval T_s. The outputs of the first module **2502** are frequency-domain signal components $r=(r_0, r_1, \ldots, r_{N-1})$ corresponding to a particular user's assigned carriers. The first module **2502** is typically adapted to generate phase offsets ΔΦ corresponding to a plurality of phase spaces (i.e., time offsets).

A second software module **2514** takes the form of a combiner, which performs a frequency-domain to time-domain transform. Equalization (not shown) may be performed by either or both first and second modules **2502** and **2514**, respectively. Time-domain equalization and/or frequency-domain equalization may be employed. Various combining techniques, such as any appropriate optimal-combining technique may be employed. The combined frequency-domain components produce a time-domain signal, such as shown in FIGS. **1**, **2**B, and **3**B. The time-domain signal may include an analog or digital waveform. Alternatively, a time-domain signal may include a sequence of digital symbol values.

Each set of phase offsets ΔΦ corresponds to a particular phase space or time offset. Each received data symbol is characterized by a data-modulated pulse centered at a particular time instant. The inclusion of phase selection in the reference signals used in the multipliers **2511.1** to **2511**.N of the first software module **2502** provides for selection of signal values at predetermined instants in time. Thus, the process of combining **2514** the phase-offset signals generated in the first module **2502** is part of a time-instant to symbol-mapping process. Decision processing **2507** provides for estimation of the received data. Decision processing **2507** is a mapping process that maps received signal values corresponding to each pulse (i.e., equally spaced instants in time used to transmit symbol values) into decision variables (i.e., estimated signal values).

FIG. **26**B illustrates a CI receiver, including a receiver module **2501**, a matched filter or projection module **2502**, a plurality M of integrators **2504.1** to **2504**.M, and a decision device **2507**. The projection module **2502** includes a discreet Fourier transform (e.g., FFT **2512**). Equivalently, other types of filters may be included, such as to select one or more subcarrier components allocated to a particular user. N frequency-domain components generated by the FFT **2512** are phase shifted by a plurality M of phase-shift systems (e.g., interval delay systems) **2510.1-2510**.M. The N signal components corresponding to each phase-shift system **2510.1-2510**.M are combined in an associated combiner **2514.1** to **2514**.M to generate a time-domain signal.

A plurality M of time-domain signals is output from the projection module **2502**. Each of the M time-domain signals is integrated over each symbol interval T_s by the integrators **2504.1** to **2504**.M. Signal values generated by the integrators **2504.1** to **2504**.M are processed by the decision module **2507** to generate a sequence of estimated data symbols.

Various embodiments may include variations in system configurations and the order of steps in which methods are provided. For example, the order of frequency-domain combining (illustrated by the combiners **2514.1** to **2514**.M) and time-domain combining (illustrated by the integrators **2504.1** to **2504**.M) may be switched. Multiple steps and/or multiple components may be consolidated.

FIG. **26**C illustrates a subcarrier weighting source code segment **2591** and a CI combining source code segment **2592** residing on a computer-readable medium **2599**. Source code segment **2591** is adapted to process one or more received channel measurements (such as frequency-domain or time-domain measurements) for generating a plurality of subcarrier weights. These weights are adapted to compensate for one or more channel effects, including, but not limited to, multipath, dispersion, and co-channel interference. The weights may be adapted to provide CI decoding. The weights may be adapted relative to one or more channel and/or data-quality measurements. The weights may be configured relative to data-processing measurements, such as hard-decision, soft-decision, and/or iterative feedback decision processing. The weights are typically applied to a plurality of subcarriers, such as frequency components produced by a filter bank or an FFT. Subcarrier weighting may include filtering, such as providing for acquiring subcarrier frequencies allocated to at least one predetermined user. Consequently, subcarrier weights may include both zero and non-zero values. Subcarrier weighting may include channel decoding, source decoding, spread-spectrum decoding, formatting, multiple-access decoding, demultiplexing, decryption, array processing, and/or modulation.

Source-code segment **2592** is adapted to combine the received and weighted carriers to generate a processed signal output, which is typically a sequence of symbols. At least one type of optimal combining may be provided. Code segment **2592** is adapted to receive as input at least one received signal, such as a sequence of data symbols. The received signal may be impressed onto the weights, weighted subcarriers, or waveforms generated from one or more superpositions of the weighted subcarriers. The weights are configured to map one or more input data symbols into one or more phase spaces. In some applications, data-modulated weights may be generated in source-code segment **2591**. In this case, source-code segment **2591** is adapted to process the received signal to generate at least one set of information-bearing weights.

FIG. **27**A illustrates a number M of CI receiver branches. A plurality of input couplers (e.g., antenna elements) **2701.1** to **2701**.M couple signals from a communications medium (e.g., a free-space channel, a waveguide, etc.) and process the signals. The input couplers **2701.1** to **2701**.M are typically adapted to perform any combination of front-end receiver-side processing, including amplification, filtering, frequency conversion, and/or A/D conversion. Other types of processing may be performed. For example, a plurality of optional guard interval (e.g., cyclic prefix) removal circuits **2702.1** to **2702**.M may be incorporated in the input couplers **2701.1** to **2701**.M. Similarly, each of a plurality M of serial-to-parallel converters **2703.1** to **2703**.M may be included in the input couplers **2701.1** to **2701**.M or in each of a plurality M of invertible-transform (e.g., FFT) circuits **2704.1** to **2704**.M.

Each of the invertible-transform circuits **2704.1** to **2704**.M transforms an input time-domain signal into a plurality N of frequency-domain components. The components are weighted with at least one set of CI combining weights $\alpha_m(n)$, where m=1, . . . , M and n=1, . . . , N, by a

plurality M of component-weighting modules **2705.1** to **2705**.M. In the case where MMSE combining is employed, the weights $\alpha_m(n)$ are expressed by:

$$\alpha_m(n)=h^*_m(n)/(N|h_m(n)|^2+\sigma^2)$$

where $h_m(n)$ is the channel response for the nth frequency channel of the mth spatial subchannel, and σ^2 is the noise power. Other types and combinations of combining may be employed.

A plurality M of combiners, such as IFFTs **2706.1** to **2706**.M, combine the weighted frequency-domain components to generate a plurality of time-domain signals.

Time-domain outputs of the IFFTs **2706.1** to **2706**.M are coupled to beam-forming modules **2707.1** to **2707**.M, which are adapted to provide beam-forming weights that cancel co-channel interference in a plurality of combiners **2708.1** to **2708**.M. Each combiner **2708.1** to **2708**.M may include a summing circuit, an adder, an accumulator, an integrator, or any appropriate invertible transform.

The beam-forming modules **2707.1** to **2707**.M and the combiners **2708.1** to **2708**.M may be adapted to perform any of various types and combinations of adaptive combining. In some applications, maximal ratio combining may be employed. Other combining schemes may be employed. Combining may include interference cancellation, multi-user detection, null steering, spatial interferometry multiplexing, etc. In some cases, space-time processing may be employed. Successive interference cancellation, as well as other multi-level cancellation techniques, can be used. In other cases, space-frequency processing may be provided. Channel decoding weights may be provided by either or both the component-weighting modules **2705.1** to **2705**.M and the beam-forming modules **2707.1** to **2707**.M. Symbols output by the combiners **2708.1** to **2708**.M are converted to a data stream by a parallel-to-serial converter **2709** prior to being demodulated and decoded **2710**.

In some disclosed aspects, the subcarriers may be selected for a particular user, such as in an orthogonal frequency division multiple access system. Subcarriers allocated to a particular user may be interleaved in frequency with subcarriers allocated to one or more other users. In another aspect of the invention, a different set of subcarriers is selected for each of a plurality of data symbols or data symbol groups transmitted by and/or to a particular user. A plurality of users may share a common set of subcarriers, yet share the channel via time division multiple access (TDMA), code division multiple access (CDMA), and/or space division multiple access (SDMA). Other multiple-access schemes may be employed. Similarly, different data symbols corresponding to a particular user may share the channel relative to the previously mentioned multiple-access schemes.

In one aspect, a signal generator or transmitter includes a subcarrier allocator, a pulse generator, a modulator, and a sequential pulse positioner. The subcarrier allocator assigns a predetermined set of subcarriers to a particular data symbol, user, or group of users. The pulse generator produces a plurality of pulses wherein the spectrum of each pulse or group of pulses is characterized by the set of subcarriers. The modulator modulates the pulses or subcarriers with at least one data symbol. The pulse positioner sequentially positions the modulated pulses.

A transmitter may include a polyphase, poly-amplitude code generator, a subcarrier allocator, a subcarrier weighting module, and a subcarrier combiner. The code generator produces at least one of a set of polyphase, poly-amplitude codes configured to produce a predetermined time-domain signal, such as a direct sequence coded signal. The transmitter may include a modulator adapted to modulate data onto the codes, the subcarriers, or the time-domain signal. The subcarrier weighting module impresses the polyphase, poly-amplitude codes onto a predetermined set of orthogonal subcarriers selected by the subcarrier allocator. The combiner combines the subcarriers to produce the time-domain signal.

A CI decoder may include receiver components illustrated in the figures and described throughout the specification and incorporated references. For example, a CI decoder may include an equalizer (such as a time-domain equalizer and/or a frequency-domain equalizer), a de-mapper, a de-interleaver, a decoder, a de-scrambler, a filter (such as a matched filter), an integrator, and/or a decision module.

CI receivers may be adapted to process either or both single-carrier and multicarrier signals. Frequency-domain analysis and processing of single-carrier signals may be performed relative to pulse characteristics. For example, number of subcarriers, subcarrier spacing, and window durations in receiver processing may be selected relative to physical signal parameters, such as pulse width, pulse shape, and pulse spacing.

In one aspect, a received signal is separated into a plurality of orthogonal subcarrier components by a time-domain to frequency-domain converter. The output of the converter is characterized by orthogonal poly-amplitude (and polyphase) coded data. The converter may be adapted to perform a Fourier transform, such as an FFT or a DFT. A combiner performs frequency-domain equalization and provides CI decoding of the coded data.

Functional aspects are described with respect to signal-waveform illustrations and corresponding descriptions. For example, FIG. **27**B illustrates a block transmission characterized by symbol duration T_s, and includes four orthogonal sinc-like pulse waveforms **341**, **342**, **343**, and **344**. Each pulse waveform (such as pulses **341**, **342**, **343**, and **344**) may be impressed with a unique data symbol.

A preceding block transmission includes orthogonal pulse waveforms **331**, **332**, **333**, and **334** and a following block transmission includes orthogonal pulse waveforms **351**, **352**, **353**, and **354**. Block transmissions are characteristic of multicarrier operation. For example, OFDM employs subcarrier blocks defined by uniform start and end times for each subcarrier, the difference in times typically being equal to the symbol duration T_s, or the symbol duration T_s plus a cyclic prefix. Cyclic prefixes, cyclic "post-fixes", or some other guard interval may be included in the signal plots, such as between the blocks shown in FIG. **27**B.

Since the pulse waveforms **341**, **342**, **343**, and **344** have the same starting and ending times, the waveform shapes **341**, **342**, **343**, and **344** are different from each other. For example, waveform **341** has all of its sidelobes to the right of its main lobe, whereas all of the sidelobes of waveform **344** occur to the left of the main lobe. This tends to increase the interference in systems that perform time-domain equalization and Rake reception. In particular, inter-pulse interference is not limited to nearby pulses because the side-lobe structure is periodic, or cyclic, over the symbol duration T_s. For example, the side-lobe amplitude (and thus, interference) of waveform **341** diminishes across pulse **342** and increases across pulse **344**. In this particular example, the pulse waveforms may be generated from four orthogonal subcarrier frequencies, which are not shown.

FIG. **28**A illustrates a CI transmitter that includes a CI coder **2802**, an IDFT (such as IFFT **2804**), a polyphase filter **2809**, and a transmission system **2807**. The CI coder **2802** is

adapted to map multiple input data symbols onto a plurality of subcarriers. This is achieved via CI coding. The IFFT **2804** is adapted to receive the plural sub-channel signals and transform them into plural time-domain signals. The polyphase filter **2809** receives the time-domain signals and outputs a plurality of filtered signals. The polyphase filter **2809** may be adapted to provide the filtered signals with a predetermined spectral profile of selected subcarriers. Polyphase filters operate by multiplying selected phases, or samples, of a filter impulse response with samples of one or more input signals.

FIG. **28**B illustrates a CI reception method that implies an apparatus for carrying out the method. A receiver step **2851** processes transmissions from a communication channel to generate received signals. Time-domain to frequency-domain conversion and filtering the resulting frequency-domain signal is achieved by projecting the received signal onto an orthonormal basis of the transmitted signals (such as indicated by a projection step **2852**). Projecting a received multicarrier signal onto an orthonormal basis of a particular user's transmitted signal produces frequency-domain signal components $r=(r_0, r_1, \ldots, r_{N-1})$ corresponding to that user's assigned subcarriers. Equivalently, the projection of a received signal onto an orthonormal basis excludes signals (e.g., carriers and/or phase spaces) that do not correspond to that orthonormal basis.

Frequency-domain to time-domain conversion is achieved by combining **2854** the received frequency-domain components produced by either band-pass filtering or projection onto a predetermined orthonormal basis. The combined frequency-domain components produce a time-domain signal. The step of recovering symbols is provided in the decision process **2857**.

FIG. **28**C illustrates a CI receiver including a receiver module **2861**, a matched filter or projection module **2862**, a plurality M of integrators **2864**.1 to **2864**.M, and a decision device or module **2867**. The projection module **2862** includes a DFT, such as an FFT **2872**. Equivalently, other types of filters may be included, such as to select one or more subcarrier components allocated to a particular user. N frequency-domain components generated by the FFT **2872** are phase shifted by a plurality M of phase-shift systems (e.g., interval-delay systems) **2870**.1 to **2870**.M. The N signal components corresponding to each phase-shift system **2870**.1 to **2870**.M are combined in an associated combiner **2874**.1 to **2874**.M to generate a time-domain signal.

A plurality M of time-domain signals is output from the projection module **2862**. Each of the M time-domain signals is integrated over each symbol interval T_s, by the integrators **2864**.1 to **2864**.M. Signal values generated by the integrators **2864**.1 to **2864**.M are processed by the decision module **2867** to generate a sequence of estimated data symbols.

Various embodiments of the invention may include variations in system configurations and the order of steps in which methods are provided. Multiple steps and/or multiple components may be consolidated.

FIG. **29**A illustrates a block waveform including a set of N orthogonal CI pulse waveforms **2941** to **2949** having a duration of T_s. CI pulse waveforms (such as pulse **2941** to **2949**) may be generated from a superposition of orthogonal subcarriers. Each of the pulse waveforms **2941** to **2949**, which represents a CI phase space, is modulated with one of a plurality of data symbols d_1 to d_N, respectively. In one aspect of the invention, each data symbol d_1 to d_N includes a code chip of an orthogonal code, such as Hadamard-Walsh (Walsh) code or a Walsh code multiplied by a long code. Pseudo-orthogonal coding may be employed. Other codes, including Gold codes, Barker codes, Kasami codes, CI codes, and/or DeBot codes, may be modulated onto the pulses **2941** to **2949**. The subcarrier weights resulting from the application of these time-domain codes provide orthogonal or pseudo-orthogonal CI codes expressed as frequency-domain codes, which are characterized by low PAPR in multicarrier synthesis.

FIG. **29**B illustrates a plurality of CI subcarrier weights w_1 to w_N generated from a set of data symbols d_1 to d_N mapped to a number N of orthogonal CI phase spaces. A CI code matrix of dimension N×N containing polyphase code chips is multiplied by a set of data vectors or a data matrix. In particular, each column of the CI code matrix (such as column **2951**) is multiplied by a corresponding data symbol (such as symbol d_2). In some cases, the CI code matrix and an N×N data matrix (not shown) may be provided with an element-by-element multiplication. Each row of a product matrix resulting from the product of the data symbols d_1 to d_N with the CI code matrix are summed to produce the subcarrier weights w_1 to w_N. For example, elements in row **2953**, after multiplication by the data symbols d_1 to d_N, are summed to generate weight w_2. Since rows and columns of the basic CI code matrix resemble the vectors of complex values used in DFTs, the subcarrier weights w_1 to w_N can be calculated using a fast transform algorithm.

FIG. **30**A illustrates transmitter apparatus and method embodiments of the present invention. An input data stream is serial-to-parallel converted and processed in a subcarrier-weighting module **3002**. The weighting module **3002** provides one or more orthogonal poly-amplitude codes to the subcarriers. The codes may also be characterized by polyphase values. The codes are typically indicative of the data and are used as subcarrier weights. In this case, block codes are provided. The weights may be used to synthesize at least one predetermined direct-sequence (e.g., DSSS or DS-CDMA) waveform. The weights are converted to at least one time-domain waveform in a frequency-domain to time-domain converter **3004**, such as an inverse Fourier transform.

The time-domain output of the converter **3004** is processed in a transmission system **3006**, which may optionally provide a guard interval or cyclic prefix (and/or postfix), perform digital-to-analog conversion, up convert the signal, provide amplification, optionally filter the signal, and provide for coupling the signal into a communication channel. Other transmitter-side signal-processing operations may be provided, including MIMO (e.g., array) processing. This transmitter embodiment may be adapted to generate multicarrier signals configured to appear as a single-carrier signal in the time domain.

FIG. **30**B shows a receiver apparatus and method of the invention. A receiver system **3001** couples single-carrier and/or multicarrier transmissions from a communication channel, and adapts the received signals for baseband or IF processing. In particular, the receiver system **3001** may perform filtering, amplification, down conversion, analog-to-digital conversion, cyclic-prefix removal, and/or other receiver processing operations that are well known in the art. The receiver system **3001** may be adapted to perform MIMO (e.g., array) processing. A received signal is separated into a plurality of orthogonal subcarrier components by a time-domain to frequency-domain converter **3003**, such as a Fourier transform. Frequency-domain equalization and decoding of the orthogonal poly-amplitude codes is performed in a combiner **3005**. The combiner **3005** multiplies the frequency bin values output by the converter **3003** with a complex conjugate of at least one of poly-amplitude code.

A decision module **3007** is adapted to process the combined signal values using any combination of hard-decision and soft-decision processing.

In one aspect, a received signal for at least one user is separated into orthogonal frequency components. Channel compensation (e.g., equalization) and combining are performed to provide estimates of the transmitted symbols. ISI may be compensated via any combination of equalization and multi-user detection.

Embodiments may employ any of a number of techniques for providing channel estimating. For many of these methods, a block of pilot chips, tones, or other known signals may be inserted into the transmitted waveform. Known symbols may be mapped to CI phase spaces. Training symbols may be provided to individual subcarriers. In other embodiments, various types of coded training symbols may be transmitted. Blind adaptive estimation and equalization may be employed.

FIG. **31**A illustrates a communication method of the invention. A plurality of orthogonal polyphase/poly-amplitude codes are generated **3061** in a transmitter. The codes are modulated **3062** with different data symbols. A-frequency-domain to time-domain conversion **3063** of the modulated codes is provided to generate a time-domain output. A cyclic prefix or guard interval is optionally prepended **3064** to the time-domain output, followed by transmission processing **3065** adapted to process the signal for transmission into a communication channel **99**.

A receiver process **3071** couples the transmission from the channel **99** and performs receiver system processes typically performed to convert a received signal to a digital or analog baseband or IF signal. An optional cyclic-prefix removal **3072** may be performed as necessary prior to time-domain to frequency-domain conversion **3073**. Interfering frequency-domain signals are separated in an interference-cancellation process **3074**, which may optionally employ frequency-domain and/or time-domain equalization. Separated signal values are then post processed, which may include decision processing **3075**.

FIG. **31**B illustrates a method of receiving single-carrier or multicarrier signals, including providing for receiver-system processing **3151** of received signals, performing a time-domain to frequency-domain conversion **3153** of the received signals to produce a plurality of orthogonal subcarrier values, providing for frequency-domain-equalization of the subcarrier values, providing for CI decoding **3157** (which includes combining), and providing for decision processing **3159**.

FIG. **32** illustrates a sub-space/subcarrier processor receiver of the invention. A plurality M of receiver systems **3251** to **3259** is adapted to couple a plurality of interfering single-carrier or multicarrier signals from a communication channel. M receiver branches are provided for frequency-domain analysis of received signals. Optional cyclic prefix removal modules **3261** may be provided. A set of M time-domain to frequency-domain converters, such as DFTs **3271** to **3279**, separate received signals in each branch into a plurality N of subcarrier values. Each of a plurality of sub-space processors **3281** to **3289** processes the subcarrier values. For example, N sub-space processors **3281** to **3289** can process M signals at a time that were mapped into each of the N subcarrier frequencies.

The output of each sub-space processor **3281** to **3289** is characterized by up to M sub-space values. Each of a plurality of CI decoders **3291** to **3299**, such as CI block decoders or CI sliding window decoders, combine subcarrier values corresponding to a particular subspace.

FIG. **33**A illustrates basic components of CI signal generation software residing on a computer-readable medium **3399**. CI signal generation software is typically configured to control the function and transmission-signal output of a single carrier or multicarrier transmitter. In some cases, a CI transmission may be characterized as a single-carrier signal in the time domain having a plurality of predetermined frequency-domain (or spectral) components.

A subcarrier allocation source code segment **3301** is adapted to generate a plurality of subcarriers allocated to at least one user or allocate a plurality of input subcarriers (not shown) to a particular user. A subcarrier weighting source code segment **3302** is adapted to provide complex weights (e.g., CI codes) to a plurality of the allocated subcarriers. The weights are configured to map one or more input data symbols into one or more phase spaces.

The computer-readable medium **3399** may include any item of manufacture adapted to store or convey software and/or firmware. The source-code segments **3301** and **3302** may reside on a physical memory storage device, such as any magnetic, electrical, or optical device adapted to store data and/or computer command instructions. The source-code segments **3301** and **3302** may be implemented as gate configurations on a programmable or integrated circuit. Other means for arranging physical devices and/or electromagnetic phenomena may be employed to convey the function of the source-code segments **3301** and **3302**. Accordingly, the computer-readable medium **3399** may include any combination of FPGAs, ASICs, transient memory, and persistent memory.

Subcarrier allocation may include generating subcarriers, providing for receiving input subcarriers, retrieving subcarriers or superposition waveforms from memory (e.g., a look-up table), or selecting non-zero (or equivalently, zero) valued input bin weights of an invertible transform, such as a DFT. In some applications, subcarrier allocation can include pulse shaping, controlling symbol durations, and/or selecting subcarrier frequency spacing. Some frequencies may be selected or avoided relative to channel conditions, bandwidth requirements, and/or interference.

The subcarrier allocation source code segment **3301** and subcarrier weighting source code segment **3302** may be implemented in one program. Similarly, other processing operations typically performed in a communication system transmitter may be implemented in, or in addition to, the source-code segments **3301** and **3302**. It should be appreciated that subcarrier allocation, selection, and assignment can include providing subcarriers for system control and/or monitoring. Subcarrier allocation, as described throughout the specification may include providing for pilot tones, training sequences, and/or other subcarriers allocated to other system-control functions. Subcarrier weighting may include channel coding, source coding, spread-spectrum coding, formatting, multiple-access coding, multiplexing, encryption, modulation, and/or array processing. Systems and methods illustrated herein and described throughout the specification may be implemented as source-code segments residing on one or more computer-readable mediums.

Network control in CI communications may be adapted to enable users to share network resources (e.g., bandwidth). For example, channel resources in the form of phase spaces and/or subcarriers may be allocated to each user relative to their level of service. Bandwidth may be allocated to users relative-to any combination of individual throughput requirements, purchased level of service, and availability of bandwidth.

FIG. **33**B illustrates a subcarrier weighting source code segment **3391** and a CI combining source code segment **3392** residing on a computer-readable medium **3399**. Source code segment **3391** is adapted to process one or more received channel measurements (such as frequency-domain or time-domain measurements) for generating a plurality of subcarrier weights. These weights are adapted to compensate for one or more channel effects, including, but not limited to, multipath, dispersion, and co-channel interference. The weights may be adapted to provide CI decoding. The weights may be adapted relative to one or more channel and/or data-quality measurements. The weights may be configured relative to data-processing measurements, such as hard-decision, soft-decision, and/or iterative feedback decision processing. The weights are typically applied to a plurality of subcarriers, such as frequency components produced by a filter bank or an FFT. Subcarrier weighting may include filtering, such as providing for acquiring subcarrier frequencies allocated to at least one predetermined user. Consequently, subcarrier weights may include both zero and non-zero values. Subcarrier weighting may include channel decoding, source decoding, spread-spectrum decoding, formatting, multiple-access decoding, demultiplexing, decryption, array processing, and/or modulation.

Source-code segment **3392** is adapted to combine the received and weighted carriers to generate a processed signal output, which is typically a sequence of symbols. At least one type of optimal combining may be provided. Code segment **3392** is adapted to receive as input at least one received signal, such as a sequence of data symbols. The received signal may be impressed onto the weights, weighted subcarriers, or waveforms generated from one or more superpositions of the weighted subcarriers. The weights are configured to map one or more input data symbols into one or more phase spaces. In some applications, data-modulated weights may be generated in source-code segment **3391**. In this case, source-code segment **3391** is adapted to process the received signal to generate at least one set of information-bearing weights.

All publications and patent applications mentioned in this specification are herein incorporated by reference to the same extent as if each individual publication or patent application was specifically and individually incorporated by reference.

Various embodiments of the invention may include variations in system configurations and the order of steps in which methods are provided. In many cases, multiple steps and/or multiple components may be consolidated.

The method and system embodiments described herein merely illustrate the principles of the invention. It should be appreciated that those skilled in the art will be able to devise various arrangements, which, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. Furthermore, all examples and conditional language recited herein are intended to be only for pedagogical purposes to aid the reader in understanding the principles of the invention. This disclosure and its associated references are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

It should be appreciated by those skilled in the art that the block diagrams herein represent conceptual views of illustrative circuitry, algorithms, and functional steps embodying the principles of the invention. Similarly, it should be appreciated that any flow charts, flow diagrams, signal diagrams, system diagrams, codes, and the like represent various processes which may be substantially represented in computer-readable medium and so executed by a computer or processor, whether or not such computer or processor is explicitly shown.

The functions of the various elements shown in the drawings, including functional blocks labeled as "processors" or "systems," may be provided through the use of dedicated hardware as well as hardware capable of executing software in association with appropriate software. When provided by a processor, the functions may be provided by a single dedicated processor, by a shared processor, or by a plurality of individual processors, some of which may be shared. Moreover, explicit use of the term "processor" or "controller" should not be construed to refer exclusively to hardware capable of executing software, and may implicitly include, without limitation, digital signal processor (DSP) hardware, read-only memory (ROM) for storing software, random access memory (RAM), and non-volatile storage. Other hardware, conventional and/or custom, may also be included. Similarly, the function of any component or device described herein may be carried out through the operation of program logic, through dedicated logic, through the interaction of program control and dedicated logic, or even manually, the particular technique being selectable by the implementer as more specifically understood from the context.

Any element expressed herein as a means for performing a specified function is intended to encompass any way of performing that function including, for example, a combination of circuit elements which performs that function or software in any form, including, therefore, firmware, microcode or the like, combined with appropriate circuitry for executing that software to perform the function. The invention as defined herein resides in the fact that the functionalities provided by the various recited means are combined and brought together in the manner which the operational descriptions call for. Applicant regards any means which can provide those functionalities as equivalent as those shown herein.

The invention claimed is:

1. A method for communication by a user device in a wireless network, comprising:

encoding a set of data symbols with a set of complex-valued codes, to produce a set of subcarrier values;

modulating the set of subcarrier values onto a set of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers assigned for use by the user device, to produce a plurality of modulated subcarriers; and

producing a time-domain waveform that comprises a superposition of the plurality of modulated subcarriers, the time-domain waveform to be transmitted in the wireless network by the user device;

wherein the set of subcarrier values comprises a first polyphase code that encodes a first of the set of data symbols and at least a second polyphase code that encodes at least a second of the set of data symbols;

wherein the first polyphase code causes constructive and destructive interference between the plurality of modulated subcarriers to produce a first periodic pulse waveform having a peak value that is centered at a first time in an OFDM symbol interval, and the second polyphase

code causes constructive and destructive interference between the plurality of modulated subcarriers to produce a second periodic pulse waveform having a peak value that is centered at a second time in the OFDM symbol interval, the second time different from the first time.

2. The method of claim **1**, wherein an mth one of the plurality of polyphase codes comprises a set of N code chips, wherein each code chip is expressed by $e^{j2\pi nm/N}$, where i is the square root of −1, π is Pi, and n is an integer that varies to provide incremental phase offsets to the set of N code chips.

3. The method of claim **1**, wherein the first time and the second time are separated by some integer multiple of T_s/N, where T_s is the OFDM symbol interval and N is the plurality of subcarrier frequencies.

4. The method of claim **1**, wherein the OFDM symbol interval $T_s=L/f_s$, where L is an integer that is greater than zero, and fs is subcarrier frequency spacing of the OFDM signal.

5. The method of claim **1**, wherein the periodic pulse waveform shape comprises an in-phase component and a quadrature-phase component.

6. The method of claim **1**, wherein the set of subcarrier values comprise a product of a matrix with a vector, wherein the matrix comprises the first polyphase code and the at least second polyphase code and the vector comprises the set of data symbols.

7. The method of claim **1**, further comprising adding a cyclic prefix to the time-domain waveform.

8. The method of claim **1**, wherein modulating and producing is performed with an inverse discrete Fourier transform (IDFT), and wherein modulating comprises providing a set of zero and non-zero values to input frequency bins of the IDFT according to OFDM tones assigned for use by the user device.

9. The method of claim **1**, wherein modulating comprises selecting one of a set of subcarrier frequency spacings.

10. The method of claim **1**, wherein modulating is configured to provide for orthogonal frequency division multiple access.

11. An apparatus for communication in a wireless communication network, the apparatus comprising:

at least one processor; and

a non-transitory computer-readable memory communicatively coupled to the at least one processor, the non-transitory computer-readable memory including a set of instructions stored thereon and executable by the at least one processor for:

encoding a set of data symbols with a set of complex-valued codes, to produce a set of subcarrier values;

modulating the set of subcarrier values onto a set of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers assigned for use by the user device, to produce a plurality of modulated subcarriers; and

producing a time-domain waveform that comprises a superposition of the plurality of modulated subcarriers, the time-domain waveform to be transmitted in the wireless network by the user device;

wherein the set of subcarrier values comprises a first polyphase code that encodes a first of the set of data symbols and at least a second polyphase code that encodes at least a second of the set of data symbols;

wherein the first polyphase code causes constructive and destructive interference between the plurality of modulated subcarriers to produce a first periodic pulse waveform having a peak value that is centered at a first time in an OFDM symbol interval, and the second polyphase code causes constructive and destructive interference between the plurality of modulated subcarriers to produce a second periodic pulse waveform having a peak value that is centered at a second time in the OFDM symbol interval, the second time different from the first time.

12. The apparatus of claim **11**, wherein an mth one of the plurality of polyphase codes comprises a set of N code chips, wherein each code chip is expressed by $e^{j2\pi nm/N}$, where i is the square root of −1, π is Pi, and n is an integer that varies to provide incremental phase offsets to the set of N code chips.

13. The apparatus of claim **11**, wherein the first time and the second time are separated by some integer multiple of T_s/N, where T_s is the OFDM symbol interval and N is the plurality of subcarrier frequencies.

14. The apparatus of claim **11**, wherein the OFDM symbol interval $T_s=L/f_s$, where L is an integer that is greater than zero, and f_s is subcarrier frequency spacing of the OFDM signal.

15. The apparatus of claim **11**, wherein the periodic pulse waveform shape comprises an in-phase component and a quadrature-phase component.

16. The apparatus of claim **11**, wherein the set of subcarrier values comprise a product of a matrix with a vector, wherein the matrix comprises the first polyphase code and the at least second polyphase code and the vector comprises the set of data symbols.

17. The apparatus of claim **11**, further comprising adding a cyclic prefix to the time-domain waveform.

18. The apparatus of claim **11**, wherein modulating and producing is performed with an inverse discrete Fourier transform (IDFT), and wherein modulating comprises providing a set of zero and non-zero values to input frequency bins of the IDFT according to OFDM tones assigned for use by the user device.

19. The apparatus of claim **11**, wherein modulating comprises selecting one of a set of subcarrier frequency spacings.

20. The apparatus of claim **11**, wherein modulating is configured to provide for orthogonal frequency division multiple access.

21. A computer program product for communication in a wireless communication network, the computer program product comprising a non-transitory computer readable storage device having computer readable program code stored therein, said program code containing instructions executable by one or more processors of a computer system for

encoding a set of data symbols with a set of complex-valued codes, to produce a set of subcarrier values;

modulating the set of subcarrier values onto a set of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers assigned for use by the user device, to produce a plurality of modulated subcarriers; and

producing a time-domain waveform that comprises a superposition of the plurality of modulated subcarriers, the time-domain waveform to be transmitted in the wireless network by the user device;

wherein the set of subcarrier values comprises a first polyphase code that encodes a first of the set of data symbols and at least a second polyphase code that encodes at least a second of the set of data symbols;

wherein the first polyphase code causes constructive and destructive interference between the plurality of modulated subcarriers to produce a first periodic

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pulse waveform having a peak value that is centered at a first time in an OFDM symbol interval, and the second polyphase code causes constructive and destructive interference between the plurality of modulated subcarriers to produce a second periodic pulse waveform having a peak value that is centered at a second time in the OFDM symbol interval, the second time different from the first time.

22. The computer program product of claim **21**, wherein an mth one of the plurality of polyphase codes comprises a set of N code chips corresponding to a set of integers $n=\{0, \ldots, N-1\}$, wherein each code chip is expressed by $e^{i2\pi nm/N}$, where i is the square root of −1, and π is Pi.

23. The computer program product of claim **21**, wherein the first time and the second time are separated by some integer multiple of T_s/N, where T_s is the OFDM symbol interval and N is the plurality of subcarrier frequencies.

24. The computer program product of claim **21**, wherein the OFDM symbol interval $T_s=L/f_s$, where L is an integer that is greater than zero, and f_s is subcarrier frequency spacing of the OFDM signal.

25. The computer program product of claim **21**, wherein the periodic pulse waveform shape comprises an in-phase component and a quadrature-phase component.

26. The computer program product of claim **21**, wherein the set of subcarrier values comprise a product of a matrix with a vector, wherein the matrix comprises the first polyphase code and the at least second polyphase code and the vector comprises the set of data symbols.

27. The computer program product of claim **21**, further comprising adding a cyclic prefix to the time-domain waveform.

28. The computer program product of claim **21**, wherein modulating and producing is performed with an inverse discrete Fourier transform (IDFT), and wherein modulating comprises providing a set of zero and non-zero values to input frequency bins of the IDFT according to OFDM tones assigned for use by the user device.

29. The computer program product of claim **21**, wherein modulating comprises selecting one of a set of subcarrier frequency spacings.

30. The computer program product of claim **21**, wherein modulating is configured to provide for orthogonal frequency division multiple access.

* * * * *

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(12) **United States Patent**
Shattil

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(54) **COORDINATED MULTIPOINT SYSTEMS**

(71) Applicant: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

(72) Inventor: **Steve Shattil**, Cheyenne, WY (US)

(73) Assignee: **Genghiscomm Holdings, LLC**, Boulder, CO (US)

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This patent is subject to a terminal disclaimer.

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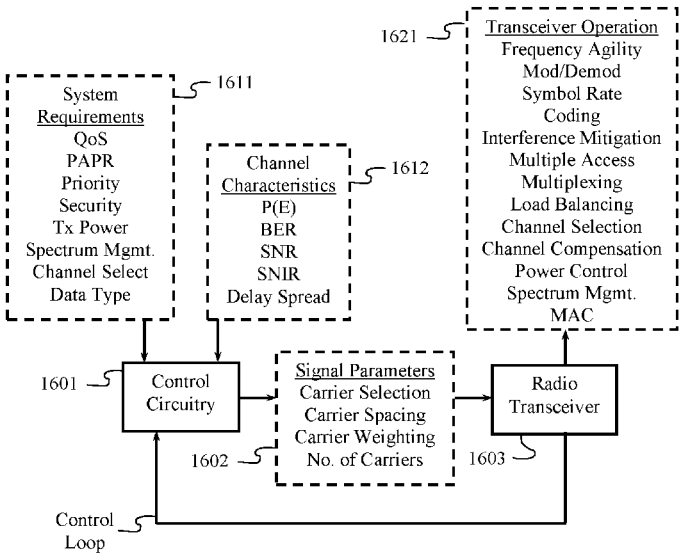
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Primary Examiner — Shailendra Kumar
(74) *Attorney, Agent, or Firm* — Steven J Shattil

(57) **ABSTRACT**

A flexible channel bandwidth for mobile radio communications is provided by provisioning a set of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers for mobile radio communications; encoding data symbols with polyphase codes derived from a discrete Fourier transform to produce encoded data symbols; and modulating the encoded data symbols onto the OFDM subcarriers to produce a superposition signal that resembles a single-carrier signal and has one of a plurality of different symbol durations. The provisioning comprises selecting one of a plurality of different selectable subcarrier spacings, to provide for the one of the plurality of different symbol durations.

