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

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CPC combination set(s) only.
See application file for complete search history.

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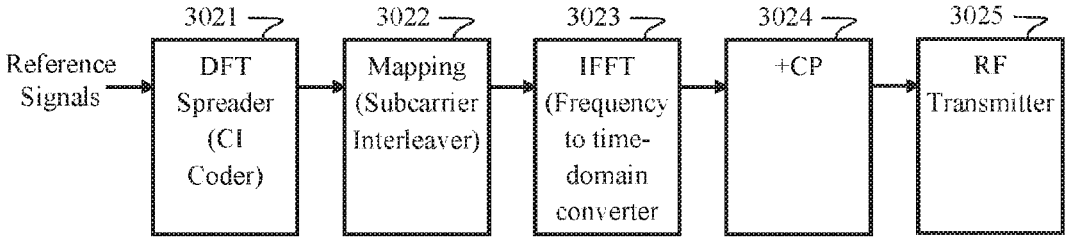
(57) **ABSTRACT**

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.

* cited by examiner

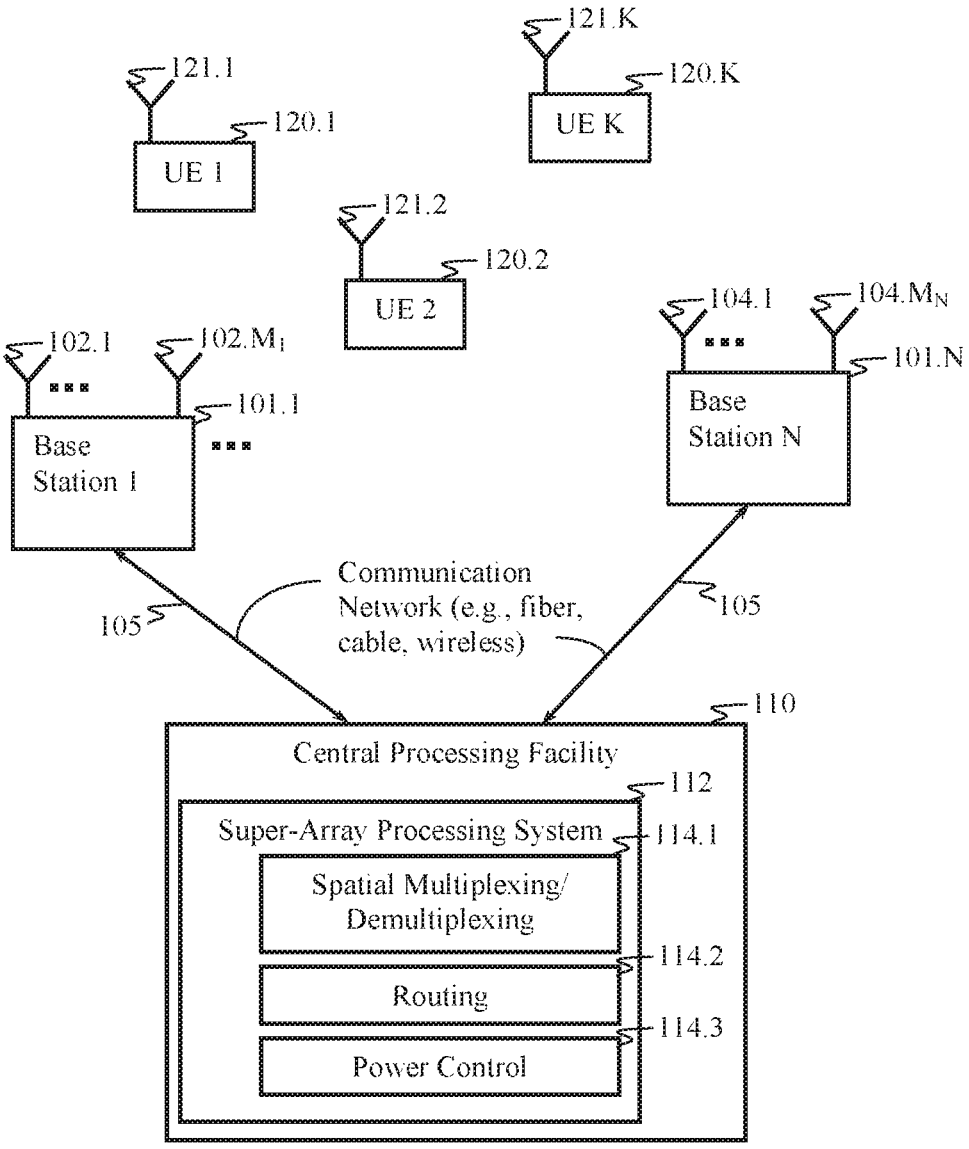
121.K
120.K
UE K
121.1
120.1
UE 1
121.2
120.2
UE 2
104.1
$104.M_N$
101.N
Base Station N
102.1
$102.M_1$
101.1
Base Station 1
105
Communication Network (e.g., fiber, cable, wireless)
105
110
Central Processing Facility
112
Super-Array Processing System
114.1
Spatial Multiplexing/ Demultiplexing
114.2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