21 Claims, 27 Drawing Sheets



Related U.S. Application Data

continuation of application No. 14/733,013, filed on Jun. 8, 2015, now Pat. No. 10,425,135, which is a continuation-in-part of application No. 13/116,984, filed on May 26, 2011, now Pat. No. 10,014,882, which is a continuation-in-part of application No. 12/328,917, filed on Dec. 5, 2008, now Pat. No. 7,965,761, which is a division of application No. 11/621,014, filed on Jan. 8, 2007, now Pat. No. 7,593,449.

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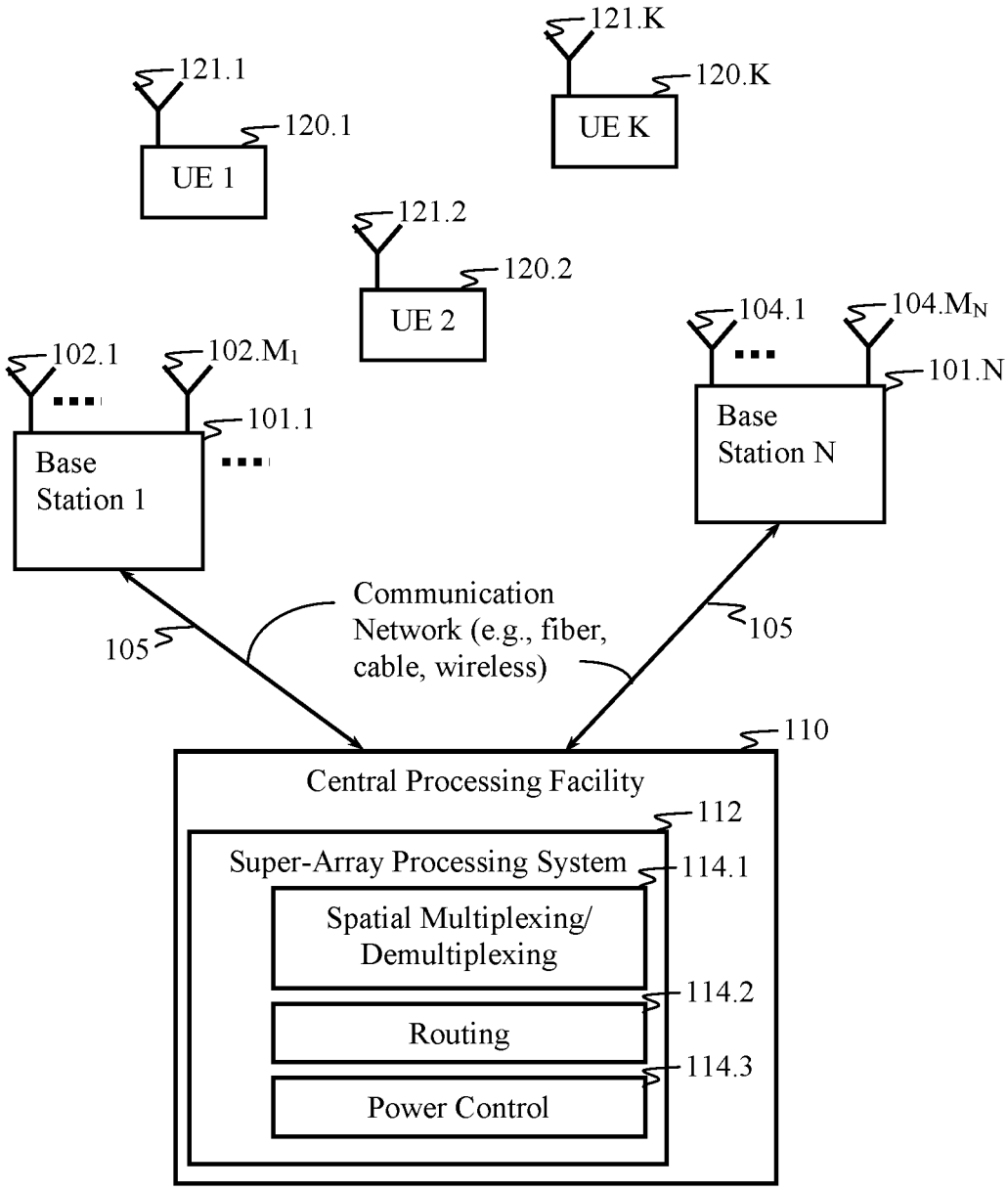

121.K
120.K
UE K
121.1
120.1
UE 1
121.2
120.2
UE 2
104.1
104.M_N
101.N
Base Station N
102.1
102.M_1
101.1
Base Station 1
105
Communication Network (e.g., fiber, cable, wireless)
105
110
Central Processing Facility
112
Super-Array Processing System
114.1
Spatial Multiplexing/ Demultiplexing
114.2
Routing
114.3
Power Control

Figure 1

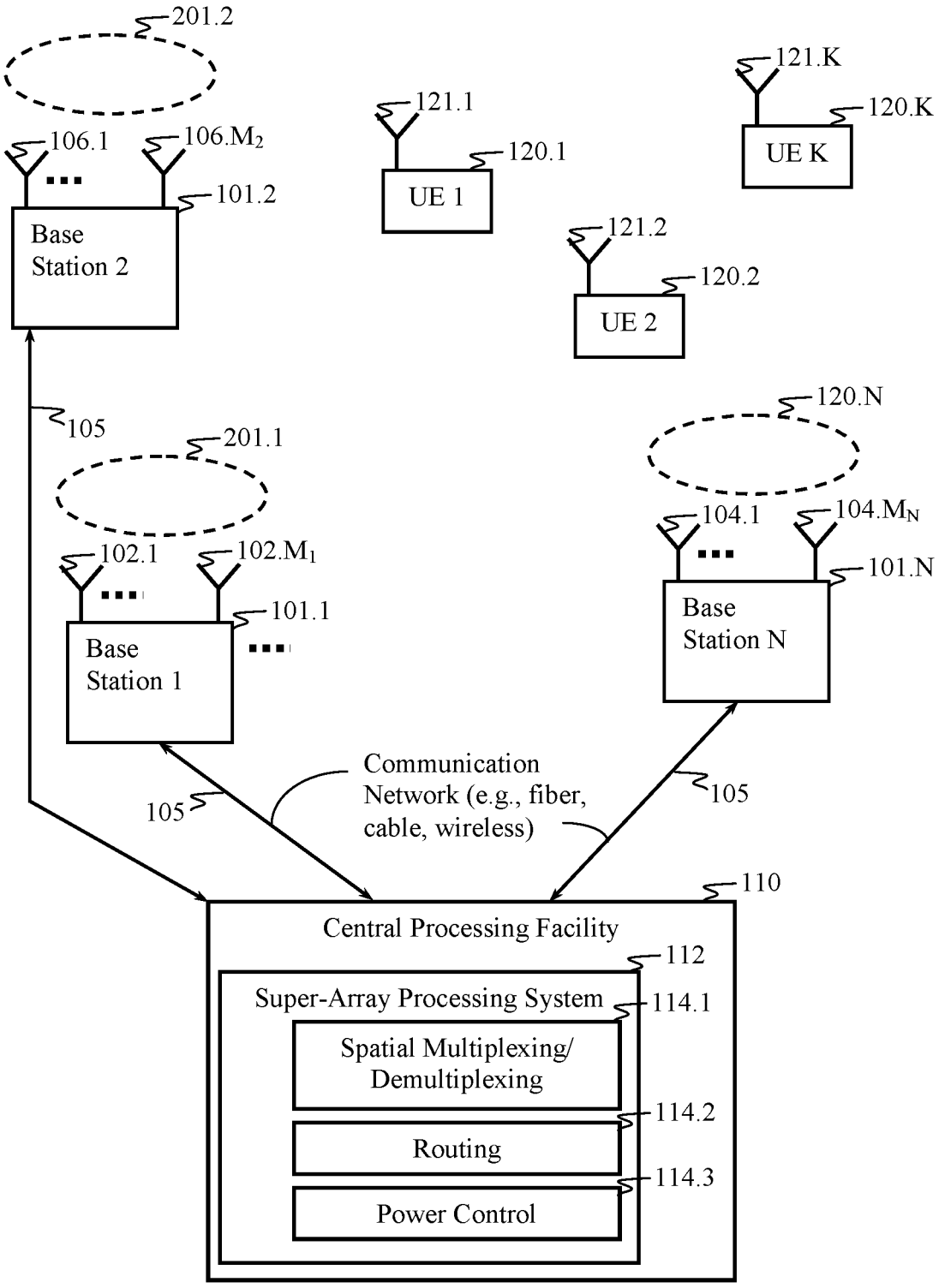

201.2
106.1
106.M2
101.2
Base Station 2
121.1
120.1
UE 1
121.K
120.K
UE K
121.2
120.2
UE 2
105
201.1
102.1
102.M1
101.1
Base Station 1
120.N
104.1
104.MN
101.N
Base Station N
Communication Network (e.g., fiber, cable, wireless)
105
105
110
Central Processing Facility
112
Super-Array Processing System
114.1
Spatial Multiplexing/ Demultiplexing
114.2
Routing
114.3
Power Control

Figure 2

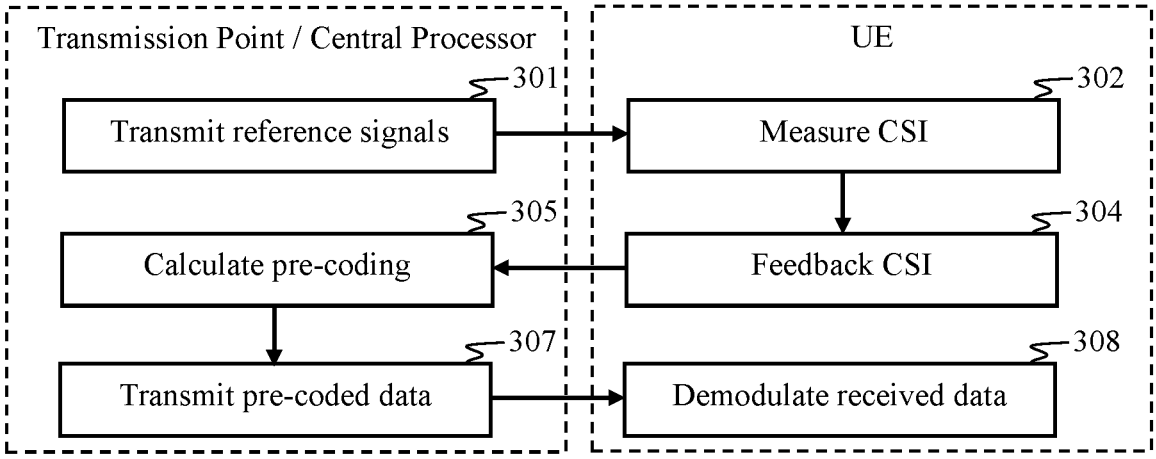


Figure 3A

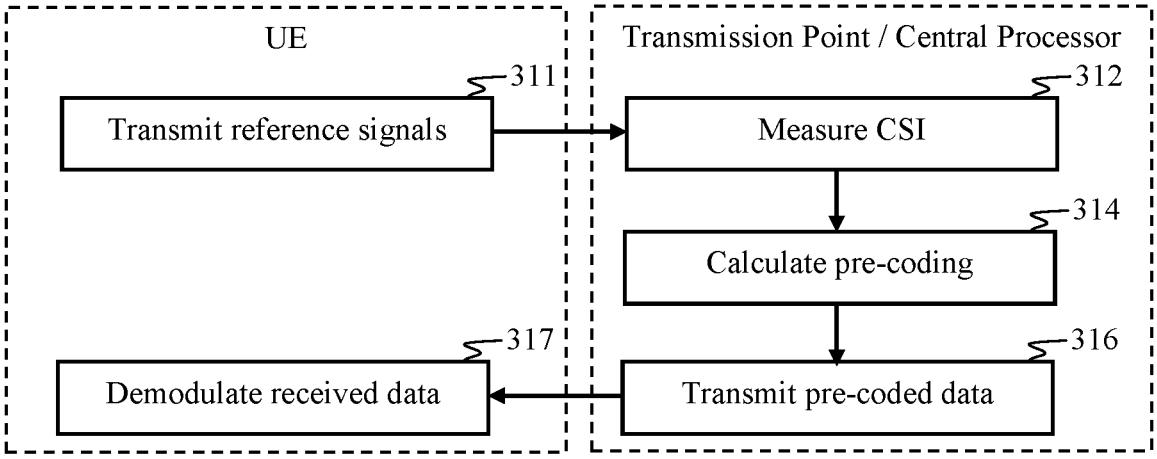


Figure 3B

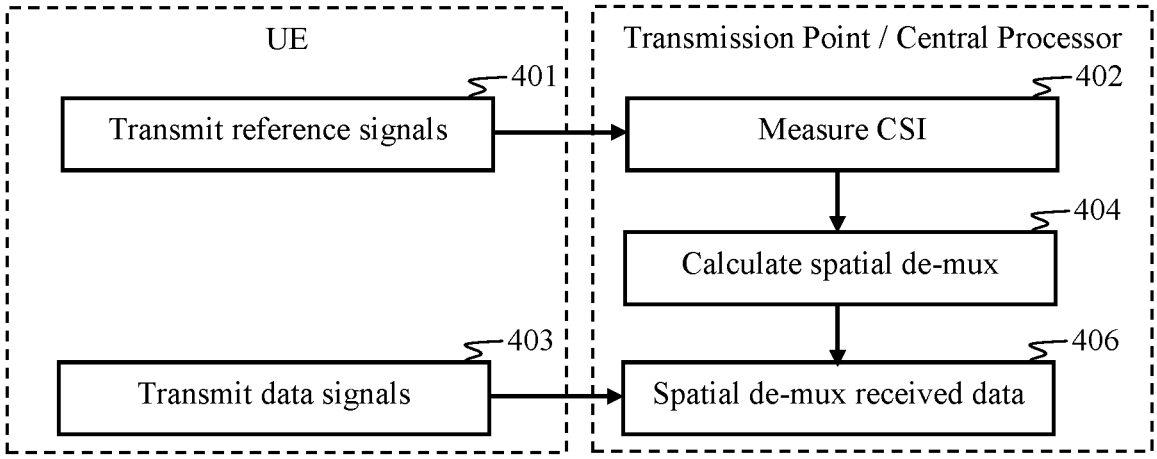


Figure 4A

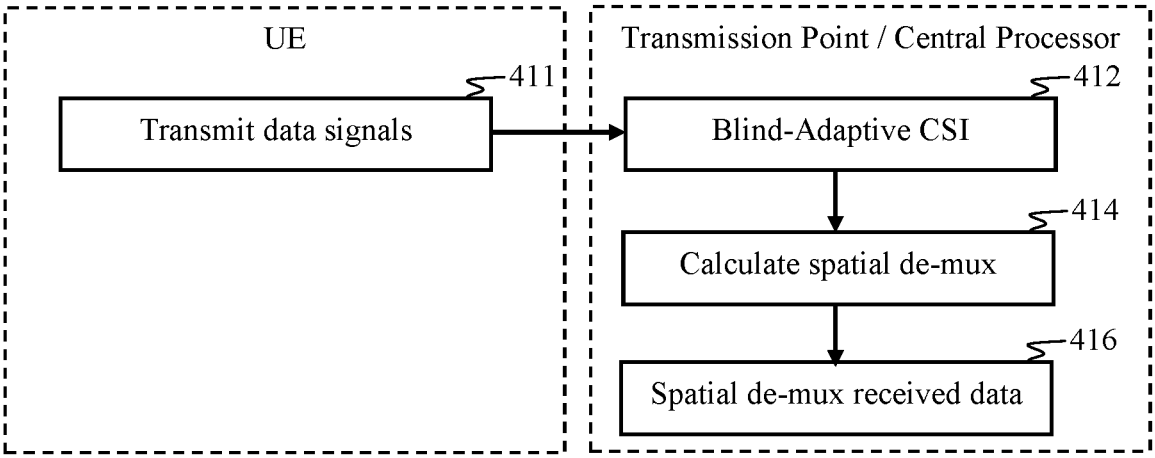


Figure 4B

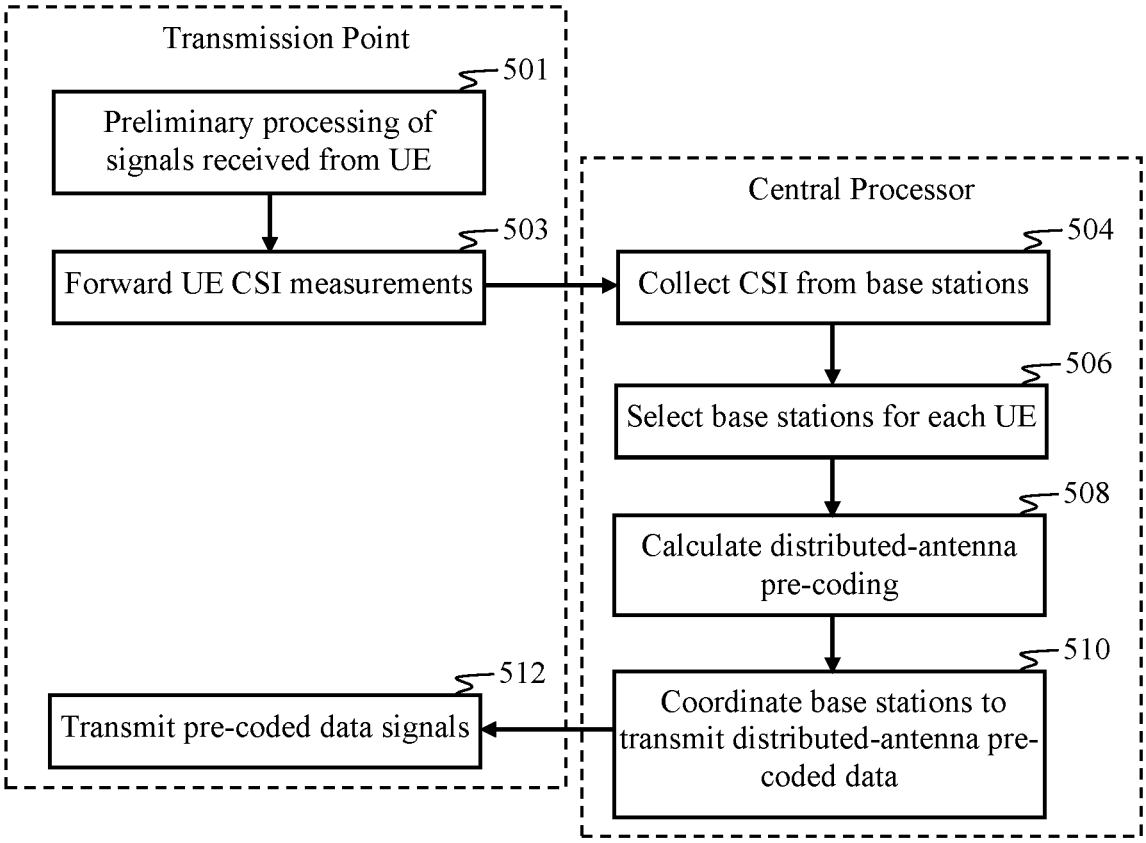

Transmission Point
501
Preliminary processing of signals received from UE
503
Forward UE CSI measurements
512
Transmit pre-coded data signals
Central Processor
504
Collect CSI from base stations
506
Select base stations for each UE
508
Calculate distributed-antenna pre-coding
510
Coordinate base stations to transmit distributed-antenna pre-coded data

Figure 5

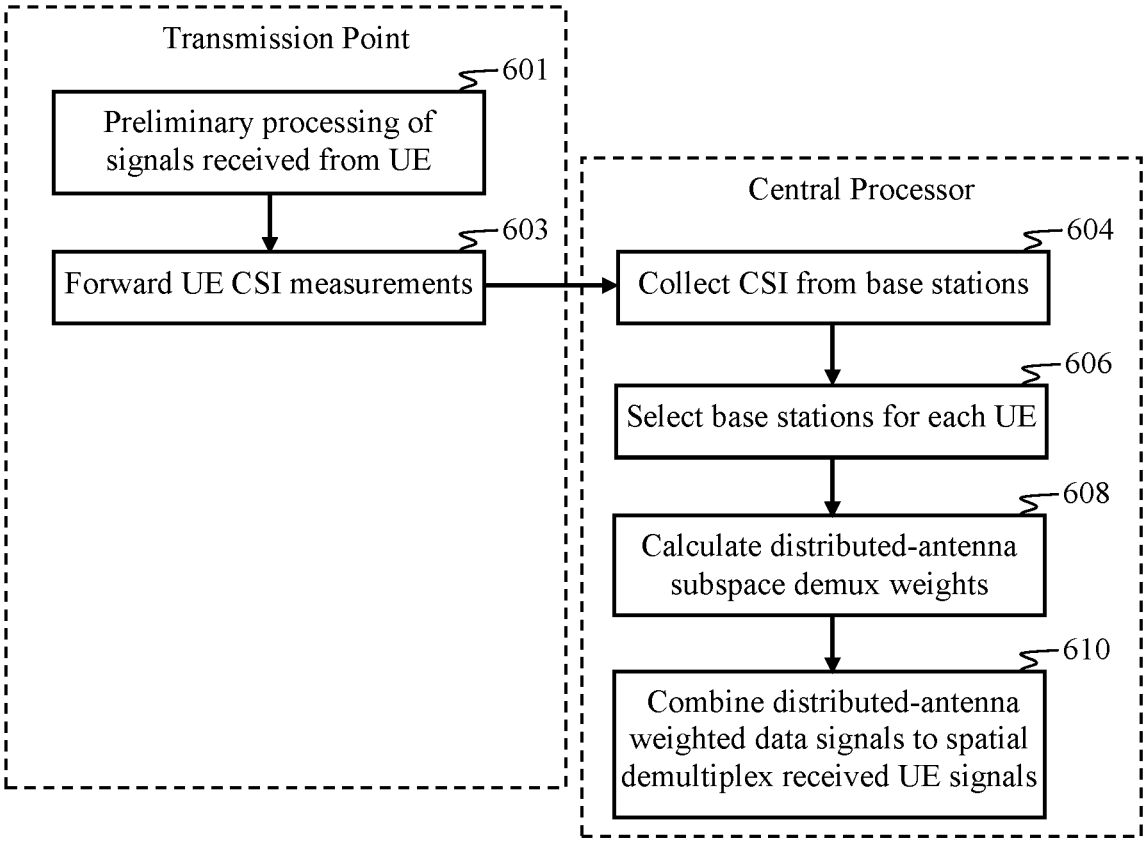

Transmission Point
601
Preliminary processing of signals received from UE
603
Forward UE CSI measurements
Central Processor
604
Collect CSI from base stations
606
Select base stations for each UE
608
Calculate distributed-antenna subspace demux weights
610
Combine distributed-antenna weighted data signals to spatial demultiplex received UE signals

Figure 6

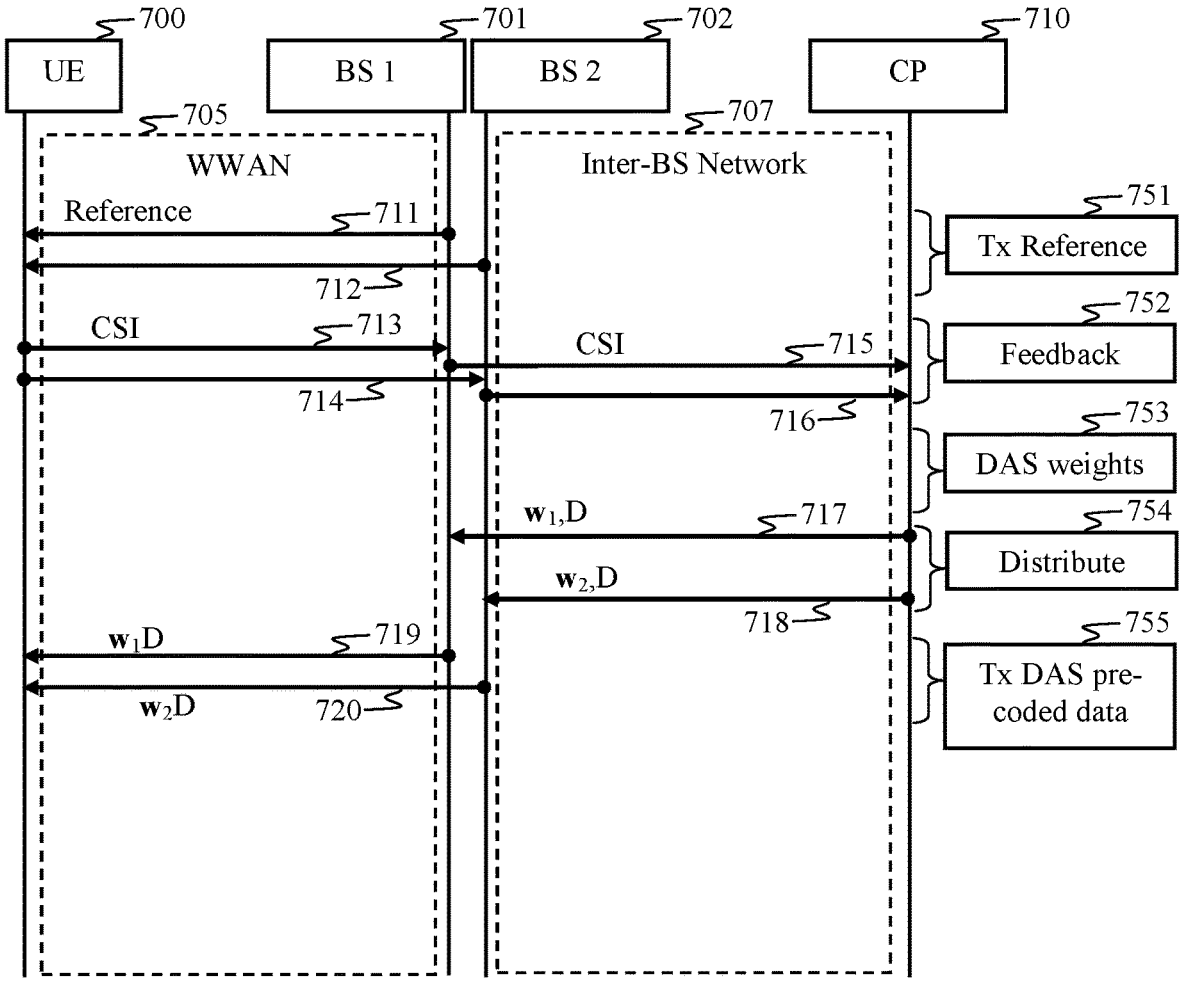

700
UE
701
BS 1
702
BS 2
710
CP
705
WWAN
707
Inter-BS Network
Reference
711
712
CSI
713
714
CSI
715
716
751
Tx Reference
752
Feedback
753
DAS weights
754
Distribute
755
Tx DAS pre-coded data
w1,D
717
w2,D
718
w1D
719
w2D
720

Figure 7

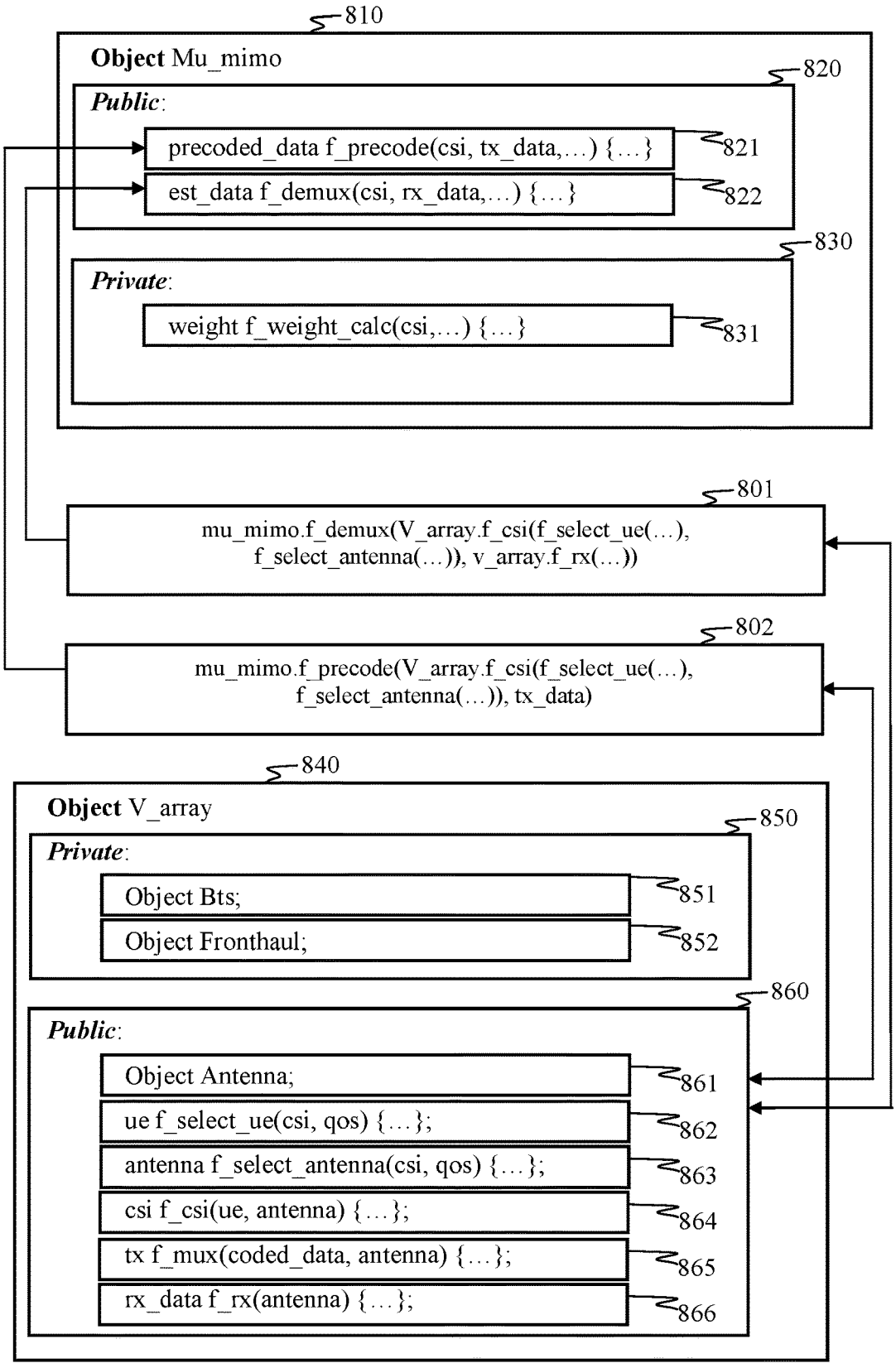

810
Object Mu_mimo
820
Public:
precoded_data f_precode(csi, tx_data,…) {…}
821
est_data f_demux(csi, rx_data,…) {…}
822
830
Private:
weight f_weight_calc(csi,…) {…}
831
801
mu_mimo.f_demux(V_array.f_csi(f_select_ue(…), f_select_antenna(…)), v_array.f_rx(…))
802
mu_mimo.f_precode(V_array.f_csi(f_select_ue(…), f_select_antenna(…)), tx_data)
840
Object V_array
850
Private:
Object Bts;
851
Object Fronthaul;
852
860
Public:
Object Antenna;
861
ue f_select_ue(csi, qos) {…};
862
antenna f_select_antenna(csi, qos) {…};
863
csi f_csi(ue, antenna) {…};
864
tx f_mux(coded_data, antenna) {…};
865
rx_data f_rx(antenna) {…};
866

Figure 8

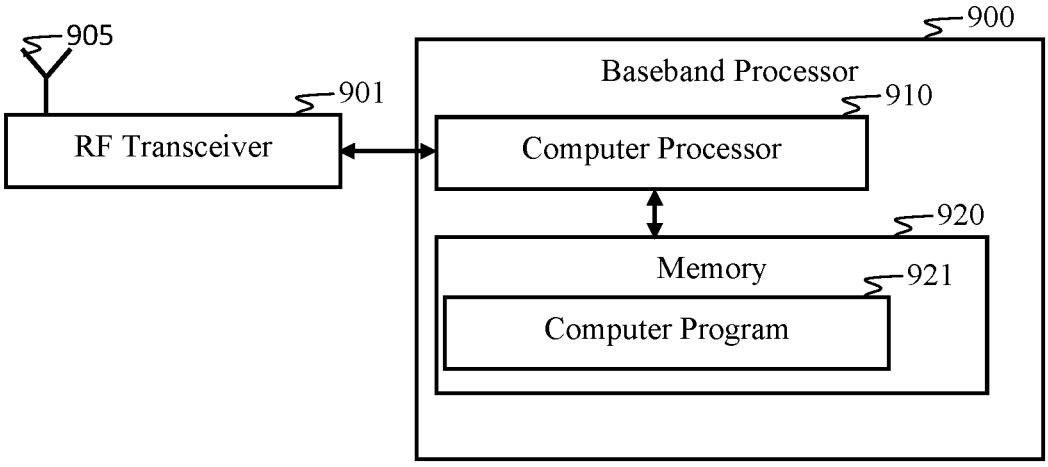

905
900
Baseband Processor
901
910
RF Transceiver
Computer Processor
920
Memory
921
Computer Program

Figure 9

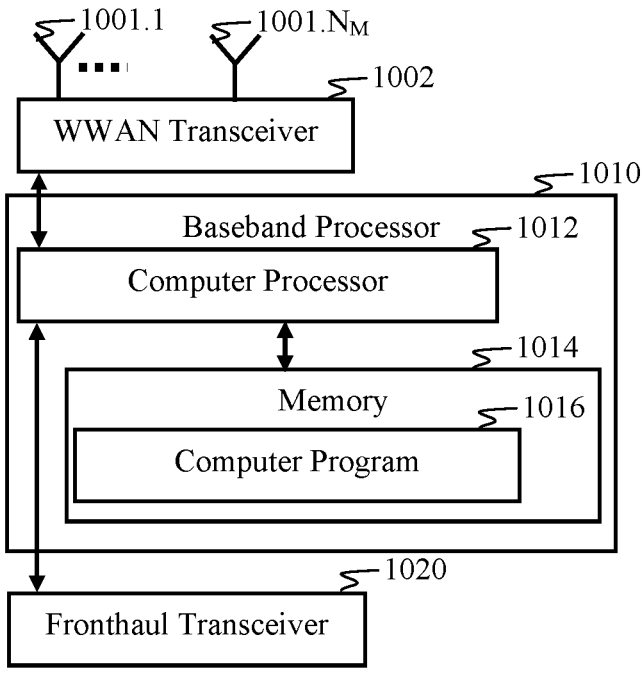

1001.1
1001.N_M
1002
WWAN Transceiver
1010
Baseband Processor
1012
Computer Processor
1014
Memory
1016
Computer Program
1020
Fronthaul Transceiver