Figure 1

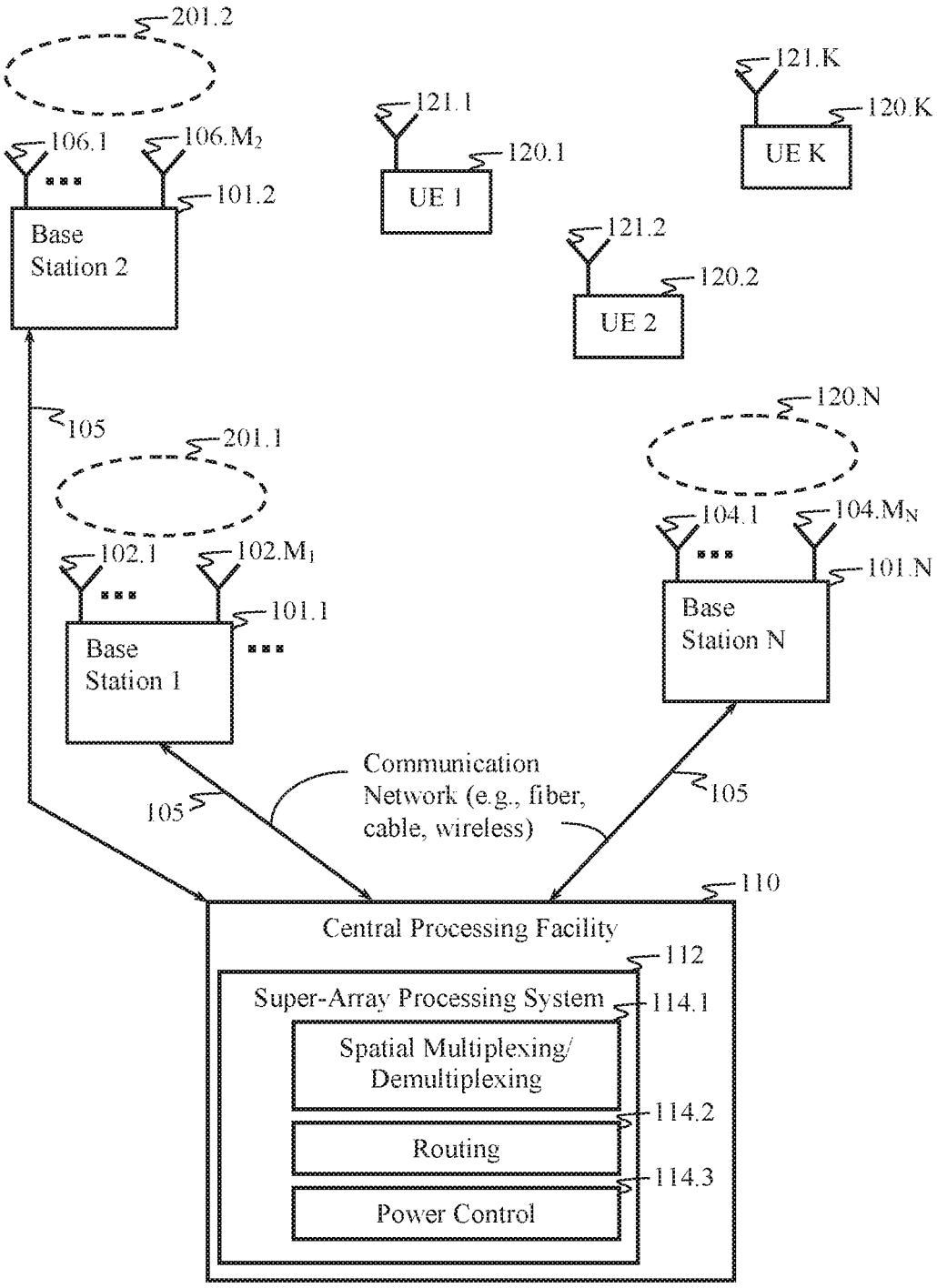
201.2
106.1
106.M2
101.2
Base Station 2
121.1
120.1
UE 1
121.K
120.K
UE K
121.2
120.2
UE 2
105
201.1
102.1
102.M1
101.1
Base Station 1
120.N
104.1
104.MN
101.N
Base Station N
Communication Network (e.g., fiber, cable, wireless)
105
105
110
Central Processing Facility
112
Super-Array Processing System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

Figure 2

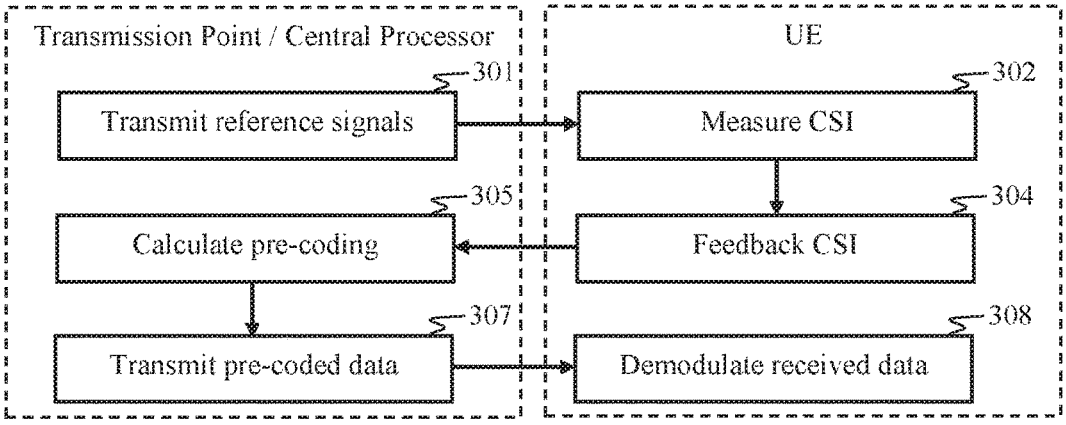

Figure 3A

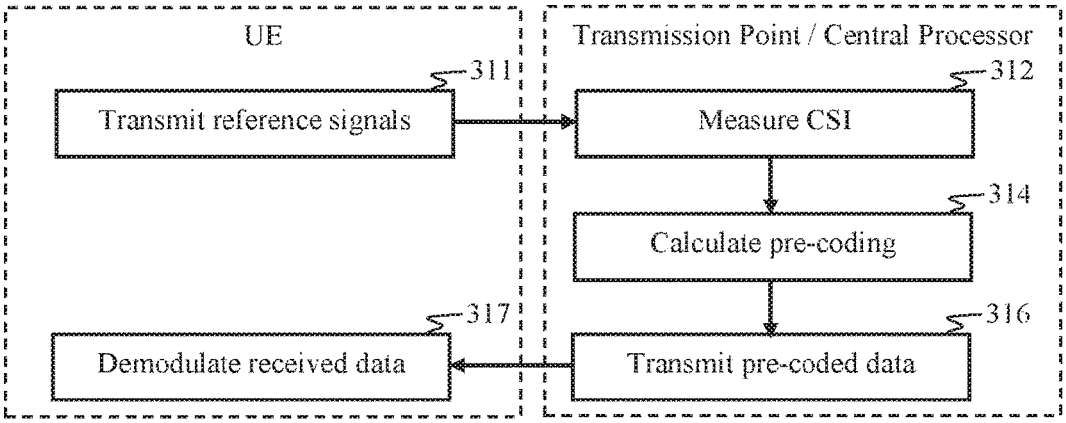

Figure 3B