Figure 10

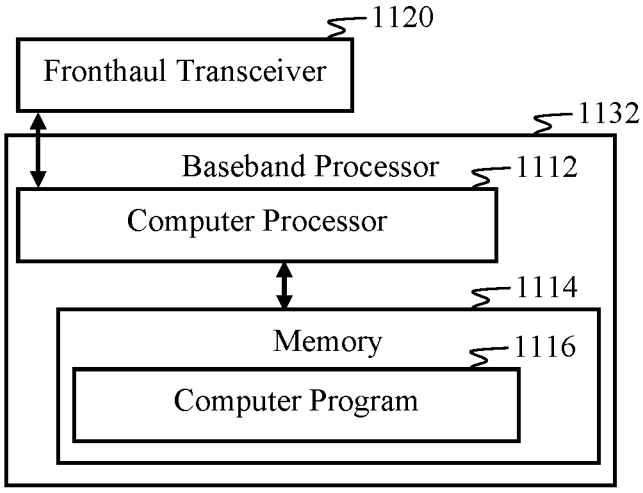


Figure 11A

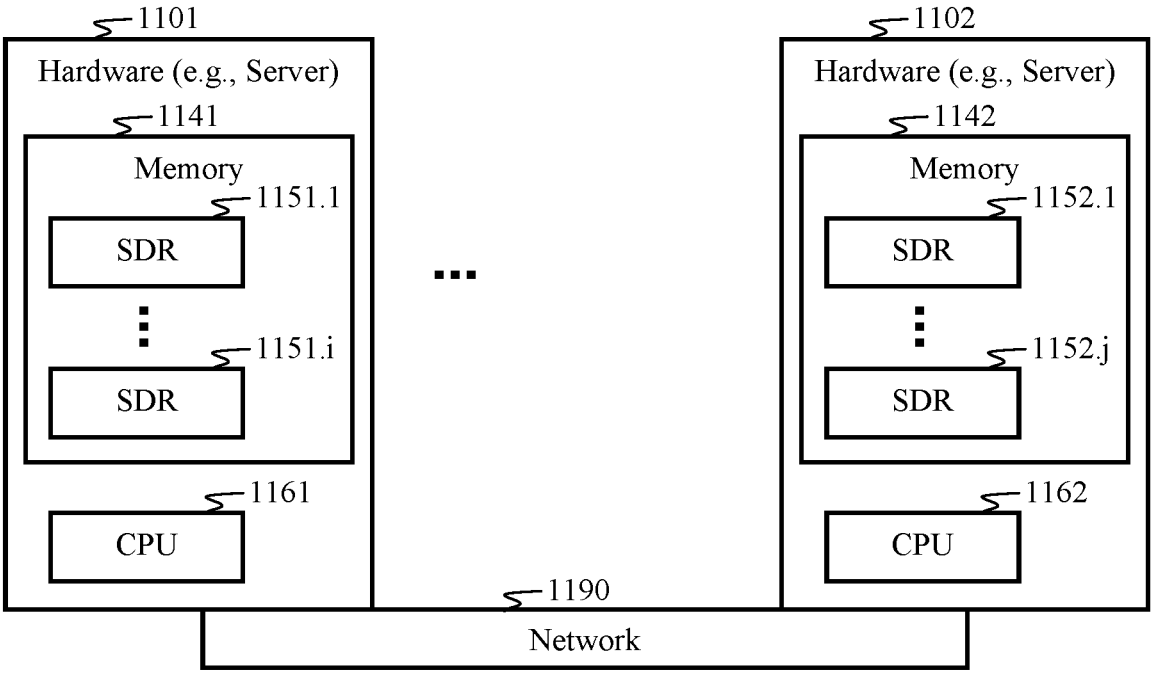


Figure 11B

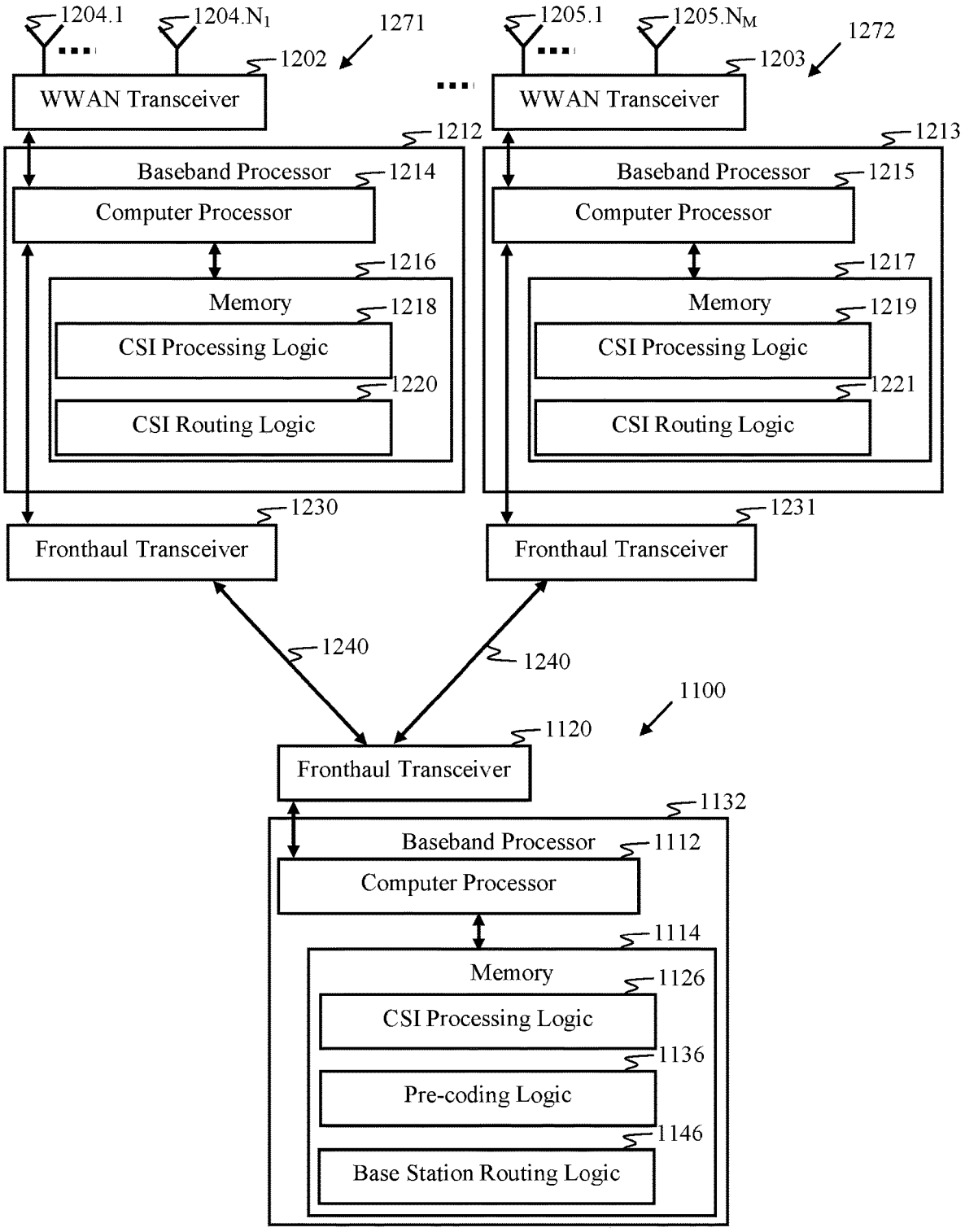

1204.1
1204.N1
1271
1202
WWAN Transceiver
1205.1
1205.NM
1272
1203
WWAN Transceiver
1212
Baseband Processor
1214
Computer Processor
1216
Memory
1218
CSI Processing Logic
1220
CSI Routing Logic
1213
Baseband Processor
1215
Computer Processor
1217
Memory
1219
CSI Processing Logic
1221
CSI Routing Logic
1230
Fronthaul Transceiver
1231
Fronthaul Transceiver
1240
1240
1100
1120
Fronthaul Transceiver
1132
Baseband Processor
1112
Computer Processor
1114
Memory
1126
CSI Processing Logic
1136
Pre-coding Logic
1146
Base Station Routing Logic

Figure 12

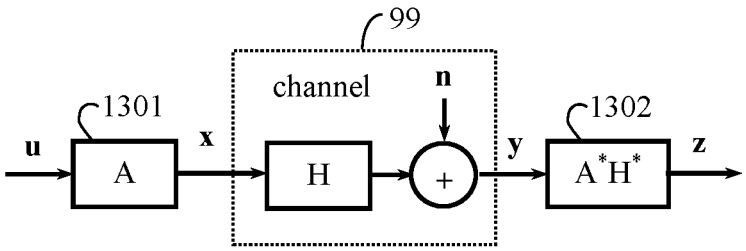


Figure 13A

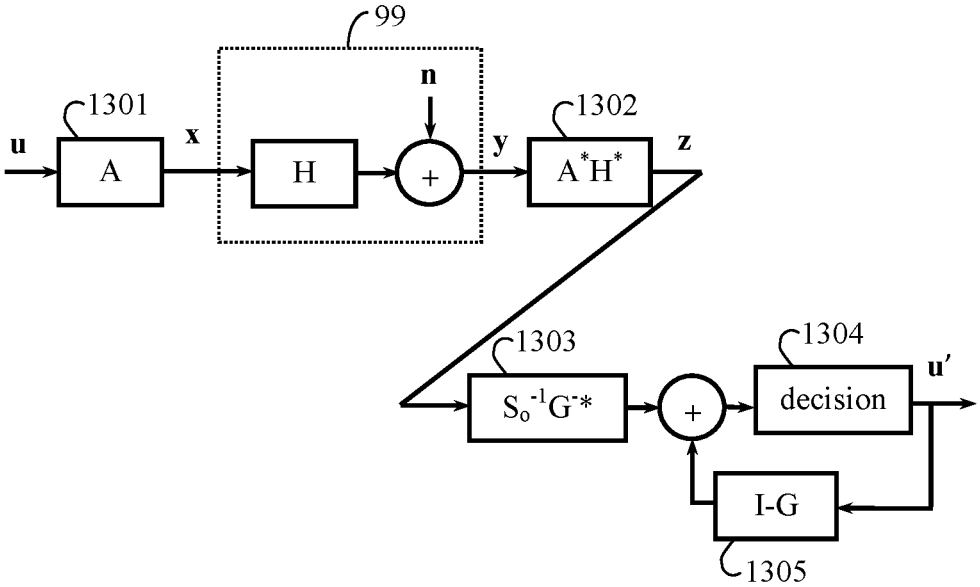


Figure 13B

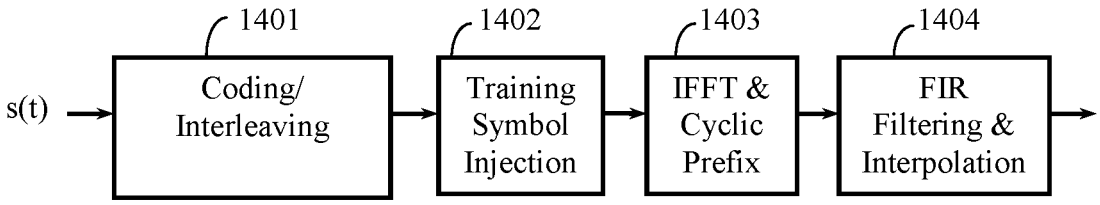


Figure 14A

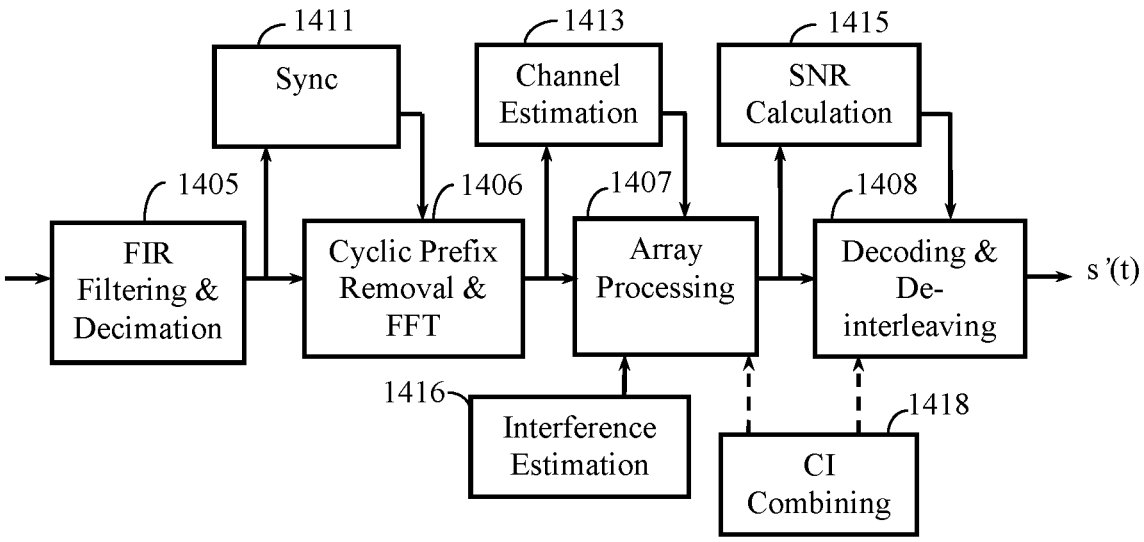


Figure 14B

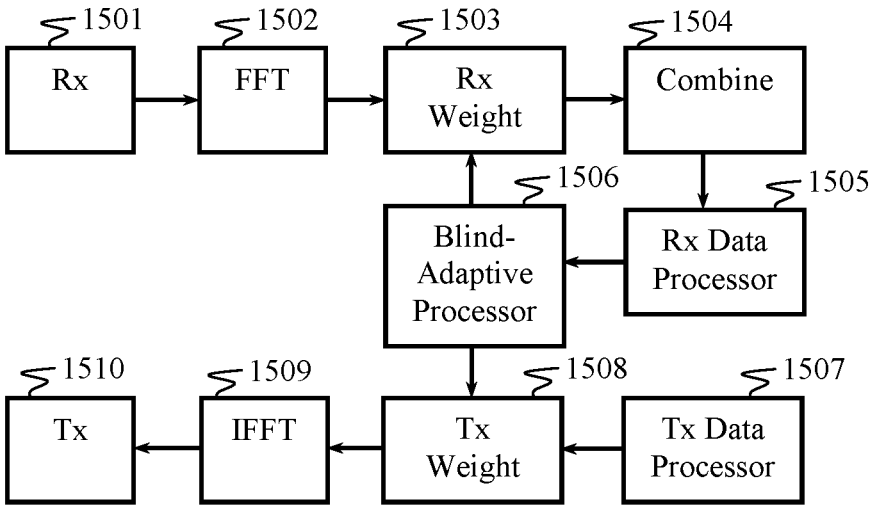

1501
Rx
1502
FFT
1503
Rx Weight
1504
Combine
1506
Blind-Adaptive Processor
1505
Rx Data Processor
1510
Tx
1509
IFFT
1508
Tx Weight
1507
Tx Data Processor

Figure 15

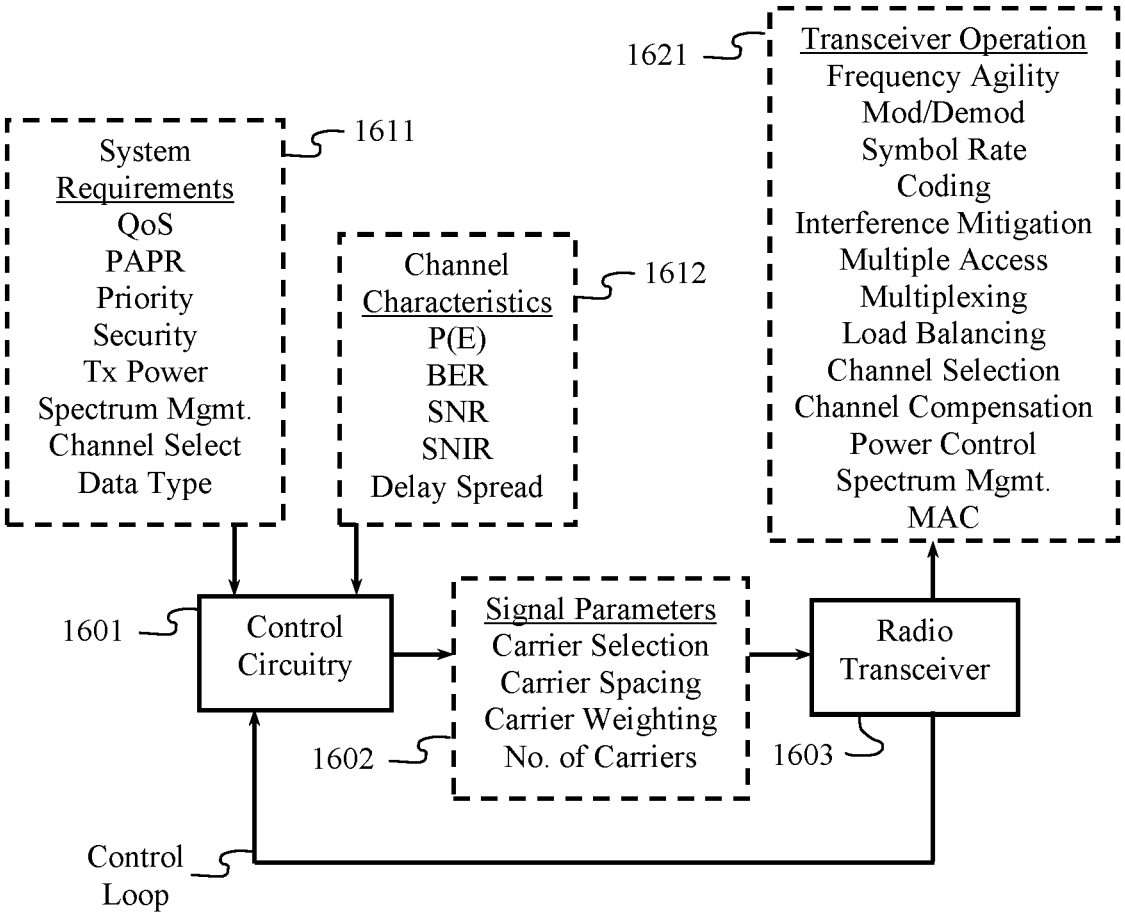

1621
Transceiver Operation
Frequency Agility
Mod/Demod
Symbol Rate
Coding
Interference Mitigation
Multiple Access
Multiplexing
Load Balancing
Channel Selection
Channel Compensation
Power Control
Spectrum Mgmt.
MAC
1611
System
Requirements
QoS
PAPR
Priority
Security
Tx Power
Spectrum Mgmt.
Channel Select
Data Type
1612
Channel
Characteristics
P(E)
BER
SNR
SNIR
Delay Spread
1601
Control
Circuitry
Signal Parameters
Carrier Selection
Carrier Spacing
Carrier Weighting
No. of Carriers
1602
Radio
Transceiver
1603
Control
Loop

Figure 16

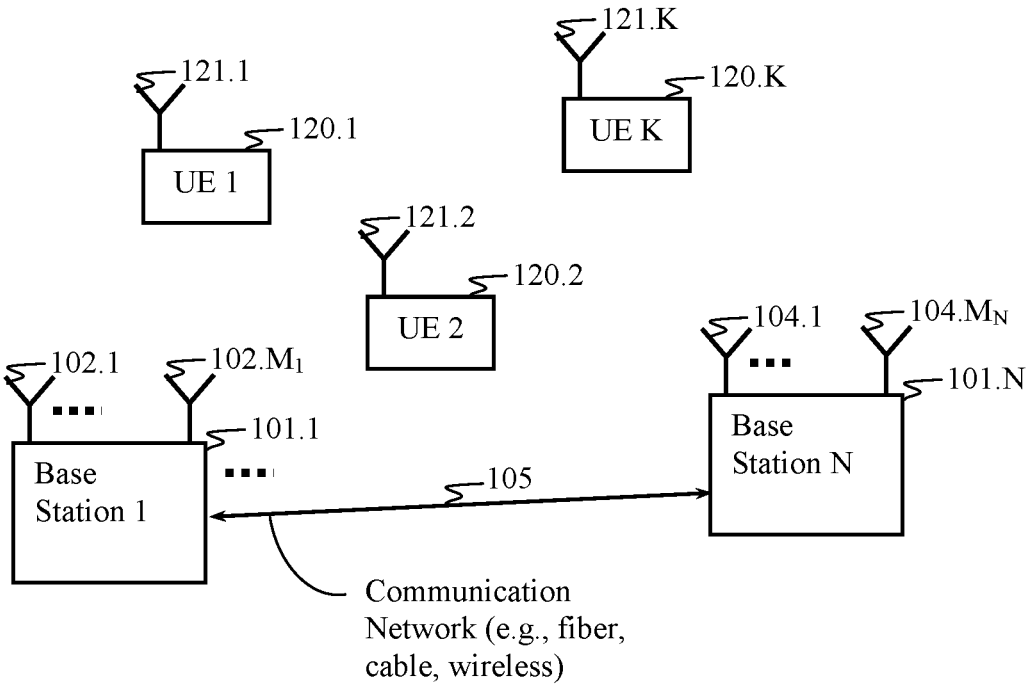

121.K
120.K
UE K
121.1
120.1
UE 1
121.2
120.2
UE 2
104.1
104.M_N
101.N
Base Station N
102.1
102.M_1
101.1
Base Station 1
105
Communication Network (e.g., fiber, cable, wireless)

Figure 17

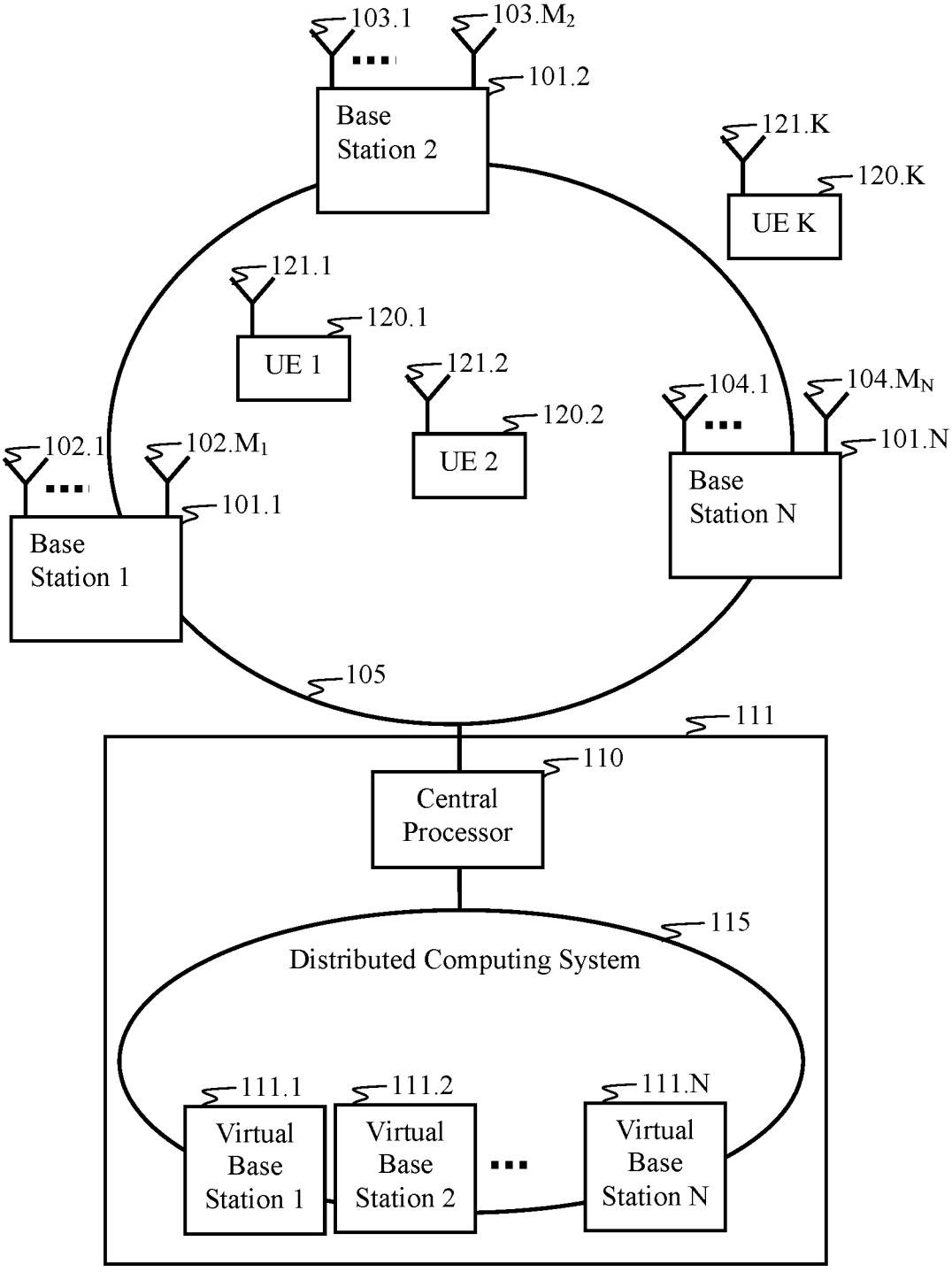

103.1
103.M2
101.2
Base Station 2
121.K
120.K
UE K
121.1
120.1
UE 1
121.2
120.2
UE 2
104.1
104.MN
101.N
Base Station N
102.1
102.M1
101.1
Base Station 1
105
111
110
Central Processor
115
Distributed Computing System
111.1
111.2
111.N
Virtual Base Station 1
Virtual Base Station 2
Virtual Base Station N

Figure 18

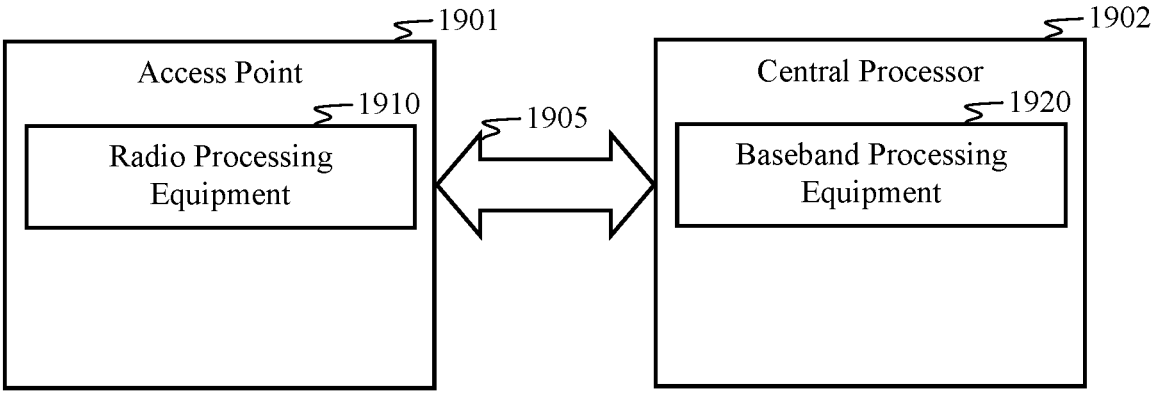

1901
Access Point
1910
Radio Processing Equipment
1905
1902
Central Processor
1920
Baseband Processing Equipment

Figure 19

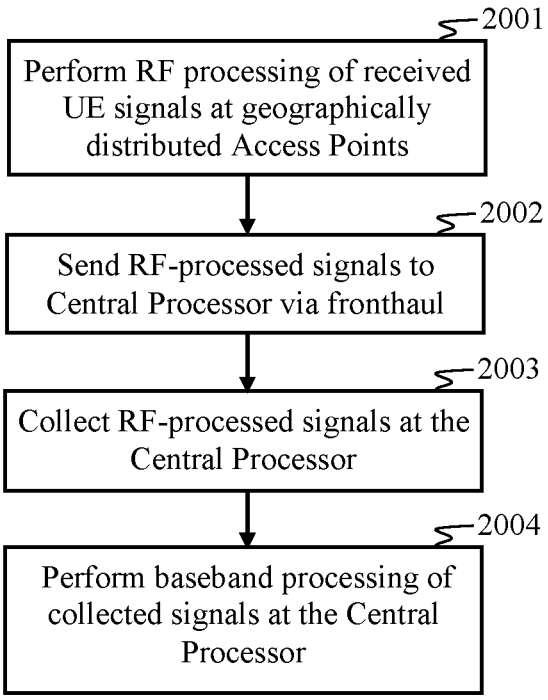


Figure 20A

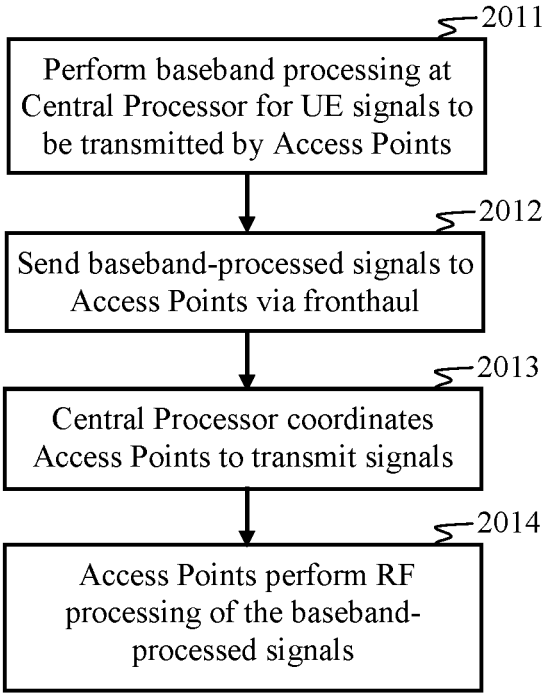


Figure 20B

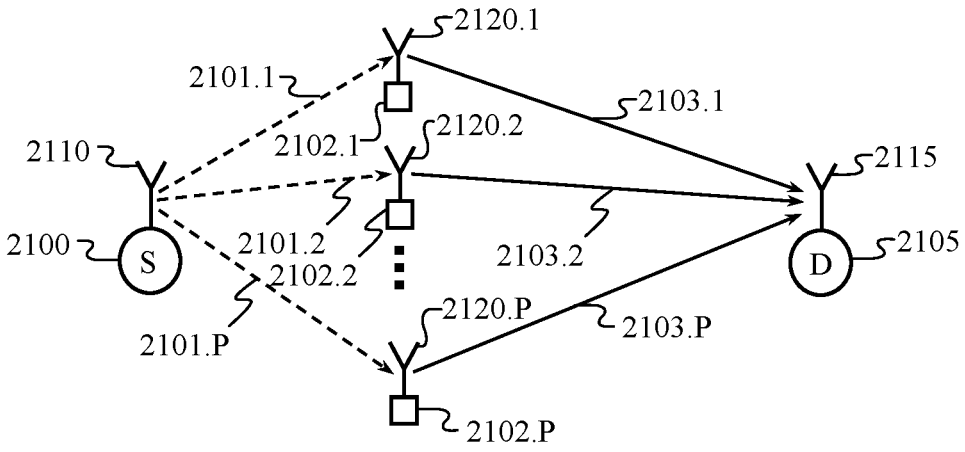

2120.1
2101.1
2103.1
2102.1
2120.2
2110
2115
2100
S
2101.2
2102.2
2103.2
D
2105
2120.P
2103.P
2101.P
2102.P

Figure 21

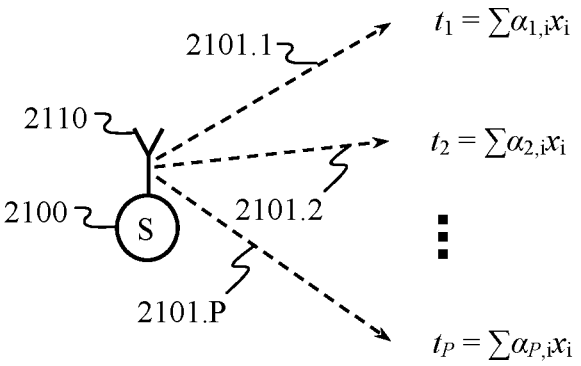


Figure 22A

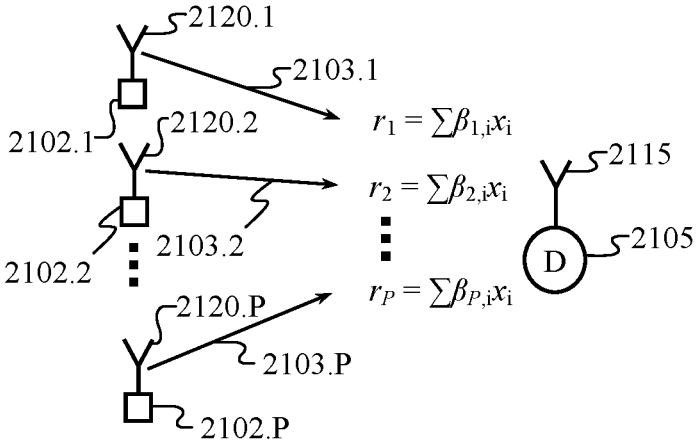


Figure 22B

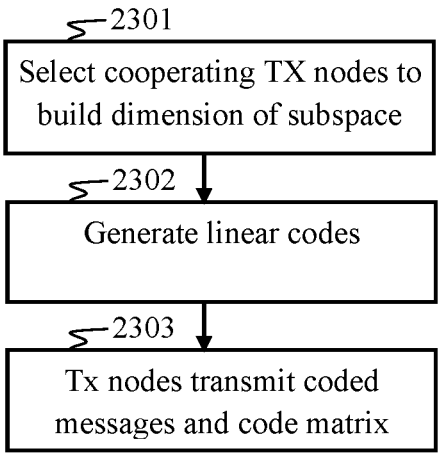


Figure 23A

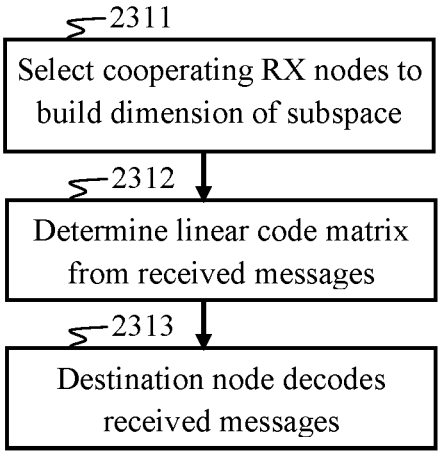


Figure 23B

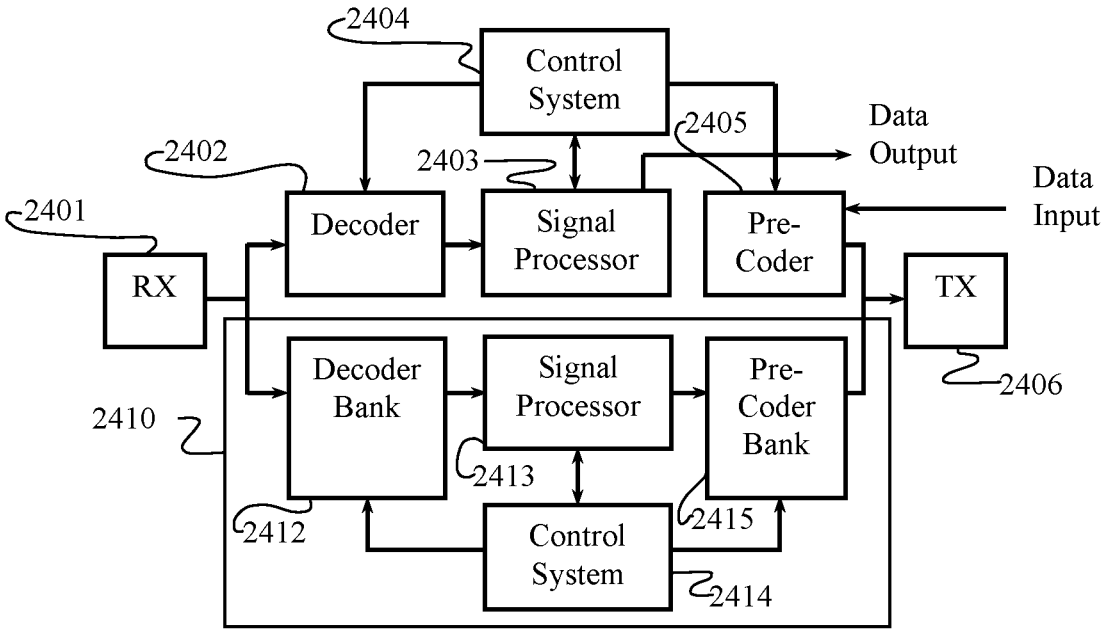


Figure 24A

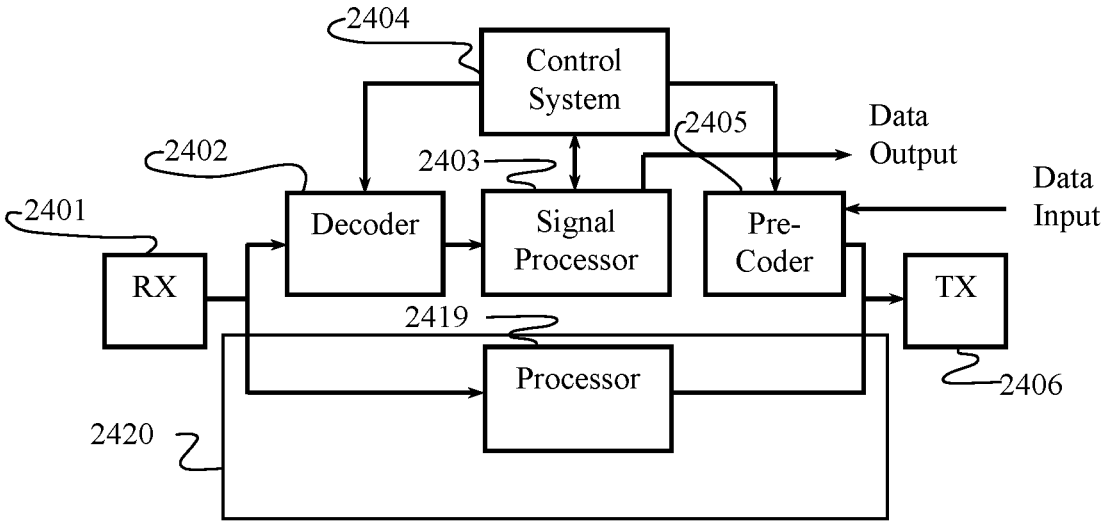


Figure 24B

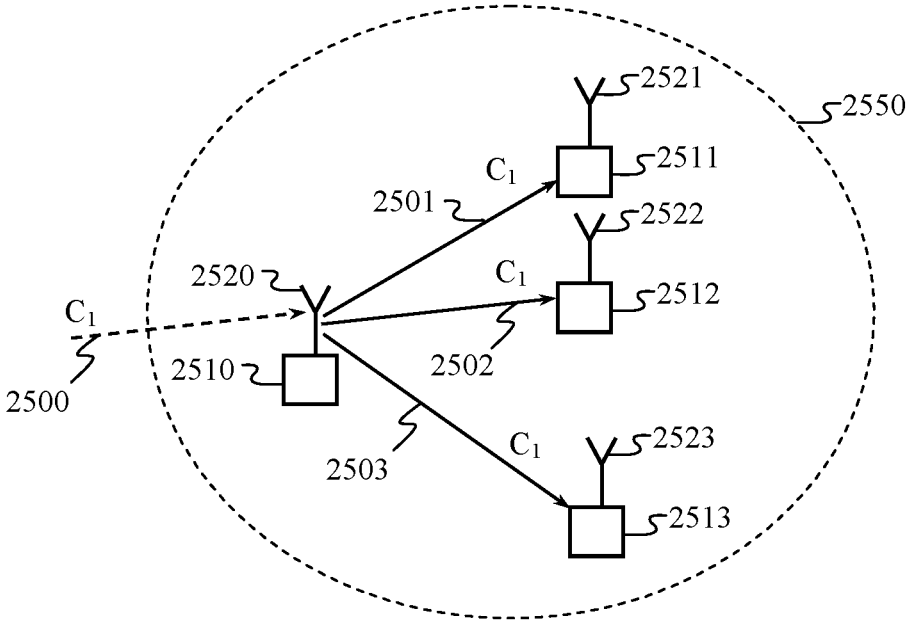


Figure 25A

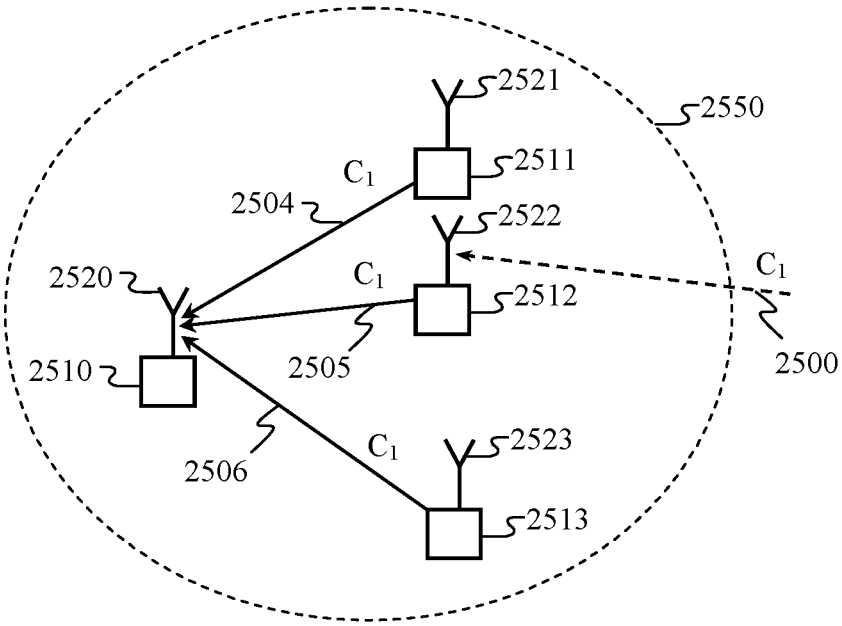


Figure 25B

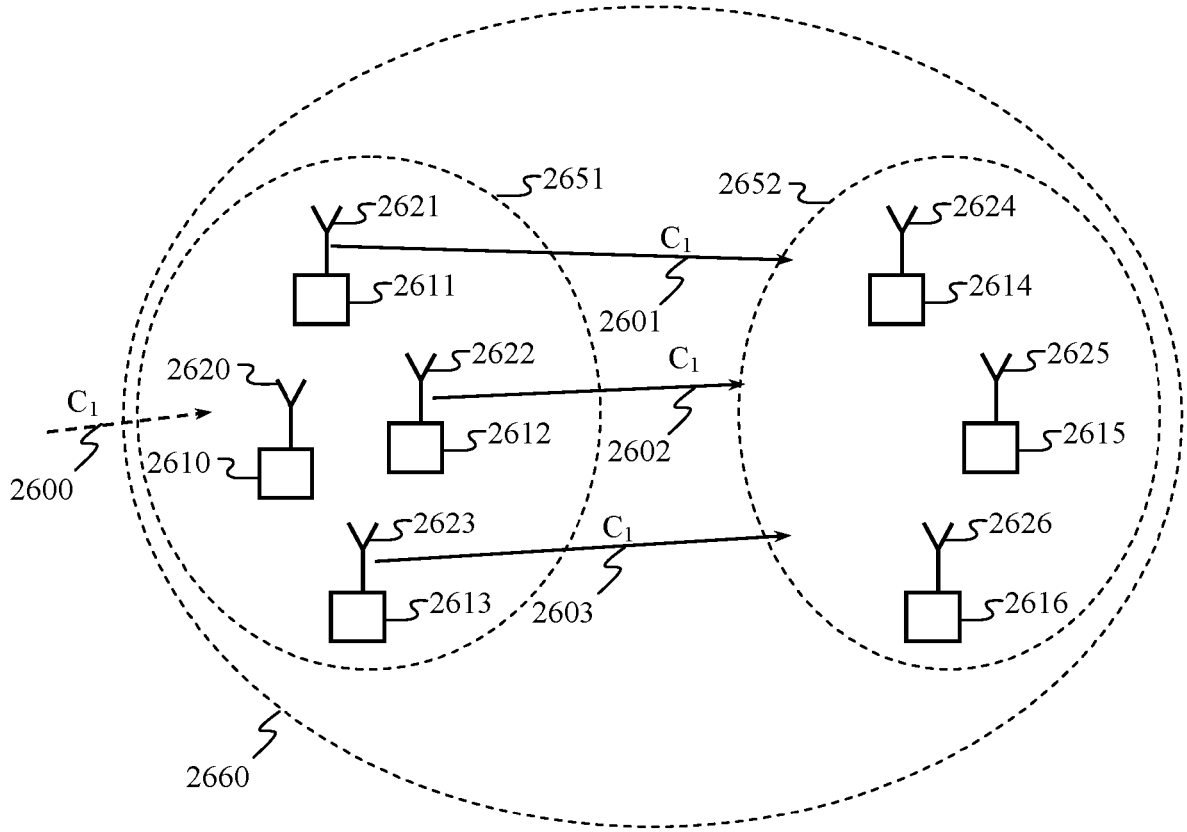

2651
2652
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C1
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2601
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C1
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C1
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2600
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C1
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2603
2616
2660

Figure 26

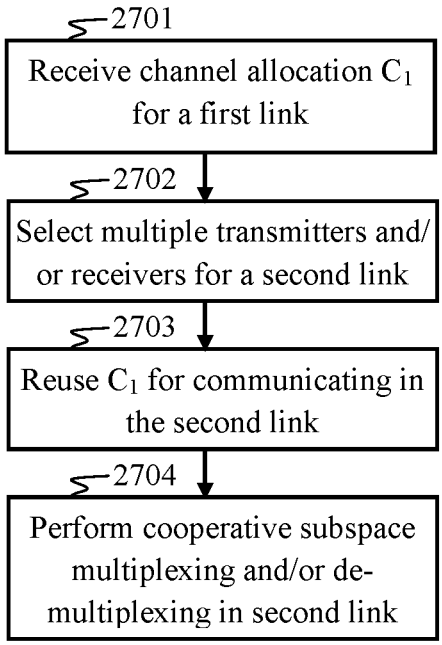

2701
Receive channel allocation C_1 for a first link
2702
Select multiple transmitters and/or receivers for a second link
2703
Reuse C_1 for communicating in the second link
2704
Perform cooperative subspace multiplexing and/or de-multiplexing in second link

Figure 27

COORDINATED MULTIPOINT SYSTEMS

RELATED APPLICATIONS

This application is a Continuation of U.S. patent application Ser. No. 16/575,713, filed on Sep. 19, 2019, now U.S. Pat. No. 10,931,338, which is a Continuation of U.S. patent application Ser. No. 14/733,013, filed Jun. 8, 2015, now U.S. Pat. No. 10,425,135, which is a Continuation-in-Part of U.S. patent application Ser. No. 13/116,984, filed May 26, 2011, now U.S. Pat. No. 10,014,882, which is a Continuation-in-Part of U.S. patent application Ser. No. 12/328,917, filed Dec. 5, 2008, now U.S. Pat. No. 7,965,761, which is a Divisional of U.S. patent application Ser. No. 11/621,014 filed Jan. 8, 2007, now U.S. Pat. No. 7,593,449, all of which are expressly incorporated by reference in their entireties.

BACKGROUND

I. Field

The present invention relates generally to wireless communication networks, and more specifically to cooperative signal processing between wireless transceivers.

II. Background

The background description includes information that may be useful in understanding the present inventive subject matter. It is not an admission that any of the information provided herein is prior art or relevant to the presently claimed inventive subject matter, or that any publication, specifically or implicitly referenced, is prior art.

Communication over the spatial modes of a point-to-point MIMO channel was developed in the early 90s [e.g., S. J. Shattil, U.S. Pat. No. 6,211,671] then gradually extended to multi-user (MU-) MIMO channels [e.g., S. J. Shattil, U.S. Pat. No. 6,008,760].

In a conventional cellular communication system, transmissions to different users are formed independently. Hence, the transmission to one user can act as interference to other users. Because the system forms the transmission to each user independently, the system has no way of knowing how a transmission to a particular user will impact other users in the vicinity. As a result, interference between cells is a main factor limiting the performance of current cellular systems. For users near a cell boundary, inter-cell interference is especially problematic.

Fading and interference are the two key challenges faced by designers of mobile communication systems. While fading puts limits on the coverage and reliability of any point-to-point wireless connection, e.g., between a base station and a mobile terminal, interference in prior-art networks restricts the reusability of the spectral resource (time, frequency slots, codes, etc.) in space, thus limiting the overall spectral efficiency expressed in bits/sec/Hz/base station.

The conventional approach to interference mitigation is spatial reuse partitioning, which prevents any spectral resource from being re-used within a certain cluster of cells. Typically, the frequency re-use factor is much less than unity such that the level of co-channel interference is low. Thus, interference is controlled by fixing the frequency reuse pattern and the maximum power spectral density levels of each base station. Some CDMA systems allow for full frequency re-use in each cell, but at the expense of severe interference at the cell edge, resulting in a significant data rate drop at the terminals and a strong lack of fairness across cell users. Some interference mitigation can be achieved via limited inter-cell coordination, such as soft handover techniques. Inter-cell interference is typically treated as noise at the receiver side and is handled by resorting to improved point-to-point communications between the base station and the mobile station using efficient coding and/or single-link multiple-antenna techniques.

Some of the proposals for increasing the capacity of cellular networks include using more spectrum, increasing the number of transmit/receive antennas on each station, using dedicated beams to serve users, and micro-cell deployment. However, none of these approaches adequately address inter-cell interference, which is a primary bottleneck for spectral efficiency.

In the traditional cellular architecture, each base station only connects to a fixed number of sector antennas that cover a small area and only provide transmission/reception in its coverage area. Ideally, in such networks, the coverage areas of different base stations do not substantially overlap, as the system capacity is limited by interference. In these networks, interference makes it difficult to improve spectrum efficiency and network capacity. Another drawback to traditional cellular systems is that the base stations are built on proprietary platforms as a vertical solution.

Operators of prior-art cellular systems are faced with many challenges. For example, the high complexity of traditional base stations requires costly initial investment, site support, site rental, and management support. Building more base station sites imposes substantial infrastructure and operational expenses on the network operator. Furthermore, since the base stations can't share processing power with each other, network energy efficiency, processing efficiency, and infrastructure utilization efficiency are low because the average network load is typically far lower than the peak load. Specifically, each base station's processing capability can only benefit the active users in its cell. Thus, a base station's processing capability is wasted when the network load within its cell is low, while at other times it may be oversubscribed. Also, an idle or lightly loaded base station consumes almost as much power as it does under peak loads.

These and other drawbacks of the prior art can be reduced or eliminated by exemplary aspects of the disclosure.

As explained above, prior-art broadband wireless technologies are band-limited or interference-limited, meaning that their spectral efficiency reaches an upper limit set by the laws of Physics, such as indicated by the Shannon formulas. While the spatial domain adds another dimension to exploit via cell planning and sectoring, increasing the cell density (e.g., micro-cells, pico-cells, femto-cells) beyond a certain point fails to mitigate the performance decline as more users demand services. This is because smaller cells result in increased inter-cell interference, which establishes a practical upper bound for cell density. While the spectral efficiency of prior-art technologies is limited by the laws of Physics, the demand for data bandwidth keeps growing. As a result, today's cellular networks are already experiencing declining data rates per user.

Thus, there is a compelling need in the broadband wireless industry for systems and methods of wireless communications in which network performance is not hard-limited by the laws of Physics, but rather increases according to advances in computer processing technologies, such as indicated by Moore's law. Only systems and methods such as disclosed herein can meet the growing demands for broadband wireless data services.

SUMMARY

Aspects of the disclosure describe cooperative-MIMO processing which comprise MIMO processing wherein the multiple input (MI) comprises downlink transmissions from multiple base transceiver stations and the multiple output (MO) comprises uplink transmissions to multiple base transceiver stations. Aspects of the disclosure also indicate that cooperative-MIMO processing can employ user equipment (UEs). In accordance with some aspects, combinations of base transceiver stations and UEs are configured for cooperative-MIMO processing.

In accordance with the deficiencies of the prior art, some aspects of the disclosure can eliminate problems due to inter-cell interference near cell boundaries by simply eliminating the cell boundaries. For example, unlike soft hand-off in which two base stations merely employ the same radio channel to serve a handset at a cell boundary, geographically distributed base stations can be coordinated to function together as a distributed antenna system with overlapping coverage areas and configured to perform subspace antenna array processing. Since subspace antenna array transmissions can produce constructive and destructive interference zones (i.e., amplified-signal and cancelled-signal zones) in a rich scattering environment, provisioning of radio resources in accordance with networks and methods disclosed herein can benefit from types of spatial reuse that far outperform cellular-based (e.g., honeycomb) spatial reuse schemes that rely on signal attenuation via path loss.

Whereas prior-art cellular systems strive to reduce inter-cell and intra-cell interference, aspects of the disclosure exploit interference to achieve substantial performance gains. Some exemplary aspects dramatically improve system performance, including throughput, coverage, signal quality, and spectral efficiency, by exploiting inter-cell (and/or intra-cell) interference. Furthermore, since capacity in a downlink multi-user MIMO system depends on the number of transmitting antennas, coordinating multiple geographically distributed base transceiver stations to cooperatively perform multi-user MIMO processing can effectively increase the number of transmitting antennas, and thus, downlink system capacity (which can translate into a combination of serving more users, increasing data rates per user, and improving quality metrics of the communication links). Some aspects of the disclosure produce similar benefits for uplink performance in a multi-user MIMO system.

In some aspects, radio transceivers operating in networks disclosed herein can perform either or both client and server operations. By way of example, a UE may be configured to operate as a base transceiver antenna in a Cooperative-MIMO configuration with one or more base transceiver systems, thereby increasing the rank of the channel matrix, which enables more subspace channels to be employed in the uplink and/or downlink. The UE may be coordinated with the one or more base transceiver systems via a fronthaul network, including the radio access network (e.g., the WWAN). By way of example, a base transceiver system may be configured to operate as a UE in a local group of UEs organized in a Cooperative-MIMO configuration. The base transceiver can be configured to communicate with the local group via a local area network (e.g., a UE fronthaul network used to coordinate the group of UEs) in order to increase the rank of the channel matrix employed for uplink and/or downlink subspace processing.

Aspects of the disclosure may be provided for achieving a large number of objectives and applications which are too numerous to list herein. Therefore, only some of the objects and advantages of exemplary aspects are discussed in the Summary and in the Detailed Description. In some aspects of the disclosure, interference is dealt with using cooperative MIMO so as to increase the number of co-channel links that can coexist with acceptable quality of service. For example, in the high-SNR regime, this figure of merit corresponds to the maximum number of concurrent interference-free transmissions, which is referred to as the multiplexing gain of the network, or the number of degrees of freedom in the information-theoretic terminology.

Some aspects of the disclosure provide various types of interference-aware multi-cell coordination. For example, in some aspects, base stations no longer tune separately their physical and link/MAC layer parameters (power level, time slot, subcarrier usage, beamforming coefficients, etc.) or decode independently of one another, but instead coordinate their coding and/or decoding operations on the basis of global channel state and user data information exchanged over fronthaul (e.g., backhaul) links among multiple cells. Coordination protocols can exploit existing fronthaul links (e.g., WiMax, 4G LTE, optical fiber) or may require a design upgrade to accommodate additional overhead. There are various degrees of cooperation, offering a trade-off between performance gains and the amount of overhead placed on fronthaul and/or other channels, including over-the-air feedback channels.

In some aspects of the disclosure, such as disclosed in the '850 application, certain network control functions are performed in a cooperative fashion by a central processing unit for a set of cooperating base transceiver stations. The central processing unit can be incorporated in one of the cooperating base transceiver stations, which can be connected with any of the other cooperating base transceiver stations via a low-latency, high-capacity fronthaul network. Various network control functions can be performed by the central processing unit, including resource allocation (e.g., scheduling) and power control.

In some aspects of the disclosure, antenna array processing performed by the central processing unit can mitigate inter-cell interference caused by simultaneous transmissions scheduled on the same frequency resource by nearby base transceiver stations. In one aspect, the central processing unit coordinates beamforming (e.g., calculates array-processing weights from channel measurements and coordinates transmissions of the base transceiver stations) such that one base transceiver station provides for coherent combining of its transmissions at a target UE while at least one other base transceiver station produces transmissions that destructively combine at the target UE. In another aspect, the central processing unit is configured to perform joint processing of subspace signals for coordinated multi-point transmissions, wherein multiple base transceiver stations serve a target UE with subspace-coded transmissions. For example, multiple base transceiver stations can be provided with subspace pre-coding weights calculated from channel measurements, and their transmissions can be coordinated such that the set of base transceiver stations functions jointly as an array of transmitters that produces multiple non-interfering subspace channels. Specifically, first portions of subspace-coded transmissions from antennas on multiple ones of the base transceiver stations combine coherently at the target UE to produce at least a first data stream, whereas at least second portions of the subspace-coded transmissions from different ones of the base transceiver stations combine destructively at the target UE to cancel at least a second data stream, wherein the at least second data stream is intended for at least one other UE.

Subspace processing in the disclosed aspects can include various techniques, including, but not limited to, maximum ratio combining (MRC), zero-forcing (ZF), and minimum mean square error (MMSE) techniques.

In one aspect of the disclosure, a network of M connected J-antenna base stations can serve a total of MJ terminals in an interference-free manner simultaneously, regardless of how strong the interference is. To achieve this remarkable result, multi-user spatial pre-coding and decoding can be employed on the downlink and uplink, respectively.

In accordance with some aspects of the disclosure, a cloud radio access network (C-RAN) comprises multiple geographically distributed base transceiver stations, a high-bandwidth low-latency optical transport network (e.g., a fronthaul network), and a central processor. The base transceiver stations are connected to the central processor via the fronthaul network. Furthermore, the central processor may comprise distributed computing resources. For example, the central processor may comprise (or be communicatively coupled to) high-performance programmable processors and real-time virtualization technology. Some aspects employ a software defined radio (SDR) platform.

In one aspect of the disclosure, a C-RAN system comprises base transceiver stations that operate solely as radio units (e.g., remote radio heads), while the RAN baseband processing is performed at a central processor within the operator's network. Fronthaul links, such as fiber optic links or wireless links, connect each base transceiver station to the central processor. The centralization of both uplink and downlink baseband processing at the central processor enables many benefits, including allowing the central processor to perform cancellation of the downlink-uplink interference, since the downlink signal is known at the central processor.

Centralized signal processing disclosed herein greatly reduces the amount of base transceiver equipment needed to cover the same area. Cooperative processing, such as Cooperative-MIMO in a distributed antenna system, provides higher spectrum efficiency. Real-time cloud infrastructure (which can be based on an open platform and utilize base station virtualization) enables processing aggregation and dynamic resource allocation, reducing the power consumption and increasing the infrastructure utilization rate. This network architecture is advantageous for LTE-Advanced, which requires tight coordination between neighboring cells, as such coordination is facilitated at the central processor where RAN baseband functions of the base transceiver stations are pooled.

In another aspect of the disclosure, methods for providing C-RAN communications comprise performing RAN baseband processing at a central processor, while a distributed antenna system comprising a network of geographically distributed base transceiver stations acts solely as down-converters in the uplink and up-converters in the downlink. The fronthaul links carry baseband information. In one aspect, in the uplink, UE signals received by the base transceiver stations are forwarded to the central processor, which performs joint decoding. In another aspect, in the downlink, the central processor performs pre-coding and then communicates the resulting baseband signals via the fronthaul links to the base transceiver stations. Each base transceiver station simply up-converts the baseband signal and transmits it to the UEs.

With centralized processing of the C-RAN architecture, power consumption due to air conditioning and other equipment at the base transceiver sites can be reduced. In many aspects, the distance from the base transceiver stations to the UEs can be decreased, since Cooperative-MIMO processing can mitigate the effects of interference between base transceiver stations, allowing for a much higher density of base transceiver stations. With smaller cells, the power required for signal transmission is reduced, which can decrease power consumption in both the RAN and the UEs. Furthermore, because baseband processing is implemented via a shared resource among a large number of base transceiver stations, more efficient utilization of processing resources and lower power consumption can be achieved.

In aspects of the disclosure, the base station baseband processors and site support equipment are aggregated in a centralized location. This centralized management and operation can be far more efficient than managing a large number of base station sites in a traditional RAN network. If each base transceiver station's functionality is simpler, the size, cost, and power consumption can be reduced. Thus, base transceiver stations can be smaller, less expensive, and easier to deploy with minimum site support and management requirements. Centralized operation also facilitates sharing of the control signaling, traffic data, and channel state information in the system, which can enable joint processing and scheduling to mitigate inter-cell interference and improve spectral efficiency.

In some aspects of the disclosure relating to non-transitory computer-readable medium with instructions stored thereon, the term "virtual" is used. While virtualization typically refers to the abstraction of computer resources in which the physical characteristics of a computing platform are hidden from users and/or applications, the term, virtual, can also relate to an abstraction of a network configuration wherein signal-processing functions do not require certain details of a distributed antenna system. In some aspects, portions of methods and systems that provide for channel characterization and calculating antenna array weights for subspace multiplexing and/or demultiplexing do not require certain information about the distributed antenna system. For example, some of the signal-processing functions can be independent of whether the system comprises a conventional antenna array or a plurality of separate RAN transceivers communicatively coupled together via a fronthaul network. Some signal-processing functions can be independent of whether they are performed at a base transceiver station or at a central processor to which the base transceiver station is communicatively coupled. This enables MIMO and other baseband processing to be performed at the central processor.

In some aspects of the disclosure, central processing comprises distributed computing. Thus, a network operator can dynamically allocate processing resources within a centralized baseband pool to different virtualized base stations and different air interface standards. This allows the operator to efficiently support a variety of air interfaces and adjust to varying network loads across different geographical areas. Within a centralized baseband pool, physical layer processing resources can be efficiently managed and allocated via real time virtualization. Thus, a base station instance can be adapted through the flexible resource combination, which can adjust, allocate, and re-allocate resources based on each virtualized base station's requirements in order to meet its demands. This provides Cooperative-MIMO operations with the required processing resources dynamically. Furthermore, centralizing the hardware platform can provide cost effectiveness for managing, upgrading, and expanding the base station network.

In accordance with some aspects of the disclosure, a plurality of transmitting nodes is employed by a source node

to build the dimension of the subspace spanned by the coded transmissions. In one aspect, the plurality of transmitting nodes is selected to ensure that a set of pre-coded transmissions is characterized by sufficient rank to allow a destination node to decode received signals. For example, selecting a sufficient number of transmitting nodes and encoding (e.g., pre-coding) original data signals can produce a sufficient number of linearly independent (i.e., algebraically unique) combinations of the original data signals to permit the destination node(s) to resolve the original data signals. The transmitting nodes can be selected based on channel measurements and/or their geographic locations such as to ensure that their transmissions are uncorrelated. Each of the transmitting nodes transmits a subset of a total number (i.e., plurality) of subspace-coded components and a corresponding code matrix, wherein at least one of the transmitting nodes has a rank that is insufficient for decoding the plurality of subspace coded components (e.g., a destination node needs to receive signals from a plurality of the transmitting nodes in order to achieve sufficient rank for decoding the received signals). The corresponding code matrix can take the form of a preamble (or header) that comprises the code matrix. When the codes comprise channel-specific codes based on the naturally random channel, then the codes comprise random codes.

As disclosed in some aspects herein, the transmitting nodes can function as routers, relays, repeaters, etc., configured to encode received signals prior to retransmission or simply pass through received signals prior to retransmission. In some aspects, the transmitting nodes can combine multiple signals to be transmitted. In some aspects, the naturally random channel provides random linear coding to transmissions, such as when transmitting nodes are selected to produce transmissions with uncorrelated multipath effects (e.g., fading).

In accordance with some aspects of the disclosure, a destination node can employ a plurality of receiving nodes to cooperatively receive a plurality of subspace-coded components and their corresponding code vectors, wherein the rank of at least one of the receiving nodes is insufficient for decoding the coded components. Thus, receiving nodes can function as routers, relays, repeaters, etc. The destination node builds up the dimension of the subspace spanned by code vectors it collects from the receiving nodes so it can decode the coded components. For example, the destination node can receive signals from multiple receiving nodes in order to decode the subspace-coded components. The receiving nodes can be selected to provide uncorrelated channels.

As disclosed herein, intervening nodes can function as either or both transmitting nodes and receiving nodes. Whereas in conventional routing, intervening nodes simply replicate and forward their received packets, cooperative network coding (such as disclosed in the '163 application) enables relay nodes to combine information received from multiple links for subsequent transmissions. The '163 application discloses various types of linear network codes, including polyphase codes derived from a discrete Fourier transform and random codes, such as derived from the natural randomness of wireless multipath channels, and combinations thereof.

In some aspects of the disclosure, assigned wireless network channels (such as network channels allocated to a particular frequency band and time interval) are reused. For example, cooperative subspace processing (e.g., Cooperative-MIMO) generates a plurality of parallel subspace channels that can simultaneously occupy the same spectral resource. If OFDM is employed, this means that multiple parallel spatial subchannels can occupy the same set of OFDM subcarriers, or tones. In some aspects, cooperative subspace processing provides for communicatively coupling together multiple geographically distributed transceivers (e.g., base transceiver stations and/or wireless client devices) via a fronthaul network to enable joint processing operations.

In some aspects of the disclosure, a network channel is allocated to a transceiver operating in a first network, wherein the transceiver is part of a group of transceivers comprising a second network. The network channel is reused by the group of transceivers for communicating in the second network in a manner that avoids interfering with the first network. By way of example, the group of transceivers employs spatial multiplexing, such as cooperative subspace processing, to mitigate interference between the first network and the second network.

In one aspect of the disclosure, a transceiver employs a channel allocation for a first communication link in a first group of transceivers comprising a first network. A second group of transceivers that is different from the first group but comprises the transceiver reuses the channel allocation for communicating in at least a second communication link. The second group is configured to employ any of various interference-mitigation techniques that permit the reuse of the channel allocation while minimizing co-channel interference with the first network. In some aspects, the second group is configured to employ interference-mitigation techniques that mitigate the effects of co-channel interference in the second link due to transmissions in the first link.

By way of example, if the channel allocation is for a downlink channel, the second group can perform either or both transmit-side and receive-side spatial multiplexing to cancel interference from transmissions in the first link that could interfere with one or more receivers in the second link. If the channel allocation is for an uplink channel, the second group can perform transmit-side spatial multiplexing to cancel interference from transmissions in the second link that could interfere with receivers employing the first link. The second group can perform either or both transmit-side and receive-side spatial multiplexing to cancel interference due to transmissions in the first link that could interfere with one or more receivers employing the second link.

As described throughout the '163 application, aspects disclosed herein can be implemented in a cloud-based SDR platform.

Groupings of alternative elements or aspect of the disclosed subject matter disclosed herein are not to be construed as limitations. Each group member can be referred to and claimed individually or in any combination with other members of the group or other elements found herein. One or more members of a group can be included in, or deleted from, a group for reasons of convenience and/or patentability. When any such inclusion or deletion occurs, the specification is herein deemed to contain the group as modified, thus fulfilling the written description of all Markush groups used in the appended claims.

All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided with respect to certain embodiments herein is intended merely to better illuminate the inventive subject matter and does not pose a limitation on the scope of the inventive subject matter otherwise claimed. No language in the speci-

fication should be construed as indicating any non-claimed element as essential to the practice of the inventive subject matter.

Additional features and advantages of the invention will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The features and advantages of the invention may be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims. These and other features of the invention will become more fully apparent from the following description and appended claims, or may be learned by the practice of the invention as set forth herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Flow charts depicting disclosed methods comprise "processing blocks" or "steps" may represent computer software instructions or groups of instructions. Alternatively, the processing blocks or steps may represent steps performed by functionally equivalent circuits, such as a digital signal processor or an application specific integrated circuit (ASIC). The flow diagrams do not depict the syntax of any particular programming language. Rather, the flow diagrams illustrate the functional information one of ordinary skill in the art requires to fabricate circuits or to generate computer software to perform the processing required in accordance with the present disclosure. It should be noted that many routine program elements, such as initialization of loops and variables and the use of temporary variables are not shown. It will be appreciated by those of ordinary skill in the art that unless otherwise indicated herein, the particular sequence of steps described is illustrative only and can be varied. Unless otherwise stated, the steps described below are unordered, meaning that the steps can be performed in any convenient or desirable order.

FIG. **1** is a block diagram of a communication system architecture in accordance with an exemplary aspect of the invention.

FIG. **2** illustrates a network configuration for super-array processing in accordance with some aspects of the invention.

FIG. **3**A is a flow diagram of a super-array processing method in accordance with an aspect of the invention.

FIG. **3**B is a flow diagram of a super-array processing method in accordance with an aspect of the invention in which channel information is estimated from measurements of reference signals transmitted by the UEs. The reciprocal nature of the channel can enable channel estimation of received uplink signals to be used to calculate pre-coding for the downlink channel.

FIGS. **4**A and **4**B are flow diagrams depicting spatial demultiplexing implemented via multi-cell MIMO cooperation in wireless networks.

FIG. **5** is a flow diagram depicting a method in accordance with an aspect of the disclosure in which multiple geographically distributed transmission points are coupled to a central processor via a fronthaul network, and the central processor calculates pre-coding weights for spatial multiplexing and coordinates the transmission points to transmit subspace pre-coded downlink signals to multiple UEs.

FIG. **6** is a flow diagram depicting a method in accordance with an aspect of the disclosure in which multiple geographically distributed transmission points are coupled to a central processor via a fronthaul network, and the central processor is configured to perform spatial demultiplexing of UE uplink transmissions received by the distributed transmission points.

FIG. **7** is a flow diagram depicting messages passed between UEs, base transceiver stations, and a central processor corresponding to a super-array processing method.

FIG. **8** comprises pseudo-code that depicts data structures and processing functions that can be implemented by a computer processor programmed to perform methods, such as super-array processing methods, in accordance with aspects of the disclosure.

FIG. **9** is a block diagram of a UE that can be configured to operate in accordance with aspects of the disclosure.

FIG. **10** is a block diagram of a base transceiver station that can be configured to operate in accordance with aspects of the disclosure.

FIG. **11**A is a block diagram of a central processor that can be configured to operate in accordance with aspects of the disclosure.

FIG. **11**B is a block diagram that depicts a cloud-based software-defined radio, which can be implemented in accordance with many different aspects of the disclosure.

FIG. **12** is a block diagram of a super-array processing system comprising a central processor communicatively coupled to multiple geographically distributed base transceiver stations via a fronthaul network.

FIG. **13**A is a flow diagram of a subspace processing method configured in accordance with some aspects of the disclosure.

FIG. **13**B is a flow diagram of a subspace processing method that employs decision feedback configured in accordance with some aspects of the disclosure.

FIGS. **14**A and **14**B are block diagrams that illustrates method and apparatus implementations of radio transceivers in accordance with aspects of the disclosure.

FIG. **15** is a block diagram of a transceiver in accordance with some aspects of the disclosure.

FIG. **16** is a block diagram depicting functional aspects of transceivers according to aspects of the disclosure.

FIG. **17** depicts a network comprising multiple geographically distributed base transceiver stations communicatively coupled together via a fronthaul network. The base transceiver stations are configurable to jointly process signals in a radio access channel that serves multiple UEs. In some aspects of the disclosure, at least one of the base transceiver stations coordinates joint processing.

FIG. **18** depicts a cloud radio access network comprising multiple geographically distributed base transceiver stations communicatively coupled to a central processor via a fronthaul network, wherein the central processor comprises a distributed computing system. In such aspects, combinations of central processing and distributed computing can provide for pooling and virtualizing base station processing, such as via an SDR.

FIG. **19** depicts a coordinated multipoint network wherein a plurality of access points are communicatively coupled to a central processor via a fronthaul network, and wherein at least some of the access points' signal processing functions (such as RAN baseband processing) are pooled at the central processor. Apparatus implementations corresponding to this aspect of the disclosure include providing for relocating access point baseband processing equipment to the central processor, which can greatly reduce the capital expense and operating expense associated with the access point network.

FIGS. **20**A and **20**B are flow charts depicting methods wherein geographically distributed access points perform RF processing in a radio access network and a central

processor performs corresponding RAN baseband processing. In some aspects the corresponding RAN baseband processing is performed by a distributed computing system.

FIG. **21** depicts a network topology comprising a source node, a destination node, and a plurality of intervening nodes. This and other network topologies shown herein depict some aspects of the disclosure, including cooperative-MIMO, cooperative subspace coding along multiple network paths, simultaneously employing multiple network paths as a single communication link, providing for reusing spectral resources across multiple links, etc.

FIGS. **22**A and **22**B depict signal transmissions propagating in a network with multiple intervening nodes between a source node and a destination node. Selecting the intervening nodes as part of a transmit and/or receive cooperative subspace processing operation can build the rank of the subspace coding matrix of coded signals propagating through the network, thus providing a sufficient number of linearly independent combination of original data to permit subspace demultiplexing at the destination node.

FIG. **23**A is a flow diagram that illustrates aspects of the disclosure pertaining to cooperative subspace multiplexing.

FIG. **23**B is a flow diagram that illustrates aspects of the disclosure pertaining to cooperative subspace demultiplexing.

FIGS. **24**A and **24**B are block diagrams depicting transceiver apparatus and method aspects configured to perform routing and/or relaying.

FIGS. **25**A and **25**B are block diagrams that depicts channel reuse, such as may be configured between a plurality of networks.

FIG. **26** depicts a cooperative-MIMO network configured to employ channel reuse.

FIG. **27** is a flow diagram that depicts channel reuse methods in accordance with some aspects of the disclosure.

DETAILED DESCRIPTION

The terms "backhaul" and "fronthaul" can be used interchangeably in some aspects of the disclosure. A fronthaul is similar to a backhaul, which, at its simplest, links a radio access network to a wired (e.g., cable or optical fiber) network. A fronthaul can comprise a backhaul, or a portion of a backhaul. For example, a fronthaul can comprise a connection between one or more centralized controllers and remote stand-alone radio heads. A fronthaul connects a central processor to multiple base transceiver stations. A fronthaul connects multiple base transceiver stations together when one or more of the base transceiver stations functions as a central processor. As used herein, a fronthaul may comprise a traditional backhaul network. For example, a fronthaul can comprise at least a portion of S1 and/or X2 interfaces. A fronthaul may be part of a base station network. In Pat. Appl. Ser. No. 60/286,850, it is disclosed that a fronthaul can comprise optical fiber, wired, and/or radio networks. In one aspect of the disclosure, point-to-point fiber links provide high bandwidth and low latency. In another aspect, radio (e.g., microwave) links can provide high bandwidth and low latency, and can be substantially less expensive to implement than fiber. Furthermore, wireless links enable mobile radios and/or other radio transceivers (e.g., remote radio equipment) to be networked together via a radio fronthaul, such as disclosed in patent application Ser. No. 10/131,163. Accordingly, a fronthaul can comprise any combination of wireless, wired, and optical fiber links that communicatively couple together a group of radio transceivers configured to perform cooperative MIMO. Here, a group of radio transceivers is also referred to as a "micro-cell" and a "pico-cell" in the '163 application, and as a "local group" and a "micro-network" in patent application Ser. No. 11/187,107, all of the patents and patent applications mentioned herein being incorporated by reference in their entireties.

Pre-coding is defined herein to comprise its ordinary and customer meaning known to those of ordinary skill in the art. By way of example, in the '163 application, pre-coding is described in the context of antenna array transmission systems with the terms, "pre-transmission processing," "pre-distortion," "channel compensation," "transmit filtering," "spatial interferometry multiplexing," and "subspace processing." The '163 application also discloses directive and retro-directive adaptation methods for calculating antenna array weights for transmission in a distributed antenna system. In one example, subspace pre-coding weights are calculated from measurements of received signals, the measurements comprising channel state information.

User Equipment (UE), as used herein, may be fixed or mobile and comprises any device used directly by an end user (or client device) to communicate in a radio access network. For example, a UE can be a cellular handset, a laptop equipped with a mobile broadband adaptor, a wearable computer, a PDA, a tablet, or any other user device configured to communicate with a Wireless Wide Area Network (WWAN). A WWAN is also referred to as a radio access network (RAN). A UE comprises an RF transceiver for fixed and/or mobile clients receiving data streams over the downlink channel of the WWAN and transmitting data via the WWAN's uplink (UL) channel. While a UE is defined in the Universal Mobile Telecommunications System (UMTS) and 3GPP Long Term Evolution (LTE) as any device that connects to a base station NodeB or eNodeB as specified in the ETSI 125/136-series and 3GPP 25/36-series of specifications, UEs include equivalent devices, such as mobile stations in GSM systems and client devices in other wireless networks. As used herein, a UE may also be referred to as a subscriber device, mobile terminal, user terminal, wireless terminal, subscriber terminal, client terminal, subscriber unit, mobile unit, subscriber device, mobile device, wireless device, client device, client terminal, client unit, mobile network device, mobile handset, wireless handset, or some other terminology indicating a WWAN-enabled client device.

In general, the various embodiments of the UE can include, but are not limited to, cellular mobile devices, personal digital assistants (PDAs) having wireless communication capabilities, portable computers having wireless communication capabilities, image capture devices such as digital cameras having wireless communication capabilities, gaming devices having wireless communication capabilities, music storage and playback appliances having wireless communication capabilities, Internet appliances permitting wireless Internet access and browsing, as well as portable units or terminals that incorporate combinations of such functions. Examples of UEs are provided in 3GPP technical specification (TS) 36.306, Release 8, the disclosure of which is incorporated herein by reference in its entirety.

A Base Transceiver Station interfaces the fronthaul network with the WWAN channel. Base transceiver stations of one embodiment comprise access points consisting of a Digital-to-Analog Converter (DAC)/Analog-to-Digital Converter (ADC) and a radio frequency (RF) chain to convert the baseband signal to RF. A base transceiver station contains radio frequency transmitter(s) and receiver(s) for communicating directly with UEs. In some cases, the base

transceiver station is a simple RF transceiver equipped with a power amplifier/antenna, and the RF signal is carried to the base transceiver station via RF-over-fiber technology as disclosed in the '850 and '163 applications. In other aspects, base transceiver stations are equipped to perform at least some RAN baseband processing operations, such as disclosed in the '850 and '163 applications. Additional features and aspects of base transceiver stations are described throughout the disclosure and in the aforementioned patent applications, which are incorporated by reference. As used herein, a base transceiver station may also be referred to as a base station, an access point, a NodeB, an evolved NodeB (eNodeB), or some other terminology. In accordance with some aspects of the disclosure, a base transceiver station is a network node.

A "network node" or "node," as used herein, is an active electronic device that is communicatively connected to a network via one or more connectors and is configured for sending, receiving, and/or forwarding information over a communication channel. A node can have multiple network connectors for a given network. For example, a node can have multiple antennas. A single device, such as a base station or a user terminal, with multiple network connectors is a single node. In a distributed network, nodes can be clients, servers, and/or peers. A peer can sometimes serve as a client and sometimes as a server. Nodes can include super nodes, which route data for other networked devices as well as themselves.

A Central Processor can include one or more servers interfacing the Internet (or other external networks) with the fronthaul. In a hierarchical network architecture, a central processor couples to the base transceiver stations and provides coordination and control for those stations. One or more base transceiver stations may function as a central processor, such as in a flat network architecture. In an LTE network, eNodeB(s) and/or access gateways can be configured to perform central processor functions. In some aspects of the disclosure, network control functions typically performed by a central processor may be assigned to any of various nodes in the network, including UEs.

In some aspects of the disclosure, the central processor computes the multi-user MIMO baseband processing and sends pre-coded data to geographically distributed base transceiver stations for downlink transmission. In some aspects, the central processor computes the multi-user MIMO baseband processing to provide spatial demultiplexing of uplink signals received by the geographically distributed base transceiver stations. In some aspects, the central processor can comprise a particular type of base transceiver station designed for certain specialized features, such as transmitting training signals for time/frequency synchronization of the base transceiver stations and/or the UEs, receiving/transmitting control information from/to the UEs, receiving the channel state information or channel quality information from the UEs, etc. In some aspects, a central processor is also referred to as a central processing facility, a cloud computing center, a cloud, a data center, a data center cloud, a central controller, a radio network controller, or a central control hub. In some aspects, a central processor can comprise multiple data centers.

Various aspects of the disclosure are described below. It should be apparent that the teachings herein may be embodied in a wide variety of forms and that any specific structure, function, or both being disclosed herein are merely representative. Based on the teachings herein one skilled in the art should appreciate that an aspect disclosed herein may be implemented independently of any other aspects and that two or more of these aspects may be combined in various ways. For example, an apparatus may be implemented or a method may be practiced using any number of the aspects set forth herein. In addition, such an apparatus may be implemented or such a method may be practiced using other structure, functionality, or structure and functionality in addition to or other than one or more of the aspects set forth herein.

The use of any and all examples, or exemplary language (e.g. "such as") provided with respect to certain embodiments herein is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention otherwise claimed. No language in the specification should be construed as indicating any non-claimed element essential to the practice of the invention. The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment or aspect described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments or aspects.

In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the invention. It should be understood, however, that the particular aspects shown and described herein are not intended to limit the invention to any particular form, but rather, the invention is to cover all modifications, equivalents, and alternatives falling within the scope of the invention as defined by the claims.

FIG. **1** is a block diagram of a communication system architecture in accordance with an exemplary aspect of the invention. A plurality N of base stations **101.1-101**.N are communicatively coupled to a central processing facility **110** (i.e., a central controller) via a communication network **105**. Each base station **101.1-101**.N comprises an antenna system for communicating with one or more mobile units (e.g., User Equipment) **120.1-120**.K. For example, the first base station **101.1** may comprise a first antenna array comprising a plurality M_1 of antennas **102.1-102**.M_1, and the Nth base station **101**.N may comprise an Nth antenna array comprising a plurality M_N of antennas **104.1-104**.M_N. A plurality K of mobile units **120.1**, **120.2**, and **120**.K are shown, each having its own antenna system **121.1**, **121.2**, and **121**.K, respectively. Each antenna system **121.1**, **121.2**, and **121**.K may comprise one or more antennas. The communication network **105** that communicatively couples the base stations **101.1-101**.N to the central processing facility **110** may comprise a fiber network, a cable (i.e., wired) network, a wireless network, or any combination thereof.

In one aspect of the invention, the signal-processing architecture provides base stations **101.1-101**.N that are essentially "dumb terminals." For example, many of the signal processing operations typically performed at a base station **101.1-101**.N may be transferred to a central processor (e.g., the central processing facility **110**) that is connected to the plurality of base stations **101.1-101**.N. In some aspects of the invention, a minimal amount of signal processing is performed at each base station **101.1-101**.N. For example, each base station **101.1-101**.N can perform basic signal-processing tasks, such as amplification, RF filtering, frequency conversion (e.g., frequency up-conversion and/or frequency down-conversion), and/or other RF signal-processing functions. After basic signal processing, signals received by one or more antennas at each base station **101.1-101**.N are coupled into at least one communication channel (e.g., network **105**) linked to the central processing facility **110**. Functions of the base station **101.1-101**.N may be limited to cleaning up the received RF signal, amplifying

it, and processing the signal with respect to coupling it into the network **105**. Signals from different antennas **102.1-102**.M_1 and **104.1-104**.M_N may be transmitted on different channels (e.g., on different waveguides), or they may be multiplexed onto the same channel (e.g., with respect to wavelength division, time division, frequency division, polarization division, subspace, phase space, code division, mode division, directionality, etc.).

The central processing facility **110** processes each of the received signals from the communication channel(s). For example, the central processor **110** removes the individual signals from one or more communication channels. The removal process can include demultiplexing the signals on the channel(s). In some aspects, the central processor **110** frequency-converts the received signals to baseband, intermediate, or radio-frequency signals prior to processing. Beam-forming can be performed in RF, IF, and/or after conversion to baseband.

Thus, in some aspects of the invention, by relocating most (or all) of the base station processing operations to the central processing facility, the capital expenditures and operating costs of the radio access network can be greatly reduced. This can also facilitate rapid and less costly network upgrades and expansion. In one aspect, all the RF processing of the radio access network signals is performed at the base transceiver stations, whereas baseband processing is performed at the central processing facility. Baseband signals of the radio access network are communicated between the base transceiver stations and the central processing facility via a fronthaul radio network, some other wireless network, waveguide (e.g., cable), an optical fiber network, or a combination thereof. RF processing of the fronthaul network signals (which is different than RF processing of the radio access network signals) may be performed by the base transceiver stations and the central processing facility.

As depicted in FIG. **1**, signal-processing operations performed at the central processing facility **110** can include spatial multiplexing and/or spatial demultiplexing **114.1**, routing **114.2**, and power control **114.3**. The central processing facility **110** can be configured to perform super-array processing. In one aspect of the invention, the central processing facility **110** comprises a super array processing system **112**. In some aspects of the invention, the super array processing system **112** comprises one or more subsystems or modules, such as a spatial multiplexing/demultiplexing system **114.1**, a routing system (e.g., router) **114.2**, and a power control system **114.3**.

In one aspect of the invention, the super array processing system **112** comprises one or more general-purpose computers programmed to function as a special-purpose computer configured to perform various aspects of the disclosure, such as Cooperative-MIMO processing in a distributed antenna system. In another aspect, the super array processing system **112** comprises one or more special-purpose processors, such as integrated circuits, discrete circuits, and/or other specialized hardware configured to perform Cooperative-MIMO processing. As disclosed herein, a distributed computing system may be employed for implementing aspects of the invention, such as spatial multiplexing, spatial demultiplexing, and/or baseband signal processing operations typically performed by base transceiver stations. Such distributed computing systems may comprise a network of general-purpose computers (programmed to function as a special-purpose computers), such as servers, located in one or more data centers. A distributed computing system may comprise a network of special-purpose processors or a combination of special-purpose processors and general-purpose computers. Similarly, components of system **112**, as well as any other components, processors, systems, and devices mentioned in the disclosure, may each comprise one or more general-purpose computers, one or more special-purpose processors, or combinations thereof, and may optionally comprise a distributed computing platform.

In accordance with some aspects of the invention, the centralized architecture simplifies physical-layer system upgrades, since processing equipment used for multiple base stations **101.1-101**.N resides at a common location (i.e., the central processing facility **110**). Upgrades to improved modulation schemes, new receiver combining techniques, enhanced array-processing, etc. can be provided at the central processing facility **110** instead of at each base station **101.1-101**.N. Similarly, adding or upgrading base station antennas (e.g., antennas **102.1-102**.M_1 and **104.1-104**.M_N) is simplified since the antennas installed at each base station **101.1-101**.N may simply be coupled to the central processing facility **110** via the communication network **105**. Adding base stations to the network can be quick and less costly due to the low cost and complexity of each base station **101.1-101**.N. Thus, any signal-processing upgrade associated with the base stations **101.1-101**.N is performed at the central processor **110**.

In aspects of the invention that employ spatial multiplexing/demultiplexing, the system capacity scales linearly with the number of base station antennas (e.g., antennas **102.1-102**M_1 and **104.1-104**.M_N) within range of the UEs **120.1-120**.K. This is because the spatial multiplexing gain (i.e., the number of independent data streams that can be sent concurrently over MIMO subchannels) is proportional to the number of antennas **102.1-102**M_1 and **104.1-104**.M_N serving the UEs **120.1-120**.K.

Unlike conventional MIMO in which all of the transmitting antennas reside on a single device (e.g., a single base station), a cooperative-MIMO transmitting system in accordance with aspects of the disclosure comprises antennas residing on multiple devices (e.g., the base stations **101.1-101**.N). The super array processing system **112** coordinates the base stations **101.1-101**.N to synthesize an antenna system comprising geographically distributed antennas, which provides superior decorrelation of the transmission paths between transmitting antennas and receiving antennas in the MIMO system. Since MIMO antennas in prior-art systems reside on a single device, the length of the MIMO array is only a few wavelengths, which is usually insufficient for providing the spatial selectivity required to match the spatial multiplexing gain to the number of transmitting antennas. Thus, in prior-art MIMO systems, the rank of the MIMO channel matrix is typically less than its dimension. Adding more antennas to a prior-art MIMO system almost always results in diminishing levels of return with respect to capacity, whereas aspects of the invention solve this problem.

Since the system (depicted in FIG. **1**) capacity scales linearly with the number of base station antennas, particularly if the antennas are geographically distributed, it is advantageous to add more base stations as UE density increases. There are several benefits to doing this. Unlike prior-art cellular systems, inter-cell interference is not a problem in the radio access network depicted in FIG. **1**. Rather, it is exploited for spatial multiplexing gain, whereas enormous effort is made in today's cellular systems to avoid inter-cell interference, particularly for smaller cells. In aspects of the invention, base stations can be added in the

general vicinity of increased user density without cell planning and extensive modifications to the radio access network. The central processing facility **110** immediately adapts to the new radio access network architecture to add capacity to the target area.

Since optimal spatial multiplexing gain is typically achieved when SNR is high (e.g., close to a MIMO base transceiver station), distributed antenna systems disclosed herein can provide closely proximal base transceivers for UEs throughout the coverage area that provide both high SNR and spatial selectivity. Unlike prior-art cellular systems in which each UE is linked to a single base station until it is handed off to another base station, aspects of the invention provide for maintaining concurrent links between the UE and multiple base stations throughout the UE's session. Thus, as the UE moves through the coverage area, it maintains a consistently high SNR.

In other aspects of the invention, Cooperative-MIMO processing on the client side can provide distributed antenna systems comprising cooperating UEs that enable similar MIMO benefits.

In some aspects of the disclosure, all of the base station processing is performed in the central processing facility **110** (which may be an offsite data center as long as latency constraints are met) instead of by the individual base stations **101.1-101**.N. Thus, even at very high densities of UEs, not only can all UEs remain connected to the network, but the UEs do not incur the overhead normally incurred by large numbers of UEs sharing one base station in a cell.

The central processing facility **110** could be scaled indefinitely to accommodate increasing UE density and data demands. As the number of UEs and demand grows, not only is it easy to deploy additional base stations, as described above, but it is easy to expand the computing capability in the central processing facility **110** to accommodate the added base stations.

In accordance with some aspects of the invention disclosed in the '163 application, a distributed (e.g., cloud) computing environment may be employed to perform the base station processing. Also, the '163 application discloses that the base station processing may be performed in an SDR. Thus, the implementation of the base station processing may occur entirely on general-purpose CPUs. One implementation of the central processing facility **110** in accordance with previously cited disclosure could include a data center comprising multiple switches and general-purpose servers that connect to the fronthaul network **105** via general-purpose digital links, such as 10 GbE or other links.

FIG. **2** illustrates a network configuration for super-array processing in accordance with some aspects of the invention. In one aspect, multiple mobile units (e.g., UEs **120.1-120**.K) are each serviced by multiple base stations (e.g., base stations **101.1-101**.N) simultaneously. In one aspect of the invention, each base station **101.1-101**.N comprises an antenna array. For example, the first base station **101.1** comprises an M_1-element array **102.1-102**.M_1, a second base station **101.2** comprises an M_2-element array **106.1-106**.M_2, and the Nth base station **101**.N comprises an M_N-element array **104.1-104**.M_N. In super-array processing, the base station arrays (e.g., arrays **102.1-102**.M_1, **106.1-106**.M_2, and **104.1-104**.M_N) are configured to work together to exploit the propagation environment, such as to enhance signal reception for each mobile user **120.1-120**.K, reduce power transmission requirements, and mitigate undesired interference.

For the purpose of describing an exemplary aspect of the invention, signals transmitted by mobile unit **120.1** may be received at multiple base station antenna arrays (e.g., at base stations **101.1**, **101.2**, and **101**.N). Adapting each base station antenna beam pattern (e.g., beam patterns **201.1**, **201.2**, and **201**.N) can enhance reception of signals transmitted by each mobile unit **120.1-120**.K. Transmissions to each mobile unit **120.1-120**.K can also be enhanced. For example, a transmission from base station **101.2** intended for mobile unit **120.2** may cause interference at mobile unit **120.1**. However, this interference can be mitigated by including a cancellation signal in the transmission from base station **101.1** and/or base station **101**.N. Since all of the base stations **101.1-101**.N in this exemplary aspect are connected to the central processing facility **110**, signal processing at this facility **110** can be performed to allow multiple base stations to work together and thereby enhance the radio coverage, bandwidth efficiency, and power efficiency.

With respect to each mobile unit **120.1-120**.K, all of the interfering signals transmitted by the multiple base transceiver stations **101.1-101**.N coherently combine to produce the exact waveform intended for that mobile unit with a high SNR (e.g., SINR). For example, first portions of waveforms transmitted by the multiple base transceiver stations **101.1-101**.N combine coherently at a first mobile unit (e.g., **101.1**) to produce a first set of data signals intended for the first mobile unit **101.1**. Similarly, second portions of the transmitted waveforms combine coherently at a second mobile unit (e.g., **101.2**) to produce a second set of data signals intended for the second mobile unit **101.2**. However, the first portions combine destructively to cancel at the second mobile unit **101.2** and the second portions combine destructively to cancel at the first mobile unit **101.1**. In some aspects of the invention, the high-SNR waveforms exist only in a small volume around the corresponding intended mobile unit. Since these highly localized regions of high SNR are synthesized interference zones, the diameter of these three-dimensional regions (such as may be indicated by a full-width half-maximum amplitude or power) can be less than a wavelength.

Propagation effects due to sparse antenna arrays are described in U.S. patent application Ser. No. 09/906,257, which is incorporated by reference in its entirety. When randomly spaced sources (or equivalently, sources transmitting random carrier frequencies) are employed, interference patterns (i.e., superpositions of the transmitted signals) away from the main lobe (i.e., where signals are configured to combine coherently, or in phase) tend to have little variation between minima and maxima, particularly when many sources (or frequencies) are employed.

In the spatial dimensions, a rich scattering environment can provide a large number of effective sources (i.e., each scatterer is an effective source). It is anticipated that some aspects of the invention may employ very large numbers of transmitters to generate signals that coherently combine in 3-dimensional space at a desired receiver(s). When very large numbers (e.g., hundreds or more) of transmitters and/or effective sources are employed, the signal amplitude (or power) can fall off dramatically at a short distance (even a fraction of a wavelength) from the superposition peak. The signal levels can remain at a consistently low SNR throughout 3-dimensional space except, perhaps, very close to the transmitters. With a sufficiently large number of transmitters, it may be possible to transmit signals from each transmitter that are so low in power that the signals intended for a particular user device are indistinguishable from background noise throughout almost all of the coverage area except in a small volume at the user device where they coherently combine. Thus, some aspects of the invention can

provide a type of physical-layer low probability of interception/low probability of detection (LPI/LPD) benefit due to spatial processing that is analogous to LPI/LPD benefits of ultra-wideband signals. Such LPI/LPD benefits can enhance security in wireless networks.

Array processing can be performed at the central processor **110** to adapt transmission and reception beam patterns to improve one or more operating criteria, such as signal-to-noise, signal-to-noise plus interference, probability of error, bit error rate, etc. Various aspects include the use of known training sequences and pilot signals, as well as blind adaptive techniques. Open-loop and/or closed-loop feedback techniques can be used.

In one aspect, each UE may be assigned an orthogonal uplink pilot. However, the maximum number of orthogonal pilots is limited by the duration of the coherence interval divided by the channel delay spread. Thus, aspects of the invention may employ any of various channel estimation algorithms, such as blind techniques, that circumvent the use of pilots altogether. By way of example, the '163, '854, and '107 applications disclose blind techniques that jointly estimate the channels and the payload data.

Even though the propagation channel is reciprocal (between uplink and downlink in time-division duplex systems), the RF front-ends in the base transceivers and UEs may not be reciprocal between the uplink and downlink. Accordingly, calibration of the hardware to ensure reciprocity may be performed, such as disclosed in the '163 application.

The array-processing aspects of the invention can also be used in conjunction with control of other system operating parameters, including, but not limited to, power control, throughput, bandwidth, channel coding (e.g., convolutional, block, trellis, etc.), and frequency band scheduling. In one aspect, the system reduces the transmit power of a mobile unit when array processing enhances the signal-to-noise-plus-interference of that unit's radio link. In another aspect, the level of array processing is adjusted with respect to some quality factor associated with each unit. For example, array processing may be performed only for units that exceed a certain degree of signal degradation, require a certain amount of throughput, or have a predetermined quality-of-service level (QOS). Array processing can be used for data links in a system that provides data and voice services, since digital links require a higher QOS. Array processing can be used to compensate for signal-quality degradation for units assigned to interfering channels.

It should be appreciated that signal processing at the central processing facility **110** may be performed by multiple computer processors via distributed computing (e.g., cloud computing) such as disclosed in the '163 application. In some aspects, the base station signal processing at the central processing facility **110** can be implemented in a real-time SDR to provide for software-defined networks that enable more dynamic organization of resources, such as disclosed in the '163 application. The central processor **110** may comprise one or more servers in a data center configured to compute baseband waveforms using an SDR, such as described in the '163 application.

Since multiple base transceiver stations **101.1-101**.N are employed to serve each UE **120.1-120**.K via Cooperative-MIMO subspace processing, it is advantageous for the coverage areas of base transceiver stations **101.1-101**.N employing the same spectral resources to overlap. This is contrary to how cellular base stations are positioned in a conventional cellular network. Prior-art base stations conform to a cellular layout that is carefully planned to minimize transmission overlap. However, aspects of the disclosure are not constrained to such cell plans because subspace processing can produce constructive and destructive interference zones throughout the radio access network's coverage area to enable spectral reuse, potentially for very large numbers of UEs, even UEs that are in close proximity to each other (e.g., on the order of a few wavelengths, or even less). This enables universal spectral reuse while facilitating deployment of the radio access network infrastructure. In some aspects, the base transceiver stations **101.1-101**.N can be placed pseudo-randomly throughout the radio access network, such as to take advantage of locations that are convenient and/or less costly, and with less concern about coverage area and the presence of obstructions in the propagation environment.

In some aspects, since each UE **120.1-120**.K is concurrently served by multiple base transceiver stations **101.1-101**.N with overlapping coverage areas, a failure of a small number of base transceiver stations **101.1-101**.N is less likely to cause a service disruption. Rather, the spatial multiplexing/demultiplexing **114.1** can adapt to changes in the configuration of the base transceiver stations **101.1-101**.N, such as to ensure uninterrupted service.

The spatial multiplexing/demultiplexing **114.1** can perform various spatial processing techniques, including (but not limited to) ZF, MMSE, MRC, and/or successive interference cancellation. In some aspects, MRC can offer certain advantages due to the ease in which it can be implemented in a distributed manner and its computational simplicity (e.g., when used for demultiplexing, received uplink signals can be multiplied by the conjugate channel responses, and pre-coding downlink transmissions is similarly simplified). The combination of the MRC receiver (for the uplink) and its counterpart, maximum ratio pre-coding (for the downlink) comprise matched filtering, which is disclosed in the '163 and '854 applications. MRC can be advantageous when channel responses associated with different terminals are substantially uncorrelated.

As disclosed in the '163 application, the fronthaul network **105** can take various forms, including a mesh architecture. Since at least some of the fronthaul links **105** can be wireless (such as disclosed in the '850 application), and given that the base transceiver stations **101.1-101**.N can comprise remote radio heads (or other simple radio transceivers), as disclosed in the '850 application, the base transceiver station **101.1-101**.N hardware can be a fraction of the cost of prior-art base stations and can be deployed more quickly. Furthermore, as disclosed in the '163, '854, and '107 applications, UEs **120.1-120**.K and other devices (not shown) in the radio access network can function as base transceiver stations, such as to dynamically adapt to increased network loads and/or increased UE density, compensate for base station outages, and/or expand the coverage area.

FIG. **3**A is a flow diagram of a super-array processing method in accordance with an aspect of the invention. A plurality of base transceiver stations (e.g., transmission points, or access points) is configured to transmit reference signals **301**, which are measured by UEs to calculate channel state information **302**. For example, the '850 application discloses that reference signals, which include known training sequences and pilot signals, are transmitted, and a channel model is developed by a receiver upon receiving the transmitted reference signals. The channel state information can comprise channel information relative to multiple base station antennas residing on multiple geographically distributed base stations.

The UEs feedback the channel state information to the transmission points **304**, and the transmission points and/or the central processor calculate pre-coding weights **305** therefrom. The '850 application discloses that open-loop and/or closed-loop feedback may be employed. While channel state information can comprise quantized channel estimates, channel state information can comprise alternative indicators, such as codewords. In some aspects of the invention, such as disclosed in the '850 application, step **305** comprises selecting UE's for which array processing is to be performed, wherein only UE's having a predetermined quality-of-service level are selected. In some aspects disclosed in the '850 application, different levels of array processing may be performed, the level of array processing being selected with respect to a quality factor associated with each UE.

Multiple transmission points are coordinated by the central processor to transmit the pre-coded data **307** to each UE. In some aspects of the invention, such as in accordance with the disclosure of the '163 application, step **305** and/or **307** comprises selecting a portion of the network to serve a particular UE. For example, a predetermined set of transmission points is selected to process transmissions to a particular UE based on received pilot signal power. Upon receiving the transmissions, each UE demodulates the received signals **308**. Since UE's may comprise antenna arrays, such as disclosed in the '850 application, step **308** may comprise array processing, including MIMO processing.

In accordance with one aspect of the invention disclosed in the '163 application, network processing functions are computed by a plurality of spatially separated processors. For example, the central processor can be replaced by a distributed computing system. The distributed computing system can comprise a plurality of transmission points. In some aspects, the distributed computing system can comprise UE's, repeaters, and/or other network equipment.

In accordance with aspects disclosed in the '850 application, super-array processing comprises a coordinated multi-point technology which sends and receives signals from multiple sectors or cells to a given UE. By coordinating transmission among multiple cells, interference from other cells can be reduced and the power of the desired signal can be increased.

In one aspect of the invention, signaling over a fronthaul network can be used between base stations (e.g., eNodeB's) to coordinate among cells. In another aspect of the invention, multiple remote radio equipments (RREs) are connected via an optical fiber fronthaul carrying a baseband signal between cells and a central eNodeB, which performs the RAN baseband signal processing and control, so the radio resources between the cells can be controlled at the central eNodeB. Other aspects of the invention include combinations of distributed control based on independent eNodeB configurations and centralized control based on RRE configurations.

FIG. **3**B is a flow diagram of a super-array processing method in accordance with an aspect of the invention in which channel information is estimated from measurements of reference signals transmitted by the UEs. This exemplary method can be useful when time division duplexing (TDD) is employed, such as wherein the uplink and downlink channels assigned to each UE share the same frequency band. For estimation of channels at the transmitter in TDD networks, one can rely on the reciprocity of the uplink and downlink channels so that channel estimation on the uplink can be used for downlink transmission.

In one aspect of the invention, each UE transmits a known reference signal **311**, such as one or more known training sequences and/or pilot signals, which are described in the '850 application. The transmitted reference signals are received by antennas of multiple base transceivers, and the channel state information is measured **312** by the base transceiver stations and/or at least one central processor. As disclosed in the '850 application, the channel state information can comprise frequency-domain channel state information. In one aspect, measured channel state information is coupled by the base transceiver stations to the central processor to be used for calculating pre-coding weights **314**. In accordance with another aspect, the central processor performs steps **312** and **314**. As disclosed in the '163 application, steps **312** and **314** can comprise reference-signal processing, blind adaptive techniques, directive, and/or retro-directive techniques. Communication between the base transceiver stations and the at least one central processor is provided by a high speed network backbone, or fronthaul, which may comprise optical fiber, wired connections, wireless connections, or any combination thereof. Pre-coded data is transmitted **316** by multiple transmission points under the control of the central processor. Each UE receives pre-coded transmissions from multiple transmission points and demodulates the received data **317**.

In one aspect of the invention, joint transmissions by multiple cells (i.e., base transceiver stations) to a given UE employ the same time and frequency radio resources. Dynamic cell selection provides for selecting a portion of the base station network to serve a particular UE. Furthermore, UE's can be selected for array processing, such as based on a UE's quality of service level. Pre-coding between the cells provides for coherent transmission, which results in in-phase combining at the receiver. With uplink multi-cell reception, the signal from a UE is received by multiple cells and combined. The UE does not need to be aware of whether multi-cell reception is occurring, so it should have little impact on the radio interface specifications.

As described in the '850 application, some aspects of the invention provide for sharing data and channel state information among groups of base stations to coordinate their transmissions in the downlink and jointly process the received signals in the uplink. These techniques can effectively turn otherwise harmful inter-cell interference into useful signals, enabling significant power gain, increased channel rank, and/or diversity advantages. While some systems disclosed herein describe cellular base stations by way of example, it should be appreciated that additional and/or alternative radio transceivers may be employed, including fixed relay stations, remote radio heads, mobile stations, peer-to-peer radio transceivers, access points, and combinations thereof.

FIGS. **4**A and **4**B are flow diagrams depicting spatial demultiplexing implemented via multi-cell MIMO cooperation in wireless networks. In dense networks where interference emerges as the key capacity-limiting factor, multi-cell cooperation can dramatically improve the system performance. Remarkably, such techniques can literally exploit inter-cell interference by allowing the user data to be jointly processed by several interfering base stations, thus mimicking the benefits of a large virtual MIMO array.

In FIG. **4**A, UE's transmit reference signals **401** and data signals **403**. Transmitted reference signals received by multiple base transceiver stations are measured to generate channel state information **402**, from which spatial demultiplexing weights are calculated **404**. In one aspect of the invention, a central processor measures the channel state

information **402** and calculates demultiplexing weights **404** for a geographically distributed set of base transceiver stations. In another aspect of the invention, each base transceiver station measures the channel state information **402**, which is then forwarded to at least one central processor. In some aspects of the invention, distributed computing may be employed for calculating the spatial demultiplexing weights **404**. For example, computational parts of step **404** may be performed by multiple base transceiver stations. The central processor then demultiplexes the data transmissions **406** received from the UEs.

In FIG. **4**B, the transmission points and/or the central processor employ blind-adaptive processing, such as disclosed in the '163 application, to demultiplex received data transmissions. Data signals transmitted **411** by the UE are received and processed by multiple base transceiver stations and at least one central processor. Blind adaptive processing provides channel state information **412**, which is used to calculate spatial demultiplexing weights **414**, which are used to demultiplex **416** the data transmissions received from the UEs.

FIG. **5** is a flow diagram depicting a method in accordance with some aspects of the invention in which multiple transmission points and at least one central processor cooperate to produce subspace pre-coded downlink transmissions to multiple UEs. A base transceiver station (e.g., a transmission point) performs preliminary processing **501** of signals received from at least one UE and communicates channel state information corresponding to each UE to at least one central processor **503**. The channel state information can include channel measurements made by the UEs and/or the base transceiver stations. Thus, step **501** can comprise measuring the channel(s) of each UE. The central processor collects channel state information communicated by multiple base transceiver stations **504**, selects which base transceiver stations will serve each UE **506**, calculates the distributed-antenna pre-coding **508**, and coordinates the base transceiver stations to transmit pre-coded data signals to the UEs **510**. Each base transceiver station then transmits pre-coded data signals to the UEs **512**.

A base transceiver station (or transmission point), as used throughout the disclosure, can comprise a NodeB (such as employed in a UTRAN system) or an eNodeB (such as employed in an EUTRAN system). A central processor, as used throughout the disclosure, can include a radio network controller (RNC) in a UTRAN system or an eNodeB in an EUTRAN system. EUTRAN consists only of eNodeBs on the network side. The eNodeB performs tasks similar to those performed by the NodeBs and RNC together in UTRAN.

E-UTRA uses OFDM-MIMO antenna technology depending on the terminal category and can use subspace pre-coding for the downlink to support more users, higher data rates, and lower processing power. In the uplink, LTE uses both OFDMA and Carrier Interferometry (also called Single-Carrier Frequency-Division Multiple Access), such as disclosed throughout the '850 and '163 applications. This mitigates the very high peak-to-average power ratio (PAPR) of conventional OFDM. For the uplink, in release 8 and 9, multi-user MIMO/Spatial division multiple access (SDMA) is supported.

LTE supports both Frequency-division duplex (FDD) and TDD modes. While FDD makes use of paired spectra for UL and DL transmission separated by a duplex frequency gap, TDD splits one frequency carrier into alternating time periods for transmission from the base station to the terminal and vice-versa. Both modes have their own frame structure within LTE, and these are aligned with each other. Thus, similar hardware can be used in the base stations and user terminals.

FIG. **6** is a flow diagram depicting a method in accordance with some aspects of the invention in which multiple transmission points and at least one central processor cooperate to perform distributed spatial demultiplexing of uplink transmissions received from multiple UEs. A base transceiver station (e.g., a transmission point) performs preliminary processing **601** of uplink signals received from at least one UE and communicates channel state information corresponding to each UE to at least one central processor **603**. The channel state information can include channel measurements made by the UEs and/or the base transceiver stations. Thus, in some aspects, step **601** can comprise measuring the channel(s) of each UE. The central processor collects channel state information communicated by multiple base transceiver stations **604**, selects multiple base transceiver station antennas (including antennas on different base stations) from which signals will be combined for each UE **606**, calculates the distributed-antenna demultiplexing weights **608**, and performs spatial demultiplexing **610** to separate multiple same-band signals transmitted by the UEs and received by multiple base transceiver stations.

With respect to aspects of the disclosure, a multi-antenna wireless communication system, such as one employing Coordinated Multipoint transmission and/or reception, can mitigate inter-cell interference. In such a system, multiple antennas are deployed across a plurality of geographically contiguous cells (or sub-cells) and connected to a central processor, e.g., via a fast backhaul. This architecture enables the central processor to jointly process downlink signals transmitted from and/or uplink signals received at the multiple antennas, in order to mitigate inter-cell interference.

In accordance with some aspects of the disclosure, to jointly process downlink signals transmitted from the multiple antennas, in particular, the central processor is provided with information characterizing the associated downlink channel responses. If the system employs FDD, the served UEs measure these downlink channel responses and feed them back to the central processor. If the system instead employs TDD, the downlink channel responses can advantageously be estimated from uplink signals received at the multiple antennas based on the assumption that for TDD, the downlink channel can be inferred from the uplink channel (e.g., the uplink and downlink channels can be reciprocal).

This assumption of reciprocity between the downlink and uplink channel, however, may sometimes be inaccurate in a multi-antenna system. For instance, each of the multiple antennas is connected to a corresponding transceiver that comprises a transmit-receive radio frequency (RF) chain. These transmit-receive RF chains may have different frequency responses, due for example to differences in the transfer characteristics of the components (e.g., analog filters, power amplifiers, etc.) making up those RF chains. If the RF chains of the multiple antennas do not have identical frequency responses, the assumption of reciprocity no longer proves accurate, which in turn can prevent advantageous estimation of the downlink channel responses from uplink signals. Accordingly, the RF chains can be initially, and perhaps periodically, calibrated with one another to account for differences in their frequency responses, such as disclosed in U.S. Pat. No. 6,211,671, which is incorporated by reference in its entirety.

FIG. **7** is a flow diagram depicting messages passed between network devices corresponding to steps in a super-array processing method. Such flow diagrams can assist a

software developer in designing software modules with instructions on non-transient computer-readable memory that program a computer processor to perform methods disclosed herein.

In one aspect of the invention, a reference signal is transmitted **751**, from which channel state information is calculated. For example, each antenna on each of a plurality of base stations **701** and **702** can transmit a reference signal (**711** and **712**, respectively), such as a known training signal or a pilot tone, which a UE **700** receives and processes to determine its channel state information.

In a feedback step **752**, the UE transmits its channel state information **713** and **714** back to its respective base station **701** and **702**. The base stations **701** and **702** relay the channel state information (e.g., messages **715** and **716**) received from their UEs to at least one central processor **710**.

As should be appreciated from the disclosure, an alternative step **751** can comprise the base stations **701** and **702** receiving transmitted reference signals from the UEs (such as UE **700**) and estimating the channels therefrom. Then the feedback step **752** comprises the base stations **701** and **702** relaying the channel state information **715** and **716** to the at least one central processor **710**.

In step **753**, the central processor **710** calculates distributed antenna system weights w_1 and w_2 **753** based on the channel state information **715** and **716**. In a cooperative-MIMO demultiplexing step (not shown), the weights can be used to demultiplex interfering data streams (not shown) in the uplink channels between the UEs **700** and base stations **701** and **702** routed to the central processor **710**.

Cooperative-MIMO multiplexing provides for employing the distributed antenna system weights for pre-coding data D to be transmitted to each UE **700**. For example, weight vectors w_1 and w_2 are used to pre-code a data matrix, and the pre-coded data signals **717** and **718** are routed to their respective base stations **701** and **702**. The base stations **701** and **702** transmit signals **719** and **720** comprising the pre-coded data to the UEs **700**.

As illustrated in FIG. **8**, software developed in accordance with aspects of the invention may comprise functionality that is separable into multiple independent and interchangeable modules. In some aspects, a module may comprise a software object. In some applications, a module may comprise a container that contains other objects. While the scale of a module may vary depending on the programming language and the application, modules are typically designed to perform logically discrete functions and interact via well-defined interfaces. It should be appreciated that in some aspects of the disclosure, modules can comprise data objects, and such data objects reside in physical memory of a computing device and can comprise executable instructions stored in memory that cause a processor to execute steps that give rise to the disclosed functionality as described below.

FIG. **8** comprises pseudo-code that depicts data structures and processing functions that can be implemented by a computer processor programmed to perform methods in accordance with aspects of the invention, including methods disclosed in the '850 application. An object, such as a virtual array object, V_array **840**, can comprise methods and data structures that package distributed-array assets (e.g., antenna systems of different base transceivers, radio signal processors associated with those antenna systems, baseband signal processing systems in the base transceivers and/or in the central processor(s), and front-haul networks) in a manner that conceals certain details. For example, the V_array object **840** may comprise a private section **850** in which a combination of data structures and functions can only be accessed within the object **840**. By way of example, objects Bts **851** and Fronthaul **852** are private members. Private data structures and functions can conceal implementation details of the object's **840** interface (e.g., how Public functions are implemented and how Public data structures are created).

The virtual antenna array object **840** includes an implementation, which is typically expressed by one or more functions, such as functions **862-866**. The implementation contains the working code that corresponds to the elements declared in the interface, such as the Antenna object **861**. Functions **862-866** may call other functions which may be internal and/or external to the object **840**. By way of example, function f_select_ue(. . .) **862** selects UEs based on some predetermined quality factor, such as disclosed in the '850 application. Function f_select_antenna(. . .) **863** selects antennas in the array to serve a particular UE, such as disclosed in the '163 application. Function f_csi(. . .) measures channel state information for each antenna/UE combination, such as disclosed in the '850 application. Function f_mux(. . .) provides for spatial multiplexed transmission of pre-coded data across the array of antennas (which may reside on multiple geographically distributed base stations), such as disclosed in the '850 application. Function f_rx(. . .) receives data from a predetermined set of antennas residing on multiple geographically distributed base stations, such as disclosed in the '850 application.

In one aspect of the invention, each Antenna object **861** is associated with an antenna on a base transceiver station (indicated by the Bts object **851**), so the virtual antenna array can include antennas associated with different base stations, such as disclosed in the '850 application. The base transceiver stations can be connected to a central processor via a fronthaul network, such as disclosed in the '850 application. Thus, the virtual array object **840** can comprise one or more Fronthaul objects **852** associated with communications between the Antenna objects **861**.

In some aspects of the invention, the virtual antenna array object **840** conceals information related to its antenna elements being distributed across multiple base transceivers (and/or UEs). For example, in some aspects, the virtual antenna array object **840** conceals information about fronthaul networks communicatively coupling signals between the antenna elements and signal processors (such as baseband processors, including MIMO processors). Thus, each virtual antenna array object **840** can conceal network communications within an object-oriented interface.

In accordance with some aspects of the invention, the virtual antenna array object **840** is part of a distributed control environment that provides services, such as access, interaction, and control of base transceiver antennas in a network of geographically distributed base transceivers.

A module interface expresses the data and/or functional elements that are provided and required by the module. For example, the virtual antenna array object **840** could receive as its input an element indicating a particular UE. Thus, a virtual antenna array could be created for each UE. The elements defined in the interface are usually detectable by other modules. In one aspect of the invention, quality factors and signal strength are some of the parameter by which physical antennas distributed across multiple base transceivers can be selected for inclusion in the virtual antenna array object **840**. In some aspects, a quality factor or signal strength comprises a measurement of a known training signal. Elements may comprise various data structures, such as lists, arrays, queues, stacks, and other objects. Each data

structure has associated operations that may be performed on it and pre-conditions and constraints on the effects of those operations.

Once a virtual array object **840** is created, it may be passed as an argument to another module, such as a multi-user MIMO object, Mu_mimo **810**. For example, function calls **801** and **802** access functional elements **822** and **821**, respectively, in the Mu_mimo object's **810** interface **820**. In some aspects, arguments in the function calls **801** and **802** can comprise function calls in the V_array object's **840** interface.

The f_precode(. . .) function **821** employs channel state information (csi) to generate a set of antenna array weights (such as via a private function, f_weight(. . .) **831**). The weights are used by function **821** to pre-code a data set (tx_data) to produce pre-coded data (precoded_data). The pre-coded data can then be transmitted by the f_mux(. . .) function **865** in the same virtual array object **840** used by the f_precode function **821**. Thus, in accordance with some aspects of the invention, the f_precode function **821** can perform multi-user MIMO pre-coding for an array of geographically distributed antennas. The f_demux(. . .) function **822** processes channel state information (csi) and received data (rx_data) from the virtual antenna array **840** to demultiplex the received data.

In the uplink, MIMO receiver processing techniques can be used to efficiently exploit the spatial dimensionalities of the MIMO channel to increase WWAN capacity. In aspects of the invention, from an algorithmic perspective, there is no discernible difference in processing a plurality of different transmissions from a single UE configured for MIMO versus processing one signal from each of a plurality of different UEs configured only for Single Input, Multiple Output (SIMO). Similarly, in some aspects of the invention in which fronthaul latency is either negligible or compensated for, there is no algorithmic difference in MIMO receiver processing whether the receiving array comprises antennas employed on multiple base transceiver stations or an antenna array on a single base transceiver station. In the downlink, in some aspects of the invention in which fronthaul latency is either negligible or compensated for, there is no algorithmic difference in MIMO transmitter processing whether the transmitting array comprises antennas employed on multiple base transceiver stations or an antenna array on a single base transceiver station. For these reasons, at least some implementation details of the virtual array object **840** can be concealed from the multi-user MIMO object **810**.

A MIMO system employs multiple (N_T) transmit antennas and multiple (N_R) receive antennas for data transmission. A MIMO channel formed by the N_T transmit and N_R receive antennas may be decomposed into N_C independent channels, wherein $N_C \leq \min\{N_T, N_R\}$. Each of the N_C independent channels is also referred to as a spatial subchannel (or subspace channel) and corresponds to a dimension. In one common MIMO system implementation, the N_T transmit antennas are located at and associated with a single transmitter system, and the N_R receive antennas are similarly located at and associated with a single receiver system. A Cooperative-MIMO system can be effectively formed for a multiple access communication system having a set of base transceiver stations communicatively coupled together and coordinated to concurrently communicate with a number of UEs. In this case, each base transceiver station and each terminal can be equipped with one or more antennas. A Cooperative-MIMO system can be effectively formed for a multiple access communication system having a multiple UEs communicatively coupled together and coordinated to concurrently communicate with at least one base transceiver station. In this case, the base transceiver station is typically equipped with multiple antennas and each terminal can be equipped with one or more antennas. However, if geographically distributed base transceiver stations are employed, each base transceiver station can be equipped with one or more antennas.

The wireless links between the distributed base transceiver station antennas and the UE antennas are modeled as a complex channel matrix H of dimensions $K \times N_T$, where K is the aggregate number of UE antennas and N_T is the number of distributed antennas. H_{DL} is the DL channel matrix and H_{UL} is the UL channel matrix. Channel reciprocity holds if DL and UL are set to the same carrier frequency:

$$H_{DL}=H_{UL}{}^{T}=H$$

where the superscript symbol, "T", denotes the transpose matrix operation.

In one aspect of the invention, channel estimation is initiated with transmission of a training signal by each of the antennas of a plurality N of base stations. Assuming M antennas per base station, there are N·M training signal transmissions.

Each UE receives each training signal through each of its antenna(s) and frequency down-converts the training signal to baseband, where it is digitized and processed. Signal characterization logic, such as represented by function f_csi(. . .) **864** characterizes the channel from the received training signal (e.g., identifying phase and amplitude distortions, such as in the case of a flat fading channel, or calculating a channel impulse response) and stores the characterization in memory. Some aspects of this characterization process are similar to that of prior-art MIMO systems, with a notable difference being that the each UE only computes the characterization vector for its own antenna(s) rather than for all K antennas, and each UE is configured to perform channel characterization from training signals transmitted from multiple base transceiver stations. In other aspects of the invention, function f_csi(. . .) **864** characterizes the channel from training signals transmitted by the UEs. Thus, function f_csi(. . .) **864** may reside on the base transceiver stations and/or the central processor. In accordance with some aspects of the invention, software objects, and even components with software objects disclosed herein may reside on multiple devices, including UEs, base transceiver stations, and central processors.

In accordance with one aspect of the invention, each UE produces a sub-matrix of a full cooperative-MIMO channel matrix H. For example, if a UE has one antenna (or it has multiple antennas and a combining system that combines signals received by the multiple antennas), then a channel estimate corresponding to a training signal transmitted by one antenna of one of the base stations is an element of a $1 \times N_T$ vector, where N_T is the total number of base station antennas, expressed by $N_T=\Sigma_{n=1}{}^{N}M_n$, where N is the number of base stations, and M_n is the number of antennas corresponding to an nth base station. In some aspects, a channel estimate comprises a complex-valued flat-fading coefficient. In some aspects, a channel estimate comprises a matrix, such as an impulse response vector.

In accordance with an aspect of the invention, a first UE having a single antenna generates a $1 \times N_T$ vector of channel characterization data: $[H_{1,1}, H_{1,2}, \ldots, H_{1,N_T}]$. A second UE having a single antenna generates a $1 \times N_T$ vector of channel characterization data: $[H_{2,1}, H_{2,2}, \ldots, H_{2,N_T}]$. A kth UE having a single antenna generates a $1 \times N_T$ vector of channel

characterization data: $[H_{k,1}, H_{k,2}, \ldots, H_{k,N_T}]$. This channel characterization data can be a data set (e.g., csi) within the V_array object **840**.

Based on channel conditions and/or proximity of a UE to each base station, a particular set of base stations may be selected to serve the UE. For example, this selection process may be performed by the f_select_antenna(. . .) function **863**. Thus, one or more UEs may be assigned to a subset of the total number of base stations. In such instances, values of the channel characterization data corresponding to a non-serving base station relative to a UE may equal zero. In some cases, certain values of the full cooperative-MIMO channel matrix H, such as matrix elements corresponding to indices of non-serving base station antennas relative for a particular UE, may be set to zero

In some aspects of the invention, a kth UE comprises multiple N_k antennas configured to perform MIMO. For each UE's antenna, a channel estimate corresponding to a training signal transmitted by one antenna of one of the base stations is an element of a $1\times N_T$ vector. Thus, the kth UE can generate an $N_k\times N_T$ submatrix of the full cooperative-MIMO channel matrix H.

The UEs upload their channel characterization sub-matrices to the base stations via the WWAN, and the sub-matrices are communicated to the central processor via the fronthaul network. Thus, in some aspects, the f_csi(. . .) function **864** can comprise components distributed across UEs, base stations, and one or more central processors. As the central processor collects the channel characterization sub-matrices, they are stored as the full $K\times N_T$ cooperative-MIMO channel matrix H, where K is the total number of UE antennas and N_T is the total number of base station antennas.

Since each UE is an independent device, each UE often receives its own unique data stream. Thus, in some aspects of the invention, the central processor sources multiple data streams and routes them as separate data streams intended for each UE. In order to do this, the central processor comprises precoding logic for precoding the signals transmitted from each antenna of each of the base stations based on the signal characterization matrix H. In one aspect of the invention, the pre-coding logic is implemented via one or more software instructions, such as the f_precode(. . .) function **821** in the Mu_mimo object **810**. The central processor then routes the precoded data (or the precoding weights and data symbols) to the plurality of base stations. Routing can be part of the f_precode(. . .) function **821**, or it can comprise a separate function call. Thus, each base station antenna is configured to transmit a subspace-coded data sequence which is a function of the data symbols and the channel matrix H.

In one aspect of the invention, cooperative MIMO improves the uplink communications (i.e., the link from the UEs to the Base Stations). In this aspect, the channel from each UE is continually analyzed and characterized by uplink channel characterization logic residing in each base transceiver station or central processor, which may be implemented by the f_csi(. . .) function **864**. For example, each UE may transmit a training signal, which the channel characterization logic analyzes (e.g., as in a typical MIMO system) to generate the channel characterization matrix H.

As described throughout the '163 application, the '854 application, and the '107 application, all of which are incorporated by reference in their entireties, various spatial processing techniques may be employed. Such processing techniques may be included within the f_precode **821** and f_demux **822** functions.

In one aspect of the invention, f_demux **822** performs linear spatial processing on the received signals (for a non-dispersive MIMO channel with flat fading) or space-time processing on the received signals (for a dispersive MIMO channel with frequency selective fading). The spatial processing may be achieved using linear spatial processing techniques such as a channel correlation matrix inversion technique, a minimum mean square error (MMSE) technique, and others. These techniques may be used to null out the undesired signals and/or to maximize the received SNR of each of the constituent signals in the presence of noise and interference from the other signals. The space-time processing may be achieved using space-time processing techniques such as an MMSE linear equalizer, a decision feedback equalizer (DFE), a maximum-likelihood sequence estimator (MLSE), and others. In some aspects, iterative cancellation techniques, such as successive interference cancellation may be employed.

In some aspects of the invention, f_precode **821** performs directive and/or retro-directive techniques for calculating antenna array weights for transmission in a distributed antenna system. Such techniques are disclosed in the '163 application. In some aspects of the invention, as disclosed in the '187 application, eigenvalue-decomposition approaches, such as singular value decomposition, may be employed for transmitter spatial processing.

For example, a MIMO channel formed by the N_T transmit antennas comprising multiple transmission nodes (e.g., base stations) and N_R receive antennas comprising multiple UEs can be characterized by an $N_R\times N_T$ channel response matrix H for each OFDM subband, wherein each matrix element $h_{i,j}$ of H denotes coupling or complex channel gain between transmit antenna j and receive antenna i. For simplicity, the MIMO channel is assumed to be full rank with $S=N_T\leq N_R$.

For data transmission with eigensteering, eigenvalue decomposition can be performed on a correlation matrix of H to obtain S eigenmodes of H, as follows:

$$R=H^H\cdot H=E\cdot\Lambda\cdot E^H,$$

where R is a correlation matrix of H; E is a unitary matrix whose columns are eigenvectors of R; Λ is a diagonal matrix of eigenvalues of R; and "^{H}" denotes a conjugate transpose.

A unitary matrix U is characterized by the property $U^HU=I$, where I is the identity matrix. The columns of a unitary matrix are orthogonal to one another, and each column has unit power. The matrix E is also called an "eigenmode" matrix or a "transmit" matrix and may be used for spatial processing by the central processor to transmit data on the S eigenmodes of H. The eigenmodes may be viewed as orthogonal spatial channels obtained through decomposition. The diagonal entries of Λ are eigenvalues of R, which represent the power gains for the S eigenmodes. The eigenvalues in Λ may be ordered from largest to smallest, and the columns of E may be ordered correspondingly. Singular value decomposition may also be performed to obtain matrices of left and right eigenvectors, which may be used for eigensteering.

For data transmission with eigensteering, the transmitting entity may perform spatial processing for each subband as follows:

$$z=E\cdot s,$$

where s is a vector with up to S data symbols to be sent on a particular subband; and z is a vector with N_T spatially processed symbols for the subband. In general, D data symbols may be sent simultaneously on D (best) eigenmodes of H for each subband, where $1\leq D\leq S$. The D data

symbols in s are spatially processed with D columns of E corresponding to the D selected eigenmodes.

For data transmission with a spatial spreading matrix, such as a CI spatial spreading matrix, the transmitting entity may perform spatial processing for each subband as follows:

$$z_{ss}=V\cdot s$$

where V is a spatial spreading matrix for the subband; and z_{ss} is a vector with up to N_T spread symbols for the subband. Each data symbol in s is multiplied with a respective column of V to obtain up to N_T spread symbols.

In general, D data symbols may be sent simultaneously on each subband with matrix spreading, where $1\leq D\leq S$. The D data symbols in s may be multiplied with a $N_T\times D$ spreading matrix V(k) to obtain N_T spatially processed symbols for z_{ss}. Each spatially processed symbol for each subband includes a component of each of the D data symbols being sent on the subband. The N_T spatially processed symbols for each subband are then transmitted on the S spatial channels of H.

As disclosed throughout the '187 application, any of various water-filling or water-pouring schemes may be employed to optimally distribute the total transmission power over the available transmission channels, such as to maximize spectral efficiency. For example, water-filling can be used to adapt individual UE transmission powers such that channels with higher SNRs are provided with correspondingly greater portions of the total transmit power. A transmission channel, as defined herein, may include a spatial (e.g., a sub-space) channel, a space-frequency channel, or some other channel defined by a set of orthogonalizing properties. Similarly, water filling may be used at a physically connected (i.e., wired) antenna array. The transmit power allocated to a particular transmission channel is typically determined by some predetermined channel-quality measurement, such as SNR, SINR, BER, packet error rate, frame error rate, probability of error, etc. However, different or additional criteria may be employed with respect to power allocation, including, but not limited to, UE battery life, load balancing, spatial reuse, power-control instructions, and near-far interference.

The modulation and channel coding for each transmission channel may be adapted with respect to the corresponding SNR. Alternatively, transmission channels may be grouped with respect to their data-carrying capability. Thus, groups of transmission channels may share common modulation/coding characteristics. Furthermore, transmission channels having particular SNRs may be used for particular communication needs. For example, voice communications may be allocated to channels having low SNRs, and thus, data-carrying capabilities. In some cases, transmission channels that fail to achieve a predetermined threshold SNR may be eliminated. In one embodiment of the invention, water filling is employed such that the total transmission power is distributed over selected transmission channels such that the received SNR is approximately equal for all of the selected channels.

In accordance with some aspects of the invention, hardware systems, such as UEs, base transceiver stations, and central processors, can include a processing element capable of executing processing threads or tasks.

As depicted in FIG. **9**, a UE can include a controller, such as at least one computer or data processor **910**, at least one non-transitory computer-readable memory medium embodied as a memory **920** that stores a program of computer instructions **921**, and at least one suitable radio frequency (RF) transmitter/receiver **901** for bidirectional wireless communications with multiple base transceiver stations via one or more antennas **905**.

As depicted in FIG. **10**, a base transceiver station includes a controller, such as at least one computer or a data processor **1012**, at least one computer-readable memory medium embodied as a memory **1014** that stores a program of computer instructions **1016**, and at least one suitable transceiver **1002** for communication with the UEs via one or more antennas **1001.1-1001.**N_M. The base transceiver station is coupled via a fronthaul transceiver **1020** to a data and control path to the central processor, such as a network control element. In one aspect of the invention, the fronthaul may be implemented as an Si interface. In another aspect, the fronthaul may comprise an X2 interface. In another aspect, the fronthaul can comprise a direct eNodeB internal interface (e.g., optical fiber connection) such as a connection between a radio remote head and an eNodeB.

Thus, there is some central unit where several base transceiver stations are connected as such, with the goal being that the base transceiver stations (e.g., transmission points, macro eNodeBs, etc.) are centrally controlled together. The control can be at the location of a macro eNodeB, but could also be at a different location.

As depicted in FIG. **11**A, a central processor, such as a network control element, comprises a controller, such as at least one computer or a data processor **1112**, at least one computer-readable memory medium embodied as a memory **1114** that stores a program of computer instructions **1116**, and at least one fronthaul transceiver **1120** coupled to a data and control path (i.e., a fronthaul network) between the central processor and multiple base transceiver stations.

At least one of the programs **921**, **1016**, and **1116** is assumed to include program instructions that, when executed by the associated computer processor(s), enable the corresponding device(s) to operate in accordance with the exemplary aspects of the invention.

The '163 application discloses SDR platforms that enable dynamic implementations of a full protocol stack, including Physical-layer processing. Some aspects are disclosed in the context of software-defined networks, such as to enable more dynamic organization of resources. Disclosed software radio implementations include instantiations of virtual base stations.

In some disclosed aspects, software radio provides associated control operations, such as identifying a particular transmission protocol used by a particular device, reserving channels for transmission, monitoring channel use (including channel reservation and channel release), requesting data transmissions and/or state information from remote devices, attaching tags to data streams for identification and/or access control, and providing instructions to remote transceivers to adjust or control processing, transmit status information, and/or identification.

By way of example, and with respect to implementing base transceiver station processing in a central processor or in a distributed computing system, a software-defined radio in accordance with one aspect of the invention can provide a base station instantiation for a UE. Specifically, the software-defined radio can perform base station processing functionality in combination with Cooperative-MIMO subspace processing to use a plurality of geographically distributed base transceiver stations that communicate with the UE via the radio access network. In an LTE network, this means that the software-defined radio implements a virtual

eNodeB to support the LTE protocol stack for that user while providing for subspace coding to support spatial multiplexing.

In one aspect, when a UE joins the network, the SDR might provide for requesting identification, performing channel reservation, and requesting state information (e.g., channel state information) from the UE. The combination of software-defined radio and Cooperative-MIMO implemented with virtualized base station processing via the central processor or even distributed (e.g., cloud) computing enables each UE to be served independently of other UEs concurrently employing the same spectrum, and possibly using the same base transceiver station hardware. This is because Cooperative-MIMO subspace processing enables multiple non-interfering subspace channels in the same spectrum to be used by each UE, even closely spaced UEs, which can eliminate the need for other multiple access partitioning of the spectral resource (such as via TDMA, OFDMA, CDMA, etc.). When the UE ends its connection with the network, the SDR releases the channel and its instantiated virtual base station.

In accordance with some aspects, consolidation of processing from multiple base stations to a central processor (e.g., an offsite data center) constitutes a virtual base station that employs multiple antennas of different base transceiver stations and remote (and possibly software-defined) base station processing. Further aspects distribute the base station processing over multiple processing cores via distributed (e.g., cloud) computing. As disclosed in the '163 application, multiple different transmission protocols may be employed simultaneously. Thus, SDR instances (e.g., virtual base stations) employing different protocol stacks may coexist within the same software-defined radio and can be implemented concurrently within the same spectrum.

A CI-based software radio can extend adaptive link-layer techniques to the physical layer. This enables more efficient use of the spectrum by dynamically adjusting physical-layer characteristics to current channel conditions, network traffic, and application requirements. CI can significantly improve wireless network performance and functionality by adapting to different requirements for bandwidth, error rate, latency, link priority, and security.

Embodiments of a CI-based communication system may include interactive capabilities between the physical layer and higher layers such that a response to changing conditions and operational requirements can be directed to an appropriate physical-layer function. For example, a base station or central processor in a mobile wireless network can dynamically create channels (e.g., spatial multiplexing channels) depending on the number of mobile units in its coverage area and their service requirements. When additional units enter the area, the system can be reconfigured accordingly.

In ad-hoc networks, base station functions (e.g., routing, power control, synchronization, geo-location services, etc.) may be distributed among various devices. Aspects of the disclosure can also include adapting base-station and access-point functions to maintain link quality and perform load balancing (including managing power budgets for devices acting as routers and relays, managing system spectrum allocations, and/or adjusting cell boundaries to adapt to changing user demands, power budgets, and spectrum use). Thus, in some aspects, the super-array processing system **112** may include a power control **114.3**.

Bandwidth can be dynamically allocated to uplink and downlink channels depending on network traffic characteristics. Units requiring real-time or broadband services may be assigned to dedicated channels, whereas units having bursty data requirements may be assigned to a shared channel. Aspects of the invention can provide for combinations of time-domain and frequency-domain processing to produce signals having desired physical-layer characteristics.

SDRs disclosed in the '163 application are configured to provide for various signal processing objectives for implementing multiple-access protocols (e.g., DS-CDMA, TDMA, OFDM, MC-CDMA), channel coding, modulation (e.g., phase modulation, frequency modulation, amplitude modulation, time-offset modulation, etc., including different constellations (e.g., binary, M-ary), multiplexing (e.g., TDM, FDM, CDM), formatting (e.g., frame length, headers, payload length, etc.), source coding, providing for frequency agility (e.g., frequency hopping, variable aggregate bandwidth, frequency selectability, etc.), encryption, and/or subchannel coding.

FIG. **11**B is a block diagram that depicts a cloud-based software-defined radio, such as disclosed in the '163 application. A plurality of hardware components (such as servers **1101** and **1102**) are communicatively coupled together via a network **1190**. Server **1101** comprises at least one processor (e.g., CPU **1161**) and at least one memory **1141**. Similarly, server **1102** comprises at least one processor (e.g., CPU **1162**) and at least one memory **1142**. A software-defined radio platform can comprise a plurality of signal-processing software components residing in one or more of the memories **1141** and **1142** of the hardware components, **1101** and **1102**, respectively. By way of example, SDRs **1151.1-1151**.*i* are stored in memory **1141**, and SDRs **1152.1-1152**.*j* are stored in memory **1142**. By way of example, the hardware components **1101** and **1102** may include a computer main frame or a workstation.

Although not shown, interfaces can couple the hardware components **1101** and **1102** together, such as via the network **1190**. Such interfaces disclosed in the '163 application include radio interfaces for a radio network. The network **1190** may comprise various types of networks, including a bus. Also disclosed in the '163 application is the concept of interfaces for the software components (e.g., **1151.1-1151**.*i* and **1152.1-1152**.*j*) as it relates to software design, such as object oriented design. Interaction and inter-connectivity between software and hardware interfaces is also contemplated for coupling together hardware and/or software components.

The SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j* may include local and/or remote computer programs configured to process signals, such as for various physical-layer signal processing, including baseband processing. For example, the SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j* may include one or more programs for performing digital signal processing. One or more of the SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j* may provide control signals to one or more hardware components such as to select, adapt, or otherwise reconfigure signal processing.

The memory can comprise various types of storage mediums (e.g., disk drive, tape drive, CR Rom, DVD, flash memory, or any other storage device) for storing application programs (e.g., the SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j*) and data. Hardware and/or the software may perform A/D conversion, as necessary. In some applications, modulation and/or demodulation may be performed digitally with any combination of software and hardware.

In one set of aspects of the invention, a software component (such as at least one of the SDRs **1151.1-1151**.*i* and **1152.1-1152**.*j*) residing at a remote receiver location (e.g., a

base transceiver station) receives signals transmitted in the radio access network, processes the received signals, and conveys some control information in the data stream (e.g., in a header or pilot channel) to hardware components residing in another location (e.g., at a central processor or another base transceiver station). Signal-processing operations may be distributed throughout a network in a way that balances processing loads and/or communication-resource (e.g., spectrum use) loads. Alternatively, in a Cooperative-MIMO network wherein UEs cooperate with a base transceiver station to perform joint processing for spatial multiplexing and/or demultiplexing signals, most of the signal processing may be performed by the base transceiver station (and/or the central processor) to reduce the cost and complexity (and power usage) of the UEs. As described with respect to centralized processing of base transceiver operations, RF processing is performed at each base transceiver station, and most or all of the baseband signal processing may be performed at a central processing facility.

In one set of aspects of the disclosure, software can be uploaded to a remote transceiver (e.g., base transceiver station) via one or more communication channels. This simplifies software updates and enhances signal-processing versatility of the network. In another set of aspects, software updates can be uploaded to a central processor (e.g., a cloud network organized by a central processor) where most or all of the baseband processing is performed.

Software-based radios can provide adaptability to different communication standards. The '163 application discloses various systems and techniques that can migrate many different transmission protocols to a common high-performance SDR platform that is suitable for all applications. In some aspects of the disclosure, the SDR platform can be configured to enable coexistence of different standard systems within the same spectrum. For example, the power emission, frequency band, or other configuration parameters of a legacy radio access network can be adjusted to accommodate the adoption of new transmission protocols while avoiding harmful interference with the legacy protocol.

As new wireless standards are developed to enhance data rate and coverage in the radio access network, the base transceiver stations and/or central processors can be updated to support those standards. In some aspects, only the central processor(s) needs to be updated. By way of example, the central processor may comprise distributed computing resources, such as multiple servers residing in one or more data centers. The servers may comprise hardware components of an SDR platform.

In one aspect, the base transceiver stations and/or central processors are SDRs equipped with programmable computational capability, such as FPGA, DSP, CPU, GPU, and/or GPGPU, configured to run algorithms for baseband signal processing in the radio access network. If the standard is upgraded, new baseband algorithms can be uploaded to the central processors and/or from the central processors to the base transceiver stations to reflect the new standard. This SDR feature allows for continuous upgrades to the radio access network, such as when new technologies are developed to improve overall system performance.

In one aspect of the disclosure, a cloud SDR network comprises a multi-user MIMO system implemented with cooperative-MIMO over a plurality of geographically distributed base transceiver stations communicatively coupled to a central processor. The central processor is configured to perform at least some of the baseband processing in the radio access network. In some aspects, the central processor and the base transceiver stations are configured to exchange information to reconfigure system parameters, such as to dynamically adapt to changing conditions of the radio access network, including the network architecture (such as described in the '187 application).

As disclosed with respect to coordinated multipoint systems with a central processor configured to perform cooperative MIMO, the base transceiver stations in a cloud SDR network can be configured to generate simultaneous non-interfering wireless links to serve different UEs with different multiple access techniques (e.g., TDMA, FDMA, CDMA, OFDMA, etc.) and/or different modulation/coding schemes. For example, if the base transceiver stations perform RF processing and the central processor performs just baseband processing, the SDRs can be configured to perform baseband processing. Based on the active UEs in the radio access network and the standard(s) they use for their wireless links, the SDRs implemented by the central processor (such as SDRs in a distributed computing environment) can instantiate virtual base station processes in software, each process configured to perform the baseband processing that supports the standard(s) of its associated UE(s) while utilizing a set of the base transceiver stations within range of the UE(s).

In accordance with one aspect of the invention, baseband waveforms from multiple ones of the SDRs **1151.1-1151.***i* and **1152.1-1152.***j* are coupled into the Super-Array Processing System **112** depicted in FIG. **2**. The baseband waveforms are combined in the Spatial Multiplexing/Demultiplexing module **114.1** using Cooperative-MIMO subspace processing to produce multiple pre-coded waveforms. The routing module **114.2** sends the pre-coded waveforms over the fronthaul **105** to multiple ones of the base transceiver stations' **101.1-101**.N antennas **102.1-102**.M_1, **106.1-106**.M_2, and **104.1-104**.M_N. The base transceiver stations **101.1-101**.N can be coordinated to concurrently transmit the pre-coded waveforms such that the transmitted waveforms propagate through the environment and constructively interfere with each other at the exact location of each UE **120.1-120**.K. The coherent combining of these waveforms at the location of each UE **120.1-120**.K results in the synthesis of the baseband waveform that had been output by the SDR instance **1151.1-1151.***i* and **1152.1-1152.***j* associated with that UE **120.1-120**.K. Thus, all of the UEs **120.1-120**.K receive their own respective waveforms within their own synthesized coherence zone concurrently and in the same spectrum.

In accordance with one aspect of the invention, each UE's corresponding synthesized coherence zone comprises a volume that is approximately a carrier wavelength or less in width and centered at or near each antenna on the UE. This can enable frequency reuse between nearby—even co-located—UEs. As disclosed in the '107 application, the Spatial Multiplexing/Demultiplexing module **114.1** can be configured to perform maximum ratio combining. Any of various algorithms for MIMO processing disclosed in the '107 application may be employed by methods and apparatus aspects disclosed herein. In some aspects, the module **114.1** can perform zero forcing, such as to produce one or more interference nulls, such as to reduce interference from transmissions at a UE that is not an intended recipient of the transmission. By way of example, but without limitation, zero forcing may be performed when there are a small number of actual transmitters (e.g., base transceiver station antennas) and/or effective transmitter sources (e.g., scatterers in the propagation environment).

By way of example, FIG. **12** is a block diagram that depicts a central processor **1100** communicatively coupled

via a fronthaul network **1240** to multiple base transceiver stations, such as base transceiver stations **1271** and **1272**. Each base transceiver station **1271** and **1272** comprises a WWAN transceiver **1202** and **1203**, respectively, and baseband processor **1212** and **1213**, respectively. WWAN transceiver **1202** comprises a number N_1 of WWAN transceiver antennas **1204.1-1204**.N_1, and WWAN transceiver **1204** comprises a number N_M of WWAN transceiver antennas **1205.1-1205**.N_M. The baseband processor **1212** comprises a computer processor **1214** and a memory **1216**. The baseband processor **1213** comprises a computer processor **1215** and a memory **1217**. In accordance with some aspects of the disclosure, the baseband processors **1212** and **121** comprise Channel State Information processing logic **1218** and **1219**, respectively, and Channel State Information routing logic **1220** and **1221**, respectively. Each base transceiver station **1271** and **1272** comprises a fronthaul transceiver **1230** and **1231**, respectively, communicatively coupled via the fronthaul network to the central processor **1100**.

In accordance with some aspects of the disclosure, Channel State Information processing logic **1218** and **1219** can collect channel information uploaded by the UEs (not shown) and/or determine channel state information from measurements of training signals transmitted by the UEs (not shown). Channel State Information routing logic **1220** and **1221** can route channel state information to at least one central processor, such as the central processor **1100**.

In some aspects of the disclosure, the central processor **1100** comprises Channel State Information processing logic **1126**, Pre-coding logic **1136**, and Base Station Routing logic **1146**. In one aspect, computer software, such as logic **1126**, **1136**, and **1146**, comprises instructions stored on a non-transitory computer-readable medium (e.g., memory **1114**), that when executed on the processor **1112**, perform the steps of storing the WWAN channel state information received from the base transceiver stations (e.g., base transceiver stations **1271** and **1272**) based on the WWAN channel state information and/or at least one quality metric that characterizes each communication link between a base transceiver station and a UE; and selecting a plurality of antennas residing on multiple base transceiver stations to provide a set of distributed antennas. For example, a set of distributed antennas can be selected to serve each UE. Next, the processor **1112** calculates subspace processing weights from each UE's channel state information for the each UE's corresponding set of distributed antennas. The corresponding instructions can be in the Pre-coding logic **1136** and/or in subspace demultiplexing logic (not shown). The processor **1112** coordinates each UE's corresponding set of distributed antennas to communicate in the WWAN via the fronthaul network. For example, the corresponding instructions for coordinating the distributed antennas can be in the Base Station Routing logic **1146**. The central processor **1100** provides for performing at least one of subspace multiplexing of WWAN signals transmitted by each set of distributed antennas and subspace demultiplexing signals received by each set of distributed antennas.

The exemplary aspects of the disclosure may be implemented, at least in part, by computer software executable by the data processor **910** of the UEs (such as the UE shown in FIG. **9**), the data processor **1012** of the base transceiver stations (such as the base transceiver station shown in FIG. **10**), by the data processor **1112** of the central processor (such as the central processor shown in FIG. **11**A), by multiple data processors in a distributed computing system (not shown), and/or by hardware, or by a combination of software, hardware, and firmware.

In accordance with one aspect of the invention, subspace multiplexing is provided by the Pre-coding logic **1136** configured to produce pre-coded subspace (i.e., spatial multiplexing) weights and to encode data with the weights, and the Base Station Routing logic **1146** configured to route the encoded data to the base transceiver stations for transmission to the UEs. In accordance with another aspect of the invention, subspace demultiplexing is provided by the Base Station Routing logic **1146** configured to route UE uplink signals received by the base transceiver stations to the central processor **1100** and the subspace demultiplexing logic (not shown) configured to produce subspace demultiplexing weights based on the channel state information and to de-multiplex (i.e., decode) the received signals. Thus, performing at least one of subspace multiplexing of WWAN signals transmitted by each set of distributed antennas and subspace demultiplexing signals received by each set of distributed antennas enables multiple UEs to employ simultaneous interference-free same-band communications.

In accordance with some aspects of the invention, certain features, such as pre-coding logic and subspace demultiplexing logic, can comprise an Application Programming Interface (API) or library that defines functionalities that are independent of their respective implementations, which allows definitions and implementations to vary without compromising each other. By way of example, and without limitation, APIs provided for base station network control can enable MIMO processing applications to operate on an abstraction of the network, such as by exploiting distributed antenna array systems and coordinated base station operations and capabilities, without being tied to the details of their implementation.

In accordance with some aspects of the disclosure, the steps of selecting antennas on multiple base transceiver stations for MIMO processing and coordinating the multiple base transceiver stations for cooperative-MIMO communications (which includes routing communication signals to and/or from the multiple base transceiver stations as part of a cooperative subspace processing operation) tie the mathematical operation (i.e., multi-user MIMO subspace processing) to specific and measurable operational benefits (i.e., based on measurable physical phenomena), such as the ability to improve WWAN performance (e.g., spectral efficiency, number of subspace channels, data rate per user, number of users supported, SNR, BER, etc.).

These steps add significantly more to MIMO processing than mere computer implementation. By employing steps, such as selecting multiple base transceiver stations to simultaneously serve each UE in a MIMO subspace processing operation, coordinating the selected multiple base transceiver stations to perform in a subspace multiplexing and/or demultiplexing process, and provisioning at least one central processor to perform subspace multiplexing and/or demultiplexing of signals transmitted by and/or received from the selected multiple base transceiver stations, the corresponding aspects of the invention go beyond the mere concept of simply retrieving and combining data using a computer.

In accordance with the disclosure, the various data processors, memories, programs, transceivers, and interfaces, such as depicted in FIGS. **9**, **10**, **11**, and **12**, can all be considered to represent means for performing operations and functions that implement the disclosed non-limiting aspects and embodiments.

The computer-readable memories (e.g., memories **920**, **1014**, **1114**, **1216**, and **1217**) may be of any type suitable to the local technical environment and may be implemented using any suitable data storage technology, such as semi-

conductor based memory devices, random access memory, read only memory, programmable read only memory, flash memory, magnetic memory devices and systems, optical memory devices and systems, fixed memory and removable memory. The computer processors (e.g., computer processors **910**, **1012**, **1112**, **1214**, and **1215**) may be of any type suitable to the local technical environment, and may include one or more of general purpose computers, special purpose computers, microprocessors, digital signal processors (DSPs) and processors based on multi-core processor architectures, as non-limiting examples.

In accordance with aspects of the invention depicted and described in the '163 application, FIG. **13**A illustrates a subspace processing method configured in accordance with some aspects of the invention. A data-sequence vector u having length N is provided to a transmit filter **1301** before being coupled into a communication channel **99**. The channel **99** acts on a transmitted data vector x via an N×N non-singular matrix H and an additive noise vector n having a variance of $N_o/2$. A signal vector y received from the channel **99** is expressed by:

$$y=Hx+n$$

The received signal vector y is processed by a matched filter **1302** to generate an output signal vector z, which is expressed by:

$$z=R_f x+n'$$

where $R_f=H^*H$ and $n'=H^*n$. An estimate of x given z is expressed by:

$$\hat{x}=R_b z+e$$

where $R_b^{-1}=R_f+(N_o/2)R_{xx}^{-1}$, R_{xx} is the covariance of x, and e is the MMSE error. Additional processing, such as any of various adaptive feedback techniques, may be incorporated at the receiver end.

Although sub-space processing is commonly associated with array processing, the '163 application also discloses coding and decoding based on sub-space processing techniques. For example, as a signal is routed from one node to at least one other node in a network, algebraically unique linear codes are applied to the data for each "hop." In one set of embodiments, sub-space processing and CI methods can be combined. Sub-space processing can include frequency-diversity interferometry and/or interferometry between one or more sets of diversity-parameter values including, but not limited to, polarizations, codes, modes, phases, and delays.

As disclosed in the '163 application, FIG. **13**B illustrates a subspace processing method that employs decision feedback. In this case, Cholesky factorization provides:

$$R_f=G^*S_oG$$

where S_o is a diagonal matrix and G is a monic, upper-diagonal matrix. A decision feedback equalizer includes a feed-forward filter **1303**, a decision system **1304**, and a feedback filter **1305**. An exemplary decision feedback equalization algorithm is represented by:

$$\tilde{z} \approx S_0^{-1}G^{-*}H^* y \text{ for } k = 0,\ N-1$$

$$\hat{x}_{N-k} \approx \text{decision}\left(\tilde{z}_{N-k} - \sum_{i=1}^{k} g_{N-k,N-k+i}\hat{x}_{N-k+i}\right)$$

end

where g_{ij} are elements of G, and $\hat{x}_i$ and $\hat{z}_i$ are elements of $\hat{x}$ and $\hat{z}$, respectively.

A decision feedback equalizer may reorder the received substreams by rearranging the rows and columns of H. For example, a layered processing approach may be employed. Symbols are detected sequentially and interference from previously detected symbols is subtracted. Received vector elements are weighted to null (or reduce) interference from undetected symbols.

Method and apparatus implementations of radio transceivers in accordance with aspects of the disclosure, such as radio transmission techniques and radio transmitters employed by UEs and/or base transceiver stations, are depicted in the block diagram of FIG. **14**A. The blocks disclosed herein can be steps of a method, functional blocks of a transmitter and/or transmitter system, and/or components of a transmitter and/or transmitter system. In some aspects of the disclosure, such as disclosed in the '850 and '163 applications, a transmitter's components can reside on different devices, such as on different network devices communicatively coupled together via a network.

An exemplary aspect of the disclosure provides for OFDM signaling. An information signal s(t) is encoded and/or interleaved in block **1401**. Various types of coding that are known in the art can be employed. For example, in the uplink, it can be desirable to produce a transmission signal with low dynamic range (i.e., peak to average power). Thus, the UEs can employ CI coding on OFDM subcarriers to produce CI-OFDM (also known as a single-carrier OFDM) signals.

The coding/interleaving block **1401** can provide for generating or otherwise acquiring symbol values to be impressed onto the subcarriers. The information signal can be provided with predetermined training symbols in a training symbol injection block **1402**. Training symbols can be used for various purposes, including, but not limited to, channel estimation, signal-quality estimation, and synchronization.

An IFFT **1403** (or equivalent process) impresses the coded data symbols onto the subcarriers and adds a cyclic prefix. FIR filtering and interpolation **1404** is performed prior to preparing the resulting signal for transmission into a communication channel, typically via an RF front end (not shown).

Various methods and systems adapted to perform the blocks shown in FIG. **14**A can be provided by transmission systems and methods pertaining to the aspects and embodiments of the disclosure. Furthermore, various other signal-processing steps that are typically performed in radio transmitters may be included herein. For example, pre-equalization steps and/or systems may be included in the transmission methods and transmitters disclosed herein.

As described throughout the disclosure, array processing may be performed in transmitters and in transmission methods. Array processing (e.g., subspace multiplexing) can be performed after FIR filtering and interpolation **1404**. In some aspects, array processing can be integrated into the coding **1401**, IFFT **1403**, and/or FIR filtering **1404** blocks.

As used herein, RAN baseband processing is the Physical Layer processing of baseband signals, such as digital baseband signals that will be transmitted in the RAN (after DAC and up-conversion), and digitized baseband signals produced from received radio signals in the RAN. RAN baseband processing is distinguished from IP processing in that RAN baseband processing is particular to the RAN. By way of example, FIR filtering **1404**, modulation (e.g., IFFT **1403**), and training signal injection **1402** are RAN baseband processes. Coding **1401** can include Physical Layer and/or higher layers. For example, forward-error correction (FEC)

is often employed by the data link layer or higher. It should be appreciated that RAN baseband processing includes RAN multiple access and RAN spread spectrum coding, but not transcoding. Interleaving **1401**, as it pertains to distributing data symbols over a physical resource (e.g., multiplexing data symbols on selected bins of a Fourier transform) constitutes RAN baseband processing, whereas interleaving data bits in a data stream does not. Many base station network coordination processes, such as scheduling, handover, routing, power control, and control signaling, are not RAN baseband processing operations. While channel estimation is a RAN baseband processing operation, conveying channel estimates, SNRs, or BERs between base stations is not. While multiple access and multiplexing (i.e., generating the physical signals wherein data is partitioned by time interval, frequency, code space, etc.) constitutes RAN baseband processing, assigning network resources to UEs does not.

Method and apparatus implementations of radio transceivers in accordance with aspects of the disclosure, such as radio reception techniques and radio receivers employed by UEs and/or base transceiver stations, are depicted in the block diagram of FIG. **14**B. The blocks disclosed herein can be steps of a method, functional blocks of a receiver and/or receiver system, and/or components of a receiver and/or receiver system. In some aspects of the disclosure, such as disclosed in the '850 and '163 applications, a receiver's components can reside on different devices, such as on different network devices communicatively coupled together via a network.

Signals received from a communication channel are input to an FIR filtering and decimation block **1405**. Filtered signals may be processed in a synchronization step **1411** to control the timing of various reception processes, such as, but not limited to, a cyclic prefix removal and FFT step **1406** and array processing **1407**. Complex-amplitude measurements associated with individual subcarriers, such as estimates obtained via known training symbols and/or unknown data symbols, may be used in a channel-estimation step **1413**. The channel estimation step **1433** can facilitate the generation of weights (e.g., array-processing and/or CI combining weights).

Array processing **1407** is performed to achieve some preferred combination of system capacity (e.g., subspace demultiplexing) and signal quality (e.g., diversity combining). For example, array processing **1407** may include spatial interferometry multiplexing and/or any other form of array processing. In some aspects, array processing **1407** may be assisted by an interference-estimation step **1416**. CI combining **1418** may be performed in conjunction with the array-processing **1407** and/or a decoding and de-interleaving **1408**. Alternatively, either or both the array-processing **1407** and the decoding and de-interleaving **1408** may perform CI combining **1418**. The decoding and de-interleaving step **1408** performs any necessary de-interleaving of data symbols received from the array-processing **1407** prior to, or following decoding **1408**. Decoding **1408** can include channel, multiple access, spread spectrum, encryption, and/or other decoding processes.

FIG. **15** is a block diagram of a transceiver in accordance with some aspects of the disclosure. A receiver system **1501** is configured to couple a received signal from a communication channel. One or more typical receiver-side signal processing techniques (such as filtering, mixing, down conversion, amplification, A/D conversion, etc.) may be performed on the received signal. A filter bank, such as an FFT **1502**, separates the received signal into a plurality of frequency components. If the received signal is an OFDM signal, the FFT **1502** retrieves a symbol measurement for each OFDM subcarrier. The components are provided with weights in a receiver weighting system **1503**. The weights may include one or more types of weights, such as channel-compensation weights, decoding weights, spatial de-multiplexing weights, multi-user detection weights, array-processing weights, wavelet-processing weights, etc. The weighted components are combined in a combiner **1504**. The combined signals may be processed in a data processor **1505**. In some aspects, the data processor **1505** may be part of a blind-adaptive processor **1506** that is adapted to generate and/or adapt weights relative to one or more performance parameters, such as channel estimates, confidence measures, data estimates, signal power, probability of error, BER, SNR, SNIR, etc.

In one aspect, the blind-adaptive processor **1506** processes information-bearing CI symbol measurements produced by the FFT **1502**. The processor **1506** may work in conjunction with the combiner **1504** to combine the measurements and estimate transmitted data. In some aspects, the combining process may include wavelet processing. The processor **1506** may work in conjunction with the data processor **1505** to provide a channel estimate based on data estimates. In some aspects, the processor **1506** can employ a time-varying channel-estimation filter. In some aspects, the processor **1506** provides channel compensation, which may be based on a statistical characterization of interference, such as a covariance matrix.

In some applications, the processor **1506** provides predistortion (i.e., pre-coding) weights to transmitted signals. A data stream is optionally processed by a transmit data processor **1507**. A transmitter weighting system **1508** is configured to weight data symbols provided to frequency bins of a frequency-domain-to-time-domain converter, such as an IFFT **1509**. Time-domain signals generated by the IFFT **1509** are provided to a transmission system configured to prepare the time-domain signals for transmission into a communication channel.

In accordance with aspects of the disclosure, transceiver operating characteristics can be adaptable, such as indicated in the block diagram depicted in FIG. **16**. In one aspect, a control circuit **1601** is configured to receive one or more system requirements **1611** and, optionally, one or more channel characteristics **1612**. The control circuit **1601** can adapt one or more signal parameters **1602** employed by a radio transceiver **1603**, such as radio transceivers employed by UEs, base transceiver stations, and/or central processors. Signal parameter adaptation and/or selection affect one or more transceiver operating parameters **1621**.

In one aspect, the control circuitry **1601** may scale a transmitted bit rate by scaling the symbol duration, the number of subcarriers, the subcarrier spacing, and/or the number of bits per symbol per subcarrier. This permits the transceiver **1603** to operate in different communications environments, which may require varying operating parameters and/or characteristics. By adapting the operating parameters and/or characteristics of the transceiver **1603**, the control circuitry **1601** can dynamically change the radio signals, thereby providing for compatibility or improving performance. For example, dynamically scaling the bit rate enables widely varying signal bandwidths, adjustment of delay-spread tolerances, and adaptability to different SNR requirements. An adaptable transceiver system can be particularly useful for mobile wireless communications, as well as other applications that support a variety of services in a variety of environments.

In accordance with some aspects of the disclosure, an OFDM system may be configured to select the number of subcarriers and a variable symbol duration. The control circuitry can dynamically select the number of subcarriers to decrease the signal bandwidth and the transmission rate while delay-spread tolerance remains the same. The control circuitry **1601** can also dynamically increase the symbol duration to decrease the transmission rate and the signal bandwidth and provide an increase in delay-spread tolerance. In some aspects, the control circuitry **1601** can be adapted to adjust the transmission rate by changing the type of modulation. In accordance with other aspects, variable transmission rates can be achieved by using adaptive coding wherein different coding schemes are selected to improve the link reliability and/or to decrease the peak-to-average power ratio.

In accordance with yet other aspects of the disclosure, adaptable transmission rates permit asymmetric data rates throughout the network. For example, individual UEs can be allocated varying sets of subcarriers depending on their data bandwidth needs. Additionally, during data downloading, for example, a mobile unit could have a larger downlink data rate than uplink data rate.

In accordance with some aspects of the disclosure, base transceiver stations employ adaptive antenna processing wherein UEs feedback their channel estimates via the uplink when uplink and downlink channel characteristics are not identical. In some aspects, power control can be performed on individual subcarriers or on groups of subcarriers. Alternatively, or in addition to power control, certain subcarriers may be selected to optimize one or more operational parameters, such as throughput, probability of error, received signal power, transmitter power efficiency, SNR, QOS, etc.

Sets of subcarriers may be selected with respect to the types of services being provided. For example, different qualities of service corresponding to different-priority links and/or different link services may be criteria for selecting subcarriers. In one case, subcarriers having little distortion and interference may be selected for services (such as data links) that do not tolerate high BER. In another case, a transmission may be divided into sections and sent on two or more groups of subcarriers (or channels). In some aspects, a more important section, such as addressing information, may be sent on higher-quality subchannels than subchannels on which payload data is sent. Addressing and other control information is typically less tolerant to errors than payload data. Thus, important parts of a transmission may be transmitted on higher-quality subspaces and/or on subcarriers having little distortion and fading.

In some aspects of the disclosure, various demand-assigned protocols govern the utilization of the bus medium. As used herein, the term bus medium, or bus, refers to a communication system or communication resources employed to communicatively couple together distributed transceiver components in a manner that resembles the functions of a computer bus. This expression covers all related hardware components (wire, optical fiber, etc.) and software, including communication protocols. By way of example, a bus can comprise a fronthaul network, a backhaul network, a local area network, and/or a wide area network. In one aspect, a bus communicatively couples together internal components residing in different networked devices, wherein the internal components are configured (such as by a central processor or via some distributed processing means) to function together as a single transceiver or transceiver system. In such aspects, a bus can comprise communication pathways, internal networks, etc. inside the networked devices.

As disclosed herein, software instructions configured to perform methods in accordance with aspects of the disclosure can provide various combinations of object-oriented design features. For example, a radio transceiver system comprising multiple components distributed across multiple networked devices may be provided with an abstraction interface wherein the multiple different constituent components are mapped to a single abstract device. Thus, the details of how the radio transceiver system is implemented (for example, whether the radio transceiver is a single discrete device or comprised of multiple constituent components communicatively coupled together via a bus) can be hidden from systems and operations configured to employ the radio transceiver system. In one example, MIMO processing algorithms can be employed across the multiple constituent components in substantially the same manner as would be employed in a single device comprising multiple antennas. As described herein, MIMO processing algorithms can include various types of algorithms, including, but not limited to, MRC, MMSE, ZF, and/or successive interference cancellation. In some aspects, certain details of the radio transceiver system implementation are provided to the abstract device. For example, certain implementation details (or at least the effects of the implementation) can help a MIMO processor compensate for latencies in the bus communications between cooperating devices in a Cooperative-MIMO configuration.

In accordance with one aspect of the disclosure, each data communication device (DCD) of a set of DCDs in a network communicates with a central access point (AP). Multiple DCDs may request access from the AP in the same request access (RA) burst. In one aspect, each of the multiple DCDs transmits its access request to the AP within a frequency-domain subchannel in the RA burst that is orthogonal to the frequency domain subchannels used by the other DCDs requesting access. In another aspect, each of the multiple DCDs transmits its access request to the AP within a subspace channel in the RA burst that is orthogonal to the subspace channels used by the other DCDs requesting access. Alternatively, other orthogonal diversity-parameter values may be employed. In some aspects, each DCD provides channel training information in the RA burst to allow the AP and/or DCD to adapt to variations in channel characteristics.

FIG. **17** is a block diagram depicting a plurality K of UEs **120.1-120**.K (e.g., mobile or fixed subscriber units) in a wireless network comprising a plurality N of base transceiver stations (e.g., access points) **101.1-101**.N. At least one of the UEs **120.1-120**.K is configured to transmit a pilot signal or known training signal that is received at the base transceiver stations **101.1-101**.N. The propagation environment ensures that the set of pilot signals received by the base transceiver stations **101.1-101**.N is unique for each UE's **120.1-120**.K location. In some aspects of the disclosure, the uniqueness of the propagation environment can be exploited to provide or enhance coding. The base transceiver stations **101.1-101**.N are adapted to process the received pilot signals. Processing operations may depend on various characteristics of the received pilot signals, including absolute and/or relative signal power levels. For example, a predetermined set of the base transceiver stations **101.1-101**.N may be selected to process signals for a given UE based on the received pilot signal power.

In one aspect, at least one of the base transceiver stations **101.1-101**.N is configured to perform channel analysis to

characterize the propagation environment of the transmissions between each UE **120.1-120**.K and the base transceiver station(s) **101.1-101**.N. Channel analysis may include delay-profile and/or flat-fading characterizations. In some aspects of the disclosure, the propagation environment is employed as a unique identifier for each UE **120.1-120**.K. In some aspects, weights calculated from channel estimates may be utilized in multiple-access codes, encryption codes, and/or authentication and verification procedures.

In some aspects of the disclosure, channel analysis is used to generate filter weights and/or array-processing weights at the base transceiver stations **101.1-101**.N to process received and/or transmitted signals. Such weights may be generated using various algorithms, such as MRC, MMSE, ZF, and/or successive interference cancellation, as well as others. The base transceiver stations **101.1-101**.N may comprise single-antenna systems or multi-antenna systems, such as antenna arrays. Received signals may be compared to some local or global timing reference, such as to analyze phase offsets and/or signal timing.

In another aspect of the disclosure, the base transceiver stations **101.1-101**.N are configured to transmit pre-coded signals to the UEs **120.1-120**.K. For example, the transmissions can be pre-coded to exploit the multipath environment between the access points **10011** to **10015** and the UEs **120.1-120**.K to constructively combine at the UEs **120.1-120**.K.

In one set of aspects, transmission (i.e., pre-coding) weights are generated from the reciprocal of a channel matrix that characterizes the propagation environment between a plurality of the base transceiver stations **101.1-101**.N and at least one of the UEs **120.1-120**.K. Channel (i.e., pre-coding) weights may be generated via any combination of deterministic (i.e., training) and blind-adaptive processing. Channel weights may be selected and/or adapted to optimize coherent combining of the base transceiver stations' **101.1-101**.N transmissions at one or more of the UEs **120.1-120**.K. Similarly, the channel weights may be selected and/or adapted to optimize coherent combining of signals received by the base transceiver stations' **101.1-101**.N from one or more of the UEs **120.1-120**.K. Any of various combining techniques may be employed.

In some aspects, channel weights are adapted to generate beam-pattern nulls at one or more of the UEs **120.1-120**.K or other transceivers. Channel weights may be adapted to provide time-varying channel compensation. Thus, beam steering, null steering, or any other time-dependent adaptive array processing may be performed. Appropriate combinations of carrier selection and carrier weighting may be provided to achieve simultaneous directionality (e.g., spatial multiplexing) and diversity benefits. In some applications, any of the base transceiver stations **101.1-101**.N may be replaced by UEs configured to function as routers, relays, and/or array elements of an adaptive transceiver array.

FIG. **18** is a block diagram of a RAN comprising base transceiver stations **101.1-101**.N configured in accordance with an aspect of the invention. The fronthaul network **105** can comprise a wireless, fiber optic, and/or wireline network that communicatively couples the base transceiver stations **101.1-101**.N to a central processor **110**. The central processor **110** is configured to process signals received from and transmitted by the base transceiver stations **101.1-101**.N.

In accordance with one aspect of the disclosure in the '163 application, the central processor **110** comprises a distributed computing system **111**. In accordance with another aspect of the disclosure in the '163 application, the central processor **110** is replaced by the distributed computing system **111**. In one aspect, the distributed computing system **111** comprises a plurality of processors, which may be geographically distributed. As used herein, the term "processor" can refer to a computer processor, a computer, a server, a central processing unit (CPU), a core, a microprocessor, and/or other terminology that indicates electronic circuitry configurable for carrying out instructions of a computer program.

The processors are communicatively coupled together via at least one network, such as a backhaul network **115**. The backhaul network **115** can comprise an optical fiber network, a wireline network (e.g., Ethernet or other cable links), a wireless network, or any combination thereof. In one aspect, the processors are programmed to function as a plurality N of virtual base stations **111.1-111**.N. By way of example, each virtual base stations **111.1-111**.N may comprise one or more of the processors and perform base station processing operations that would ordinarily be performed by one or more of the corresponding base stations **101.1-101**.N. Specifically, virtual base stations can be implemented via software that programs general-purpose processors. For example, an SDR platform virtualizes baseband processing equipment, such as modulators, demodulators, multiplexers, demultiplexers, coders, decoders, etc., by replacing such electronic devices with one or more virtual devices, wherein computing tasks perform the functions of each electronic device. In computing, virtualization refers to the act of creating a virtual (rather than actual) version of something, including (but not limited to) a virtual computer hardware platform, operating system (OS), storage device, or computer network resources.

In accordance with the art of distributed computing, a virtual base station's functions can be implemented across multiple ones of the plurality of processors. For example, workloads may be distributed across multiple processor cores. In some aspects, functions for more than one base station are performed by one of the processors.

As used herein, distributed computing refers to the use of distributed systems to solve computational problems. In distributed computing, a problem is divided into multiple tasks, and the tasks are solved by multiple computers which communicate with each other via message passing. A computer program that runs in a distributed system is referred to as a distributed program. An algorithm that is processed by multiple constituent components of a distributed system is referred to as a distributed algorithm. In a distributed computing system, there are several autonomous computational entities, each of which has its own local memory.

In accordance with aspects of the disclosure, the computational entities (which are typically referred to as computers, processors, cores, CPUs, nodes, etc.) can be geographically distributed and communicate with each other via message passing. In some aspects, message passing is performed on a fronthaul or backhaul network. The distributed computing system can consist of different types of computers and network links, and the system (e.g., network topology, network latency, number of computers, etc.) may change during the execution of a distributed program. In one aspect, a distributed computing system is configured to solve a computational problem. In another aspect, a distributed computing system is configured to coordinate and schedule the use of shared communication resources between network devices.

A distributed computing system can comprise a grid computing system (e.g., a collection of computer resources from multiple locations configured to reach a common goal, which may be referred to as a super virtual computer). In

some aspects, a distributed computing system comprises a computer cluster which relies on centralized management that makes the nodes available as orchestrated shared servers. In some aspects, a distributed computing system comprises a peer-to-peer computing system wherein computing and/or networking comprises a distributed application architecture that partitions tasks and/or workloads between peers. Such distributed peer-to-peer computing systems are disclosed in the '107 application. In some aspects, peers are equally privileged, equipotent participants in the application. They are said to form a peer-to-peer network of nodes. Peers make a portion of their resources, such as processing power, disk storage, network bandwidth, etc., available to other network participants without the need for central coordination by servers or stable hosts. Peers can be either or both suppliers and consumers of resources.

As disclosed in the patents and patent applications incorporated by reference herein, and particularly with respect to aspects of Cooperative-MIMO systems and methods, network nodes can function as either or both clients and servers. Furthermore, when wireless network nodes cooperate in subspace processing, they create network resources, such as subspace (i.e., spatial multiplexing) channels, performance gains, RAN coverage area, etc. Even when UEs cooperate as a client array (e.g., a UE cluster) in a Cooperative-MIMO implementation, each UE can improve the data bandwidth, quality of service, range, and power efficiency of the other UEs in the array, or cluster. Thus, in some aspects of a Cooperative-MIMO system, UEs can extend the network infrastructure, such as to increase per-client data bandwidth, the number of clients served, coverage area, and/or quality of service without requiring substantial capital outlays from network operator to upgrade the base station network.

In Cooperative-MIMO systems, mobile UEs can opportunistically join together via a peer-to-peer overlay network for client-side MIMO processing. In some aspects, UEs can join base transceiver arrays via an overlay network to assist in server-side MIMO processing. Due to random movement of UEs, aspects of the invention do not impose a particular structure on the overlay network. Because there is no structure globally imposed upon them, unstructured networks are easy to build and allow for localized optimizations to different regions of the overlay. Also, in some aspects, because the role of all peers in the network is the same, unstructured networks are highly robust in the face of high rates of churn (i.e., when peers are frequently joining and leaving the network).

In accordance with some aspects of the disclosure, the base transceiver stations **101.1-101**.N are "dumb terminals," wherein base station signal processing (for example, the baseband processing) is performed by the central processor **110** (which may include the distributed computing system **111**). Thus, in some aspects, the base transceiver stations **101.1-101**.N are simply radio remote units. For example, the base transceiver stations **101.1-101**.N might perform only basic signal-processing functions, such as RF processing (i.e., radio front-end processing), which can include frequency conversion and (optionally) ADC/DAC functions, while the central processor **110** (which may include the distributed computing system **111**) performs baseband processing, including channel analysis and generating base transceiver MIMO weights.

In one aspect, the central processor **110** coordinates or performs baseband signal processing corresponding to base station operations, whereas the base transceivers **101.1-101**.N provide only RF front end signal processing, including frequency conversion, and optionally, ADC/DAC. The central processor can perform waveform shaping, error detection, error correction, power control, channel selection, multiple access control, multiplexing, modulation, formatting, synchronization, coding, etc. for the plurality of base transceivers (i.e., access points) communicatively coupled to the central processor via the fronthaul network. In some aspects of the disclosure, the central processor **110** provides for base-station functionality, such as power control, code assignments, and synchronization. The central processor **110** may perform network load balancing, including providing for balancing transmission power, bandwidth, and/or processing requirements across the radio network. Centralizing the processing resources (i.e., pooling those resources) facilitates management of the system, and implementing the processing by employing multiple processors configured to work together (such as disclosed in the '163 application) enables a scalable system of multiple independent computing devices, wherein idle computing resources can be allocated and used more efficiently.

Some aspects allow base station processing resources (e.g., the processors in the distributed computing system **111**) and the remote RF units (e.g., the base transceiver stations **101.1-101**.N) to be deployed separately. For example, RAN coverage, capacity, and/or data bandwidth per UE can be improved by adding base transceiver stations, and then the SDR platform dynamically adapts to the new RAN base station configuration. Similarly, the SDR platform can adapt to the loss of one or more of the base transceiver stations **101.1-101**.N. The distributed computing system (e.g., cloud network) **111** can adapt to varying processing loads by allocating computing resources as needed. Furthermore, system upgrades, such as new transmission protocols, can be easily implemented via software upgrades to the SDR platform.

In some aspects, base-station functionality is controlled by individual base transceiver stations and/or UEs assigned to act as base stations. Array processing may be performed in a distributed sense wherein channel estimation, weight calculation, and optionally, other network processing functions (such as load balancing) are computed by a plurality of spatially separated processors. In some aspects, access points and/or subscriber units are configured to work together to perform computational processing. A central processor (such as central processor **110**) may optionally control data flow and processing assignments throughout the network.

As disclosed in the '850 application, the system depicted in FIG. **18** provides system performance benefits by centralizing (e.g., pooling) much of the equipment (and/or signal processing) typically employed at the cell sites. Cost reduction is another motivation for centralizing the radio access network, as most of a cellular network's ownership costs comprise operating costs, including site rental, power, and support and maintenance expenses. Thus, instead of distributing baseband processing equipment at the edge of the network as in conventional cellular networks, centralizing the radio access network at the central processor **110** can greatly reduce capital expenditures to build out and upgrade the radio access network, as well as reduce operating expenditures.

As disclosed in the '163 application, providing for distributed computing at the central processor **110** provides network function virtualization to the radio access network. Benefits that can be realized with some aspects of the disclosure include cost reduction from pooling and virtualizing baseband processing. This can eliminate the need to provision for peak capacity on a per-site basis, thus reducing

processing requirements. Furthermore, instead of requiring dedicated base station hardware, some of the disclosed aspects provide for the use of commercial (e.g., general-purpose) servers running software.

As disclosed in the patents and applications incorporated by reference herein, other types of networks, including wireless networks, can connect the base transceiver stations **101.1-101**.N. One of the advantages of employing the optical fiber fronthaul **105** is that optical fiber can provide the high capacity and low latency required by many aspects of the invention. For example, when a large number of baseband processors are co-located at the central processor **110**, the amount of data bandwidth in the fronthaul and the synchronization requirements between base transceiver stations **101.1-101**.N can increase substantially when high RF bandwidth and MIMO are employed. Different aspects of the invention can provide for different functional splits between centralized and distributed functions.

Some aspects of the invention can reduce fronthaul requirements by implementing at least some of the Physical Layer processing at the base transceiver stations **101.1-101**.N while implementing other processing (e.g., higher layer processing, or the higher layer processing plus some of the Physical layer processing) at the central processor **110**. Thus, in some aspects of the invention, one or more of the base transceiver stations **101.1-101**.N depicted in the figures may be replaced by UEs adapted to perform as routers, repeaters, and/or elements of an antenna array.

In one aspect of the disclosure, the base station network comprising base transceiver stations **101.1-101**.N is adapted to operate as an antenna array. In such aspects, a portion of the network may be adapted to serve each particular UE. The central processor **110** and/or the base transceiver stations **101.1-101**.N may be configured to perform other signal-processing operations, such as, but not limited to, waveform shaping, error detection, error correction, power control, channel selection, multiple access control, multiplexing, modulation, formatting, synchronization, coding, etc. In some aspects of the disclosure, the central processor **110** is replaced by a distributed computing system. In some aspects, the distributed computing system may comprise a plurality of the UEs **120.1-120**.K, repeaters (not shown), and/or the base transceiver stations **101.1-101**.N.

FIG. **19** is a block diagram that depicts apparatus and method aspects of the disclosure. Access points (e.g., access point **1901**) and at least one access controller (e.g., central processor **1902**) are connected via a fronthaul network **1905**, which may comprise an optical fiber, wireless, and/or wireline network. In some aspects, the fronthaul network **1905** may comprise standard interfaces, such as Common Public Radio Interface (CPRI) or Open Base Station Architecture Initiative (OBSAI). The access point **1901** comprises radio processing equipment **1910**, and the central processor **1902** comprises baseband processing equipment **1920**.

In accordance with some aspects of the disclosure, the entire baseband processing is carried out in the central processor **1902** while there may be no baseband processing performed at the access points **1901**. For example, the radio processing equipment **1910** may comprise analog front end circuitry and digital front end circuitry, and the baseband processing equipment **1920** comprises circuitry for the layers L1 (i.e., the Physical Layer) and higher layers. In one aspect of the invention, the radio processing equipment **1910** may perform basic signal-processing tasks, such as amplification, RF filtering, frequency conversion, as well as other RF signal-processing functions. The baseband processing equipment **1920** may perform baseband processing, including modulation/demodulation, combining, channel characterization, power control, other system control functions, quality factor analysis, coding, array processing etc.

It should also be appreciated that in some aspects, such as supported by the disclosures of the patents and patent applications that are incorporated by reference, that either or both radio processing equipment **1910** and the baseband processing equipment **1920** may each be implemented with one or more processors and one or more memories including computer program code, the computer program code comprising instruction configured to cause the processor(s) to perform the corresponding radio processing and/or baseband processing functions.

In accordance with some aspects of the disclosure, physical-layer baseband processing is performed on an SDR platform, which can be implemented on a distributed (e.g., cloud) computing system. Physical-layer baseband processing can include multiplexing, de-multiplexing, modulation, de-modulation, and/or equalization.

In one aspect of the invention, the access point **1901** is a device that serves as the air interface to the user equipment and implements analog radio frequency functions of an eNodeB. The access point **1901** may include one or more antennas for communicating with one or more UEs, and may include support for a variety of antenna types and configurations including, but not limited to, single omni-directional antennas and MIMO arrays of directional antennas. Exemplary functions that may be performed by the access point **1901** include digital-to-analog (D/A) conversion, analog-to-digital (A/D) conversion, carrier multiplexing, power amplification, and RF filtering. The central processor **1902** may be an LTE network device configured to implement radio functions of the digital baseband domain. These functions may include, but are not limited to, radio base station control and management, MIMO processing, and channel coding and de-coding.

FIG. **20**A is a flow chart depicting methods in accordance with aspects of the disclosure. Each of a plurality of geographically distributed access points performs RF processing of signals received from UEs in a radio access network **2001**, such as a WWAN. The resulting RF-processed signals are communicated to a central processor via a fronthaul network **2002**, such as an optical fiber network. The central processor collects RF-processed signals from the plurality of geographically distributed access points **2003** and performs baseband processing of the collected signals **2004**. In one aspect of the disclosure, the baseband processing **2004** comprises distributed computing performed by a distributed computing system. For example, the central processor may configure a plurality of processors to perform baseband processing.

FIG. **20**B is a flow chart depicting methods in accordance with aspects of the disclosure. A central processor performs baseband processing of UE signals **2011** to be transmitted by a plurality of geographically distributed access points to UEs served by a radio access network. In one aspect of the disclosure, the baseband processing **2011** comprises distributed computing performed by a distributed computing system (e.g., a cloud). For example, the central processor may configure a plurality of processors to perform baseband processing.

The resulting baseband-processed signals are communicated to the plurality of geographically distributed access points via a fronthaul network **2012**. The central processor may coordinate the plurality of geographically distributed access points to transmit signals in the radio access network to the UEs **2013**. Each of the access points performs RF

processing of the baseband-processed signals **2014** prior to transmitting the signals to the UEs.

In some aspects of the disclosure, the access point antennas are connected to the central processor via optical fiber. Various types of fronthaul networks may be employed, including optical fiber, wireline (e.g., cable), wireless (e.g., radio), and any combination thereof. In wireless backhaul networks, such as those disclosed in the '163 application, digitized RF signals from various nodes can be aggregated, which allows the building of networks in chain, tree, and ring topologies.

In some aspects, the access point antennas can be considered as radio remote units, and the central processor can be considered as a central hub unit. The baseband signals from multiple access points can be gathered and processed together in the central processor to provide distributed antenna system MIMO benefits, such as spatial multiplexing gain. Similar types of distributed antenna system MIMO processing (e.g., pre-coding) can be performed at the central processor for signals to be transmitted by the access points.

In one aspect of the disclosure, downlink data is transmitted via MRC spatial multiplexing with power control. It should be appreciated that different aspects can effect various types of combining via pre-coding configured with respect to signal propagation measurements in the RAN channel. Pre-coding may comprise MRC, ZF, MMSE, and/or any of a variety of adaptive techniques, including blind adaptive techniques disclosed in the '163 and '107 applications. Coding and power control can comprise open-loop and closed-loop methods. In some aspects, UEs may be selected by the central processor and scheduled for array processing based on quality metrics (e.g., channel conditions, power measurements, SNR, etc.).

In accordance with some aspects of the disclosure, a network topology is depicted in FIG. **21** comprising a source node **2100**, a destination node **2105**, and a plurality of intervening nodes **2102.1-2102**.P. The network nodes **2100**, **2105**, and **2102.1-2102**.P may comprise UEs and/or base transceiver stations. The network nodes **2102.1-2102**.P and any intervening nodes (not shown here, but depicted in the drawings of the '163 application) may be configured to function as routers and/or relays.

In accordance with some aspects of the disclosure, as the network evolves, the nodes adapt their routing tables. As network loads change, the nodes can perform load balancing, such as to ensure a predetermined range of bandwidth and transmit-power loads across the network. One or more paths to the destination node **2105** can be selected or modified to optimize loads across the network, minimize transmission power, and/or ensure received signal quality. In one aspect of the disclosure, multiple transmission paths to the destination node **2105** are employed to achieve one or more objectives, such as reducing the effects of fading, reducing transmission power in some of the relays, and/or distributing transmission power across the network.

Information intended for the destination node **2105** can be passed through the network along one or more intervening nodes **2102.1-2102**.P. One or more of the intervening nodes (e.g., nodes **2102.1-2102**.P) can provide a final radio link to the destination node **2105**. For the sake of simplicity, FIG. **21** depicts a plurality P of transmission paths **2101.1-2101**.P from the source node **2100** to the intervening nodes **2102.1-2102**.P. It should be appreciated that each transmission path can comprise multipath components. It should be appreciated that in some aspects, one or more intervening nodes (not shown) may be utilized between the source node **2100** and nodes **2102.1-2102**.P.

The source node **2100** comprises an antenna system **2110**, which may include one or more antennas. Similarly, each of the intervening nodes **2102.1-2102**.P comprises an antenna system (**2120.1-2120**.P, respectively) which may include one or more antennas. When multiple antennas are employed by a node (e.g., nodes **2100**, **2105**, and/or **2102.1-2102**.P), the node may perform any combination of diversity processing and spatial multiplexing with respect to its antenna system.

In accordance with one aspect of the invention, the source node **2100** selects a plurality P of the intervening nodes **2102.1-2102**.P to provide cooperative subspace processing, such as to increase the rank of the subspace pre-coding matrix and increase the number of linearly independent coded transmissions. In a first aspect of the disclosure, the transmission paths **2101.1-2101**.P comprise the radio access network. In a second aspect of the disclosure, the transmission paths **2101.1-2101**.P comprise a fronthaul network. In both the first and second aspects, the intervening nodes **2102.1-2102**.P comprise antennas of a Cooperative-MIMO antenna array.

As depicted in FIG. **21**, a plurality P of the intervening nodes **2102.1-2102**.P can be selected to provide a final RF link (e.g., transmission paths **2103.1-2103**.P) to the destination node **2105**. It should be appreciated that each transmission path can comprise multipath components. It should be appreciated that in some aspects, one or more intervening nodes (not shown) may be utilized between the source node **2100** and nodes **2102.1-2102**.P.

In one aspect, the destination node **2105** selects the plurality P of the intervening nodes **2102.1-2102**.P to increase the number of linearly independent coded transmissions it receives, effectively increasing the rank of the matrix that encodes the transmitted data. In one aspect of the disclosure, the transmission paths **2103.1-2103**.P comprise the radio access network, and the antenna system **2115** comprises a spatial multiplexing system configured to perform subspace processing. In another aspect of the disclosure, the transmission paths **2103.1-2103**.P comprise a fronthaul network, and the intervening nodes **2102.1-2102**.P comprise antennas of a Cooperative-MIMO antenna array.

In one aspect, the transmitted signals comprise multiple addresses corresponding to at least one path from the source node **2100** to the destination node **2105**. The transmission may include multiple addresses corresponding to a plurality P of devices (e.g., nodes **2102.1-2102**.P) that provide the final RF link to the destination node **2105**. Alternatively, the transmission may include only the destination address of the destination node **2105**. More than one destination address may be included for a particular transmission. A transmission may be duplicated when paths diverge. For example, a message with addresses to nodes **2102.1-2102**.P can be duplicated by node **2100**. In some aspects, a broadcast message includes a plurality of addresses, and the network is configured to propagate a single version of the message to all of the addresses.

In accordance with one aspect disclosed in the '163 application, a data message is provided that includes a plurality of destination addresses. Processing instructions, such as transmission weight values (e.g., a pre-coding matrix), are included with the data message. A single copy of the message is routed through nodes that form a path that is common to all of the destination addresses. The message is duplicated where the paths to the destination addresses diverge, but different linear coding is applied to the message for each of the paths. As disclosed in the '163 application,

each router or relay can provide its own unique linear codes to the messages that pass through it.

The codes may include any combination of polyphase CI codes, CI-based codes, and channel-specific spatial interferometry codes (e.g., linear codes based on the random channel). For example, the channel characteristics for each transmission path (**2101.1-2101**.P and/or **2103.1-2103**.P) can be exploited to provide addressing and/or multiple-access coding. Coding may include space-time coding, space-frequency coding, polarization coding, etc.

Some aspects of the disclosure provide for CI codes that can be implemented across one or more diversity-parameter spaces. Similar to random linear codes, all CI codes of a given set of CI code words can be constructed from a combination of linearly independent code vectors that form the CI code generation matrix. A CI coder is configured to generate a plurality of algebraically unique linear combinations of a plurality of information signals.

FIG. **22**A depicts an aspect of the disclosure wherein at least the source node **2100** transmits a plurality P of transmit messages $t_1, t_2, \ldots, t_p$ on the plurality P of network paths **2101.1**, **2101.2**, . . . , **2101**.P, respectively to the plurality P of intervening nodes (e.g., nodes **2102.1**, **2102.2**, . . . , **2102**.P). In one aspect, each of the transmit messages $t_1, t_2, \ldots, t_P$ comprises a unique linear combination of P information messages (or symbols) $x_1, x_2, \ldots, x_P$. For example, a pth transmit message t_p may employ a vector of coefficients $[\alpha_{p,1}, \alpha_{p,2}, \ldots, \alpha_{p,P}]$ that is a row or column of a code matrix having rank P. In one aspect disclosed in the '163 application, the code matrix (e.g., channel-specific coding) comprises space-time or space frequency codes (e.g., pre-coding), such as derived from channel measurements. The characteristic randomness of the P terrestrial wireless transmission paths (e.g., **2101.1-2101**.P) can provide a code matrix of random values with rank P if the transmission paths **2101.1-2101**.P are sufficiently uncorrelated.

In one aspect, the source node **2100** selects the transmission paths **2101.1-2101**.P to build up the rank of the code matrix. For example, the source node **2100** selects a sufficient number of the intervening nodes **2102.1-2102**.P to ensure that the code matrix has sufficient rank to permit the destination node **2105** to decode the received data. The source node **2100** transmits the codes along with the encoded messages through the network via the intervening nodes **2102.1-2102**.P.

FIG. **22**B depicts an aspect of the disclosure wherein the intervening nodes **2102.1-2102**.P provide a plurality P of received messages $r_1, r_2, \ldots, r_P$ on the plurality P of network paths **2103.1**, **2103.2**, . . . , **2103**.P, respectively to the destination node **2105**. In one aspect, each of the received messages $r_1, r_2, \ldots, r_P$ comprises a unique linear combination of P information messages (or symbols) $x_1, x_2, \ldots, x_P$. For example, a pth received message r_p may comprise a vector of coefficients $[\beta_{p,1}, \beta_{p,2}, \ldots, \beta_{p,P}]$ that is a row or column of a code matrix having rank P. In one aspect disclosed in the '163 application, the code matrix (e.g., channel-specific coding) comprises space-time or space frequency codes (e.g., pre-coding), such as derived from channel measurements. The characteristic randomness terrestrial wireless transmission paths (e.g., paths **2101.1-2101**.P and/or paths **2103.1-2103**.P) can provide a code matrix of random values with rank P if the transmission paths (**2101.1-2101**.P and/or paths **2103.1-2103**.P) are sufficiently uncorrelated.

In one aspect of the disclosure, the destination node **2105** selects the intervening nodes **2102.1-2102**.P to build up the rank of the received coding matrix. For example, the destination node **2105** can select a sufficient number of the intervening nodes **2102.1-2102**.P to ensure that the code matrix has sufficient rank to permit the destination node **2105** to decode the received data.

In some aspects of the disclosure, the intervening nodes **2102.1-2102**.P function as a cooperative-MIMO antenna array, which enables the destination node **2105** to receive a sufficient number of linearly independent combinations of transmitted signals to permit demultiplexing of the received signals. In one aspect, signals received by each of the intervening nodes **2102.1-2102**.P comprises a linear combination of transmitted data signals, and the linear combinations and corresponding code vectors received by the nodes **2102.1-2102**.P are communicatively coupled to the destination node **2105** via a fronthaul network comprising the paths **2103.1-2103**.P. In another aspect of the disclosure, the destination node **2105** comprises an antenna array (e.g., antenna system **2115**), and the transmission paths **2103.1-2103**.P comprise the radio access network. The nodes **2102.1-2102**.P transmit the codes along with the encoded messages to the destination node **2105**. In this aspect, the nodes **2102.1-2102**.P and/or the transmission paths **2103.1-2103**.P can provide additional coding to the signals received at the destination node **2105**. In some aspects, the code matrix may be determined by the destination node **2105** by deriving channel measurements from training (e.g., pilot) signals in the received signals. In other aspects, control signals (such as known training signals) can be encoded such that a receiver, upon correcting for channel distortions, can determine the code(s).

FIG. **23**A is a flow diagram that illustrates aspects of the disclosure pertaining to cooperative subspace multiplexing. In one aspect, a plurality of cooperating nodes is selected to build the dimension of a subspace spanned by coded transmissions **2301**. The plurality of cooperating nodes may comprise a source node. In some aspects, the source node communicates with cooperating transmitter nodes via a fronthaul network.

Linear codes are generated **2302**, for example, from channel estimates of a scattering-rich propagation environment. The natural randomness of terrestrial multipath channels can provide statistically random codes. In some aspects, linear coding is provided to transmissions via pre-coding based on channel measurements. In some aspects, linear coding may be provided to transmissions by multipath in the propagation environment. In such aspects, linear codes corresponding to different transmission channels will be algebraically unique if the channels from which the codes are derived are uncorrelated. This occurs when there is sufficient scattering. Thus, employing multipath scattering for encoding transmissions can be achieved by ensuring that transmitting antennas are sufficiently spatially separated to ensure uncorrelated subspace channels.

In some aspects of the invention, linear codes are generated **2302** and then the cooperating transmit nodes are selected **2301** to at least match the dimension of the set of linear codes (e.g., the rank of a resulting code matrix). In other aspects, the linear codes are generated **2302** to match the dimension of the subspace enabled by a pre-selected set of cooperating transmit nodes.

The cooperating transmit nodes transmit the coded messages and code matrix **2303**. In one aspect, the code vectors are transmitted along with the data payload. In some aspects, the code vectors may be included in control signals. For example, the code matrix may be conveyed by encoding known values, such as training signals. In some aspects, the

natural randomness of the channel encodes transmitted messages and training signals. Thus, transmitting the coded messages and code matrix **2303** can comprise transmitting signals from cooperating transmit nodes that are sufficiently spatially separated to provide uncorrelated transmission channels.

FIG. **23**B is a flow diagram that illustrates aspects of the disclosure pertaining to cooperative subspace demultiplexing. In one aspect, a plurality of cooperating nodes is selected to build the dimension of a subspace spanned by received coded messages **2311**. The plurality of cooperating nodes may comprise a destination node.

A matrix of linear codes is determined from the received signals **2312**. For example, cooperating receiver nodes can communicatively couple their received messages to the destination node (or some other node(s) configured to perform MIMO subspace demultiplexing) via a fronthaul network. In some aspects, the code matrix accompanies the received messages in the data payload and/or as separate control information. In some aspects, the code matrix is determined from measurements of known training signals in the received messages.

In one aspect of the disclosure, determining the code matrix **2312** can indicate a required dimension that permits decoding. Thus, selecting cooperating nodes **2311** may be performed following step **2312**, such as to ensure that a sufficient number of linearly independent combinations of the original messages are collected to enable decoding. Once the destination node (or at least one other node configured to perform MIMO subspace demultiplexing) receives a sufficient number of linearly independent combinations, the received messages are decoded **2313**.

FIG. **24**A is a block diagram depicting a transceiver and transceiver method configured to perform routing in accordance with some aspects of the invention. In one aspect, each block comprises a step or set of steps, which can be performed by one or more circuits or machine components, such as a specialized computing device programmed with instructions to perform specific functions. In one aspect, each block comprises a circuit or a portion of a circuit in a transceiver apparatus. In another aspect, each block comprises a set of instructions that programs a specialized computing device to perform one or more steps disclosed herein. In another aspect, each block and/or a plurality of the blocks comprises at least one specialized computing device programmed with instructions to perform specific functions.

Transmitted signals are received by a receiver system **2401** that outputs a baseband signal. In a wireless network, the receiver system **2401** performs RF and, optionally, baseband processes typically performed to convert an RF signal to a baseband or intermediate frequency signal. For example, the receiver system **2401** may perform channel selection, filtering, amplification, frequency conversion, and A/D conversion.

In one aspect, each transmitted signal comprises a coded data payload and a preamble (or header) that comprises the code. The codes may comprise channel-specific coding. A decoder **2402** can be configured to decode the baseband signal relative to one or more codes in the header. A signal processor **2403** may process the decoded signals prior to producing an output data stream. Signal processing may include one or more signal-processing operations, including, but not limited to, quantization, channel decoding, multiple access decoding, demultiplexing, formatting, demodulation, channel estimation, channel compensation, synchronization, filtering, error detection, error correction, signal-quality analysis, multi-user detection, phase-jitter compensation, frequency-offset correction, time-offset correction, etc.

A control system **2404** is configured to select, adapt, or otherwise control the operation of one or more transceiver components. For example, channel estimates and/or signal-quality analysis performed by the signal processor **2403** may be processed in the control system **2404**, such as to adapt decoding performed by the decoder **2402**. The control system **2404** may provide power control to a transmission system (e.g., transmission system **2406**) and/or otherwise provide network control. Similarly, coding may be adapted by the control system **2404**.

A pre-coder **2405** is configured to process input data bits to produce a coded signal that is coupled to the transmission system **2406**. The transmission system **2406** performs signal-processing operations typically performed to prepare a baseband signal for transmission into a communication channel. In a wireless network, the transmission system **2406** may perform one or more processes, including, but not limited to, D/A conversion, modulation, filtering, amplification, frequency conversion, beam forming, etc.

Signals from the receiver system **2401** can also be coupled through a routing system **2410**. In one aspect, signals from the receiver system **2401** are coupled to a decoder **2412**, which may include a bank of decoders. In one aspect of the disclosure, the decoder **2412** decodes received signals that are to be retransmitted. The decoded signals are processed in a signal processor **2413**, which may perform similar signal-processing operations as signal processor **2403**. Furthermore, the signal processor **2413** may perform pre-processing operations prior to coding in a pre-coder **2415**. The pre-coder **2415** may include a bank of pre-coders. A control system **2414** may be configured to select, adapt, or otherwise control the operation of one or more of the transceiver components **2412**, **2413**, and **2415**.

In one aspect, the control system **2414** and the coder **2415** may provide channel-compensation and/or beam-forming weights to the coded symbols. Such weights may be regarded as part of the routing process (e.g., the pre-coding). In some aspects, since routing decodes some signals that are not intended for the transceiver, the router components **2412**, **2413**, **2414**, and **2415** can be isolated from the rest of the transceiver by a fire wall **2410**.

In one aspect, the set of router components **2412**, **2413**, **2414**, and **2415** receives signals to be routed, decodes the signals **2412**, cleans up the decoded signals **2413**, and re-encodes the cleaned-up signals **2415** for retransmission **2406**. Additional pre-coded signals (e.g., from the pre-coder **2405**) can be combined with the pre-coded signals from the pre-coder **2415** prior to retransmission **2406**. As indicated by the junction that joins the pre-coder **2405** and the pre-coder **2415** prior to the transmitter **2406**, pre-coded signals to be routed may be summed with pre-coded "Data Input," which produces linear combinations of pre-coded signals.

As disclosed in the '850 and '163 applications, in some aspects, the decoder **2412** does not decode some or all of the input coded signals. Rather, the decoder **2412** maps the input coded signals to different code spaces. For example, when basic linear CI codes are employed, the code coefficients resemble Fourier Transform coefficients which are distributed uniformly on the unit circle in the complex plane. One advantage to using basic linear CI codes is that such codes are orthogonal, and some implementation do not require transmitting the decode vector(s) with the coded transmission. Orthogonal codes comprise different integer numbers of "rotations" on the unit circle in the complex plane. For non-zero rotations, a vector sum of the code coefficients

produces a zero result. For a zero rotation, all the code values are mapped to the same point on the unit circle, so the code values sum coherently. Decoding **2412** can map an input code having a first number of rotations to an output code having a second number of rotations. If the second number of rotations is zero, then summing the result yields a solution for a code space in the set of linearly independent coded data values whose coefficients are basic linear CI code values. Thus decoding **2412** can solve for one or more unknowns (i.e., information signals) in the set of linear combinations and/or map at least one code space to at least another code space.

In one aspect of the disclosure, communication signals comprise coded sets of low-bandwidth subchannels. Thus, interference resulting from multipath and effective multipath resulting from retransmissions through the network can be reduced to flat fades. Sub-carrier bandwidths may be adapted to the multipath channel in one or more parts of the network. Coding may be adapted with respect to one or more parameters, including geographical distributions of subscriber units and access points, channel conditions, link priority, security, subscriber services, number of subscribers, etc.

In some aspects of the disclosure, each network node has access to the community's transmissions. The system can allow each node to dynamically select for reception only those transmissions that are relevant to that node. Individual transceivers may be equipped with adaptable or programmable decoders designed to select and decode one or more transmissions. The transceivers may be provided with a bank of decoders to decode and process multiple received signals simultaneously.

FIG. **24**B is a block diagram of a transceiver configured to perform routing in accordance with aspects of the invention. It should be appreciated that FIG. **24**B, as well as the other block diagrams of the disclosure, can indicate both apparatus and method implementations. For example, the blocks can indicate circuits, devices, systems, or other physical components of an apparatus or system. In some aspects, the blocks indicate functional components. The grouping of the functional components can take different physical forms. In some aspects, more than one block may be embodied by one particular physical component. In some aspects, a plurality of physical components can be employed as one of the blocks. In some aspects disclosed in the '850 and '163 applications, at least some of the disclosed signal processing operations can be performed by a computer processor and a computer-readable memory comprising processing instructions that instruct the processor to physically change input signals.

In the transceiver depicted in FIG. **24**B, signals from the receiver **2401** are coupled through a routing system **2420** and then retransmitted by the transmitter **2406**. The routing system **2420** can comprise a processor **2419** configured to process received signals to be routed, and then outputting processed signals to the transmitter **2406**. The received signals to be routed may comprise baseband and/or intermediate-frequency (IF) signals. The processor **2419** can be configured to perform one or more baseband or IF processes, including, but not limited to, signal shaping, filtering, re-quantization, error detection, error correction, interference mitigation, multi-user detection, amplification, up sampling, down sampling, frequency conversion, D/A conversion, AGC, symbol remapping, etc.

It should be appreciated that in some aspects, retransmitting (e.g., relaying, routing, and/or repeating) the received signal can effectively increase the rank of the channel matrix H from the perspective of the destination receiver(s), particularly if propagation channel is a scattering-rich environment. The rank of H is the sum of non-zero singular values λ_i in which each λ_i corresponds to an eigenmode of the channel (i.e., an eigen-channel, or subspace channel). Each non-zero eigenmode can support a data stream, thus the MIMO channel can support k spatial sub-space channels, where k is the number of non-zero eigenvalues λ_i.

In accordance with some aspects of the disclosure, base-station responsibilities are assigned to (or assumed by) individual UEs. For example, base-station operations can be coordinated with simultaneous coded transmissions of a traffic channel and a control channel. Codes may include CI codes, CI-based coding, channel-specific coding, or any combination thereof. A time division duplexing method may be employed for transmit and receive operations to implement the necessary control functions for operation without a base station. At least one of the UEs can be assigned to be a network control station. By using time division duplexing for transmit and receive operations, the same frequency band(s) can be used for uplink and downlink, which can simplify channel estimation and MIMO processing.

A UE acting as a network control station can maintain power control and time synchronization normally performed by a base station. For example, power control can be maintained within predetermined time intervals by a feedback control loop using proportional integration and differentiation to smooth control such that power oscillations are maintained within desired limits. The network control functions may automatically be transferred if the connection with the transceiver is terminated or there is a predetermined degree of signal-quality degradation. The network control station can have channel control capabilities to assure transmission security. For example, the network control station may assign codes to other UEs to change the security or priority of individual communication links.

FIG. **25**A is a block diagram illustrating a network configuration that employs channel reuse between a plurality of networks. A signal **2500** having channel allocation C_1 in a first network is received by a transceiver **2510** (with antenna system **2520**). For example, the first network may comprise a WWAN, or "macro-cell." The channel C_1 is reused for communication in a second network (e.g., a micro-cell network) **2550** comprising transceivers **2510**-**2513**. For example, transmissions **2501**-**2503** employ the channel allocation C_1. As disclosed in the '163 application, the transmissions **2501**-**2503** can comprise array-processing precoding, which can permit reuse of the channel allocation C_1 by the second network via interference mitigation.

In one aspect of the disclosure, antenna systems **2520**, **2521**, **2522**, and **2523** may comprise multiple antennas, and each transceiver **2510**, **2511**, **2512**, and **2513** may be configured to perform array processing with its own antenna system. In another aspect of the invention, the transceivers **2510**, **2511**, **2512**, and **2513** can be configured to perform cooperative array processing, wherein array processing (such as subspace processing) operations are jointly processed by multiple ones of the transceivers **2510**, **2511**, **2512**, and **2513**. Combinations of local array processing (i.e., array processing on individual transceivers) and cooperative array processing (e.g., Cooperative MIMO) may be performed.

FIG. **25**B is a block diagram illustrating a network configuration that employs cooperative array processing and reuses channel C_1 allocated to a first link **2500**. In one aspect, a plurality of the transceivers (**2511**, **2512**, and **2513**) employs channel C_1 to communicate with transceiver **2520**.

For example, the transceivers **2511**, **2512**, and **2513** transmit signals **2504**, **2505**, and **2506**, respectively, to transceiver **2510**. Pre-coding operations on the transmitted signals **2504**, **2505**, and **2506** can provide for beam forming (or equivalent array processing) operations. Various combining operations may be provided to produce any combination of interference rejection, diversity enhancement, and sub-space processing (i.e., capacity enhancement). The aforementioned operations can permit a micro-cell network (e.g., network **2550**) to employ the same macro-cell channels (e.g., channel C_1) without interfering with the macro-cell network.

Methods described with respect to FIGS. **25**A and **25**B and the related disclosures in the '163 application, the transceivers **2510**, **2511**, **2512**, and **2513** can be implemented, by way of example and without limitation, with apparatus embodiments depicted in and described with respect to FIGS. **24**A and/or **24**B.

FIG. **26** is a block diagram depicting systems and methods according to some aspects of the disclosure. In one aspect, a cooperative-MIMO network **2660** comprises multiple groups of separate geographically distributed transceivers, wherein at least a first group **2651** employs cooperative subspace processing (e.g., cooperative-MIMO) to communicate with at least a second group **2652**, such as disclosed in the '107 and '163 applications. In one aspect of the disclosure, the first transceiver group **2651** comprising transceivers **2610-2613** is configured to communicate subspace signals **2601-2603** employing a common channel C_1 to the second transceiver group **2652**, which comprises transceivers **2614-2616**. Since the transceivers **2610-2616** can be configured to operate in multiple networks (e.g., macro-cell and micro-cell networks), in one aspect, network **2660** can be a micro-cell network configured to reuse channel C_1, which is used for communication in the macro-cell.

The subspace signals **2601-2603** comprise a plurality of spatial subchannels that occupy a common frequency spectrum, time interval, and code space denoted by the common channel C_1, wherein subspace processing provides for non-interfering parallel subchannels. As disclosed herein, subspace processing can comprise any combination of transmitter-side and receiver side subspace processing. For example, subspace processing can comprise pre-coding (i.e., spatial multiplexing). In some aspects, subspace processing comprises subspace decoding (i.e., spatial demultiplexing).

The transceivers **2610-2616** each comprises an antenna system (e.g., antenna systems **2620-2626**, respectively), that includes one or more antennas. Thus, in some aspects, more than one antenna per transceiver can be available for cooperative-MIMO processing. In some aspects, one or more of the transceivers **2610-2616** can perform local antenna array processing (e.g., diversity combining and/or spatial multiplexing) in addition to participating in cooperative-subspace processing. As used herein, "spatial multiplexing" can denote the general practice of subspace processing, which can comprise pre-coding (also referred to as subspace coding or spatial multiplexing) and/or decoding (also referred to as subspace decoding or spatial demultiplexing). In some cases, "spatial multiplexing" specifically denotes subspace processing on the transmitter side of a communication link (which is distinguished from spatial demultiplexing performed on the receiver side of the link), and, thus, comprises subspace coding (also referred to as pre-coding). The intended scope of the terminology used in the disclosure is indicated by the context in which it is used.

With reference to FIGS. **25**A, **25**B, and **26**, and related disclosures in the '163 application, FIG. **27** is a flow diagram that depicts methods according to some aspects of the invention. In one aspect, a client transceiver (i.e., a client node) receives a channel allocation (e.g., channel C_1) for communicating in a first communication link **2701**. For example, the client transceiver may receive a signal in channel C_1. Alternatively, the client transceiver may be allocated channel C_1 for transmitting signals. The channel allocation C_1 typically comprises a specified frequency band, time interval, and code space. When no multiple access codes are employed, the code space is simply a vector of ones (e.g., [1, 1, 1, . . . , 1]). By way of example, the channel C_1 may be allocated for communication between the client transceiver and at least one other transceiver in the first network, the channel C_1 being allocated so as not to interfere with other communication links in the first network.

A "client transceiver," as used herein, indicates a transceiver that is served by a first network via the first communication link. In some aspects of the disclosure, the client transceiver may perform additional network functions, and as such, may function as any of various network devices, such as a router, a relay, a repeater, or a gateway.

A transceiver group comprising multiple transceivers, including the client transceiver, is selected to communicate in a second communication link **2702**. In one aspect, selecting **2702** comprises provisioning a plurality of the transceivers to cooperatively transmit signals in the second link. In another aspect, selecting **2702** comprises provisioning a plurality of the transceivers to cooperatively receive signals in the second link. Pluralities of both transmitting and receiving transceivers may be selected, such as depicted in FIG. **26**.

In some aspects, the client transceiver functions as a router or relay, such as to forward communications it receives via the first link to a destination node or another intermediate node via at least a second link. The client may select **2702** the transceivers to which it forwards communications. In one aspect, communications forwarded by the client transceiver to a plurality of cooperating transceivers constitute the second link. In another aspect, transmissions from cooperating transceivers (which may or may not include the client transceiver) comprise the second link. In one aspect, the first link is part of a first network and the second link is part of a second network.

The channel C_1 is reused for communicating in the second link **2703**. Specifically, the second link simultaneously employs the same frequency band and code space as in the first link. Thus, some aspects of the invention are configured to mitigate co-channel interference between signals in the first and second links. Some aspects employ cooperative subspace processing **2704** between at least two transceivers communicating in the second link to mitigate interference between signals in the first and second links. For example, spatial multiplexing (i.e., pre-coding) performed by a plurality of cooperating transmitters can cancel transmissions in the second link that would otherwise interfere with the reception of transmissions in the first link. Spatial demultiplexing (i.e., subspace decoding) performed by cooperating transmitters can separate interfering first-link and second-link signals, such as to permit reception of either or both first-link and second-link signals by transceivers operating in the second link.

By way of example, if the first link channel C_1 is a downlink channel, then cooperative subspace multiplexing and/or demultiplexing can separate received second-link signals from received first-link signals within the transceiver group. By way of example, if the first-link channel C_1 is an uplink channel, then cooperative subspace multiplexing

(e.g., pre-coding) can cancel co-channel interference due to second-link signals received by receivers communicating in the first link. Also, cooperative subspace multiplexing and/or demultiplexing can separate received second-link signals from received first-link signals within the transceiver group.

As will be appreciated to those skilled in the art, disclosures of the '850 and '163 applications can be employed in various types of communication networks, including LTE networks, which comprise a flat network architecture as opposed to hierarchical architectures of other cellular standards.

Thus, in accordance with some aspects of the disclosure, the UEs disclosed herein comprise LTE UEs. By way of example, a UE may comprise an RF transceiver for fixed and/or mobile clients receiving data streams over a downlink channel(s) in the radio access network and transmitting data via the uplink channel(s) in the radio access network.

A base transceiver station may comprise an eNodeB, which may handle radio resource management, user mobility, and scheduling. The base transceiver stations interface the fronthaul network with the radio access network. A base transceiver station of one aspect of the disclosure is an access point comprising an RF front-end configured to convert baseband signals to RF and RF signals to baseband. The base transceiver station may comprise a Digital-to-Analog Converter (DAC)/Analog-to-Digital Converter (ADC). In some aspects, the base transceiver station is a simple RF transceiver equipped with power amplifier/antenna(s), and RF signals are communicatively coupled between the base transceiver station and the central processor via the fronthaul network, which can include RF-over-fiber technology, such as described in related patents and applications that are incorporated by reference.

A controller employed in an LTE network may comprise a base transceiver station configured to perform certain specialized functions, such as transmitting training signals, receiving/transmitting control information from/to the UEs, receiving channel state information (CSI) or channel quality information from the UEs, etc. Coordinated multipoint systems disclosed herein may comprise multiple controllers. In an LTE network, the controller may comprise a mobility management entity.

A fronthaul network configured in an LTE system may comprise a combination of S1 and X2 interfaces. By way of example, but without limitation, the fronthaul may comprise S1-MME links between the mobility management entity and eNodeBs, S1-U links between the serving gateway and eNodeBs, and X2 links between multiple eNodeBs. In some aspects, the fronthaul network comprises the S1 interface. In other aspects, the fronthaul network comprises the X2 interface.

The LTE network typically comprises a gateway, which comprises a serving gateway (S-GW) that terminates the E-UTRAN interface, and a PDN gateway (P-GW), which interfaces with external networks. In accordance with aspects of the disclosure, the central processor can be implemented by the gateway, such as the S-GW component. In other aspects, one or more of the eNodeBs can be configured to operate as the central processor.

While aspects of the disclosure describe Cooperative-MIMO processing in which high channel selectivity (wherein selectivity refers to statistical variations of spatial gains of propagating signals) is achieved via rich multipath environments and/or geographically distributed transmitters (and/or receivers), alternative aspects may employ other diversity parameters (such as signal polarization) and/or various techniques (e.g., coherence multiplexing, frequency diversity interferometry, etc.), such as described in Applicant's patents and other applications, to achieve channel selectivity. By way of example, in U.S. Pat. No. 6,331,837, which is hereby incorporated by reference in its entirety, Applicant discloses that different antenna beam patterns can provide for different spatial gains, thereby providing the selectivity necessary to achieve spatial multiplexing and/or de-multiplexing. Specifically, subspace processing can be achieved in the beamspace domain of a transmitting and/or receiving array, thus transferring the MIMO operation from the antenna elements to the beamspace. Data streams are mapped onto specific transmitted beam patterns, and beamspace multiplexed data streams are sent simultaneously. Similarly, specific radiation patterns are used to receive transmissions. Since beamspace multiplexing exploits aerial degrees of freedom, such techniques can be advantageous for arrays with closely spaced elements. In some aspects of the disclosure, one or more antenna elements in an array are parasitic elements.

One aspect of the '837 patent discloses outputs from multiple beamforming processes being input to a spatial de-multiplexing process. In the case wherein the number of active receiving antennas is less than the number of transmitting antennas, if the beamforming processes produce a number of linearly independent combinations of received transmissions at least equal to the number of transmit sources, then there is sufficient rank in the resulting channel matrix to separate the received signals. In one sense, the beamforming process can be implemented as a multiple-access coding process that maps M logical channels onto N physical subspace channels, where M>N. Although the total theoretical capacity of the channel (such as expressed by the corresponding Shannon-Hartley theorem for the corresponding MIMO implementation employed) does not increase, the capacity is partitioned across more subchannels. In one aspect, the M subchannels each have a lower SNR (and thus smaller capacity) than the corresponding N subchannels. This could be a result of more correlation between the elements of the channel matrix as its dimension increases. The reciprocal of any such process can be applied to spatial multiplexing. Various techniques, including coherence multiplexing, polarization subspace multiplexing, and frequency diversity interferometry are described, and these and the other disclosed techniques can be employed within the spatial multiplexing and de-multiplexing methods and systems disclosed herein.

The various blocks shown in the figures may be viewed as method steps, and/or as operations that result from operation of computer program code, and/or as a plurality of coupled logic circuit elements constructed to carry out the associated function(s).

In general, the various exemplary aspects may be implemented in hardware or special purpose circuits, software, logic or any combination thereof. For example, some aspects may be implemented in hardware, while other aspects may be implemented in firmware or software which may be executed by a controller, microprocessor or other computing device, although the invention is not limited thereto. While various aspects of the exemplary embodiments of this invention may be illustrated and described as block diagrams, flow charts, or using some other pictorial representation, it is well understood that these blocks, apparatus, systems, techniques or methods described herein may be implemented in, as non-limiting examples, hardware, software, firmware, special purpose circuits or logic, general purpose hardware or controller or other computing devices, or some combination thereof.

It should thus be appreciated that at least some aspects of the exemplary aspects of the invention may be practiced in various components such as integrated circuit chips and modules, and that the exemplary aspects of this invention may be realized in an apparatus that is embodied as an integrated circuit. The integrated circuit, or circuits, may comprise circuitry (as well as possibly firmware) for embodying at least one or more of a data processor or data processors, a digital signal processor or processors, baseband circuitry and radio frequency circuitry that are configurable so as to operate in accordance with the exemplary aspects of this invention.

Various modifications and adaptations to the foregoing exemplary aspects of this invention may become apparent to those skilled in the relevant arts in view of the foregoing description, when read in conjunction with the accompanying drawings. However, any and all modifications will still fall within the scope of the non-limiting and exemplary aspects of this invention.

The invention claimed is:

1. A method of enabling a flexible channel bandwidth for mobile radio communications, comprising:

provisioning a set of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers for mobile radio communications;

encoding data symbols with polyphase codes derived from a discrete Fourier transform to produce encoded data symbols; and

modulating the encoded data symbols onto the OFDM subcarriers to produce a superposition signal that resembles a single-carrier signal and has one of a plurality of different symbol durations;

wherein provisioning comprises selecting one of a plurality of different selectable subcarrier spacings, to provide for the one of the plurality of different symbol durations.

2. The method of claim **1**, wherein at least one of the plurality of different selectable subcarrier spacings equals at least one other of the plurality of different selectable subcarrier spacings multiplied by a scaling factor that is a power of two.

3. The method of claim **1**, wherein the superposition signal is provided with a cyclic prefix.

4. The method of claim **1**, wherein the provisioning comprises receiving at least one of a system requirement and a channel characteristic, and the selecting is responsive to the at least one of the system requirement and the channel characteristic to provide at least one of a predetermined transmission rate, a predetermined bandwidth, a predetermined signal-to-noise ratio, or a predetermined delay-spread tolerance.

5. The method of claim **1**, wherein the provisioning is performed by a user device or a base station.

6. The method of claim **1**, wherein the modulating employs a discrete Fourier transform with a plurality of sampling rates that comprise harmonic frequencies.

7. The method of claim **1**, further comprising determining a delay spread in a mobile radio communication network; and based on the delay spread, the selecting being performed according to a first numerology or a second numerology; wherein the first numerology is a first one of the plurality of different selectable subcarrier spacings, and the second numerology is a second one of the plurality of different selectable subcarrier spacings.

8. An apparatus for providing flexible channel bandwidth in mobile radio communications, comprising:

at least one processor; and

at least one non-transitory computer-readable memory in electronic communication with the at least one processor, and instructions stored in the at least one memory, the instructions executable by the at least one processor for:

provisioning a set of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers for mobile radio communications;

encoding data symbols with polyphase codes derived from a discrete Fourier transform to produce encoded data symbols; and

modulating the encoded data symbols onto the OFDM subcarriers to produce a superposition signal that resembles a single-carrier signal and has one of a plurality of different symbol durations;

wherein provisioning comprises selecting one of a plurality of different selectable subcarrier spacings, to provide for the one of the plurality of different symbol durations.

9. The apparatus of claim **8**, wherein at least one of the plurality of different selectable subcarrier spacings equals at least one other of the plurality of different selectable subcarrier spacings multiplied by a scaling factor that is a power of two.

10. The apparatus of claim **8**, further comprising instructions stored in the at least one non-transitory computer-readable memory, the instructions executable by the at least one processor for adding a cyclic prefix to the superposition signal.

11. The apparatus of claim **8**, wherein the provisioning comprises receiving at least one of a system requirement and a channel characteristic, and the selecting is responsive to the at least one of the system requirement and the channel characteristic to provide at least one of a predetermined transmission rate, a predetermined bandwidth, a predetermined signal-to-noise ratio, or a predetermined delay-spread tolerance.

12. The apparatus of claim **8**, wherein the provisioning is performed in a user device or a base station.

13. The apparatus of claim **8**, wherein the modulating employs a discrete Fourier transform with a plurality of sampling rates that comprise harmonic frequencies.

14. The apparatus of claim **8**, further comprising instructions stored in the at least one non-transitory computer-readable memory, the instructions executable by the at least one processor for determining a delay spread in a mobile radio communication network; and based on the delay spread, the selecting being performed according to a first numerology or a second numerology; wherein the first numerology is a first one of the plurality of different selectable subcarrier spacings, and the second numerology is a second one of the plurality of different selectable subcarrier spacings.

15. A computer program product, comprising a non-transitory computer-readable memory having computer readable program code stored therein, the program code containing instructions executable by one or more processors of a computer system for:

provisioning a set of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers for mobile radio communications;

encoding data symbols with polyphase codes derived from a discrete Fourier transform to produce encoded data symbols; and

modulating the encoded data symbols onto the OFDM subcarriers to produce a superposition signal that resembles a single-carrier signal and has one of a plurality of different symbol durations;

wherein provisioning comprises selecting one of a plurality of different selectable subcarrier spacings, to provide for the one of the plurality of different symbol durations.

16. The computer program product of claim **15**, wherein at least one of the plurality of different selectable subcarrier spacings equals at least one other of the plurality of different selectable subcarrier spacings multiplied by a scaling factor that is a power of two.

17. The computer program product of claim **15**, further comprising instructions stored in the at least one non-transitory computer-readable memory, the instructions executable by the at least one processor for adding a cyclic prefix to the superposition signal.

18. The computer program product of claim **15**, wherein the provisioning comprises receiving at least one of a system requirement and a channel characteristic, and the selecting is responsive to the at least one of the system requirement and the channel characteristic to provide at least one of a predetermined transmission rate, a predetermined bandwidth, a predetermined signal-to-noise ratio, or a predetermined delay-spread tolerance.

19. The computer program product of claim **15**, wherein the provisioning is performed in a user device or a base station.

20. The computer program product of claim **15**, wherein the modulating employs a discrete Fourier transform with a plurality of sampling rates that comprise harmonic frequencies.

21. The computer program product of claim **15**, further comprising instructions stored in the at least one non-transitory computer-readable memory, the instructions executable by the at least one processor for determining a delay spread in a mobile radio communication network; and based on the delay spread, the selecting being performed according to a first numerology or a second numerology; wherein the first numerology is a first one of the plurality of different selectable subcarrier spacings, and the second numerology is a second one of the plurality of different selectable subcarrier spacings.

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