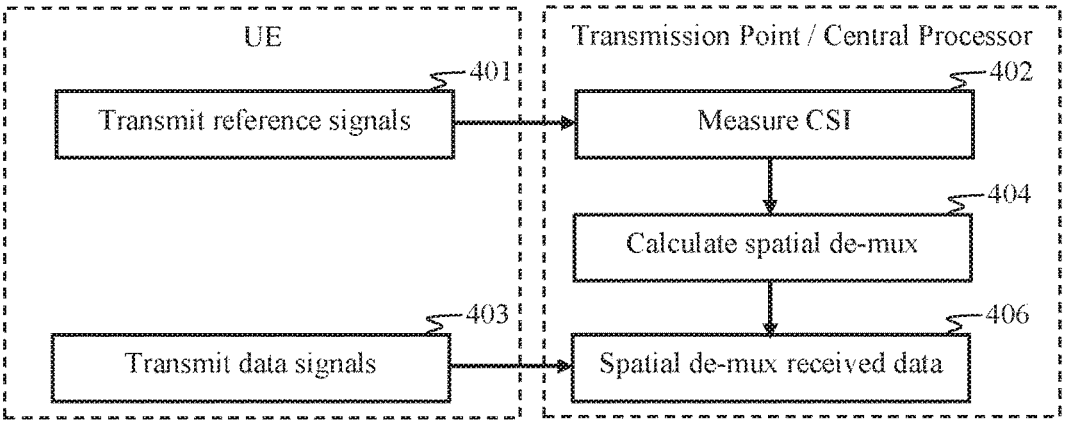

Figure 4A

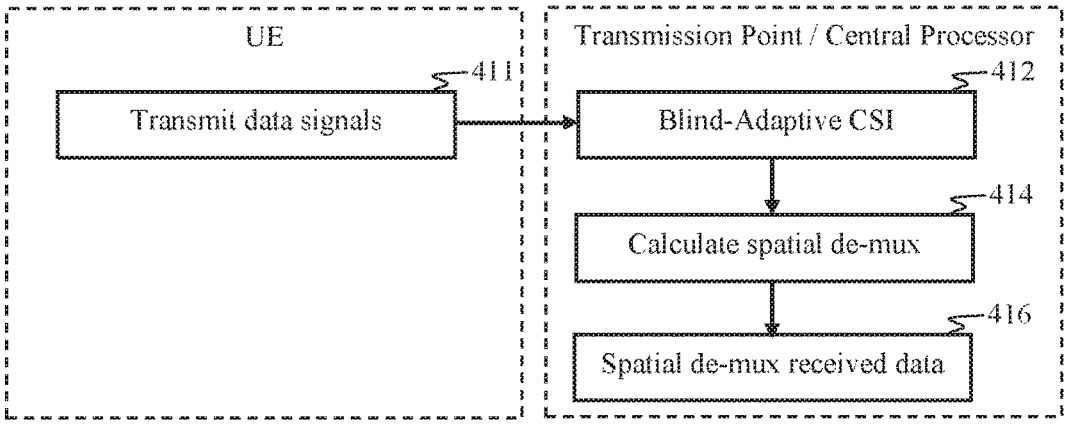

Figure 4B

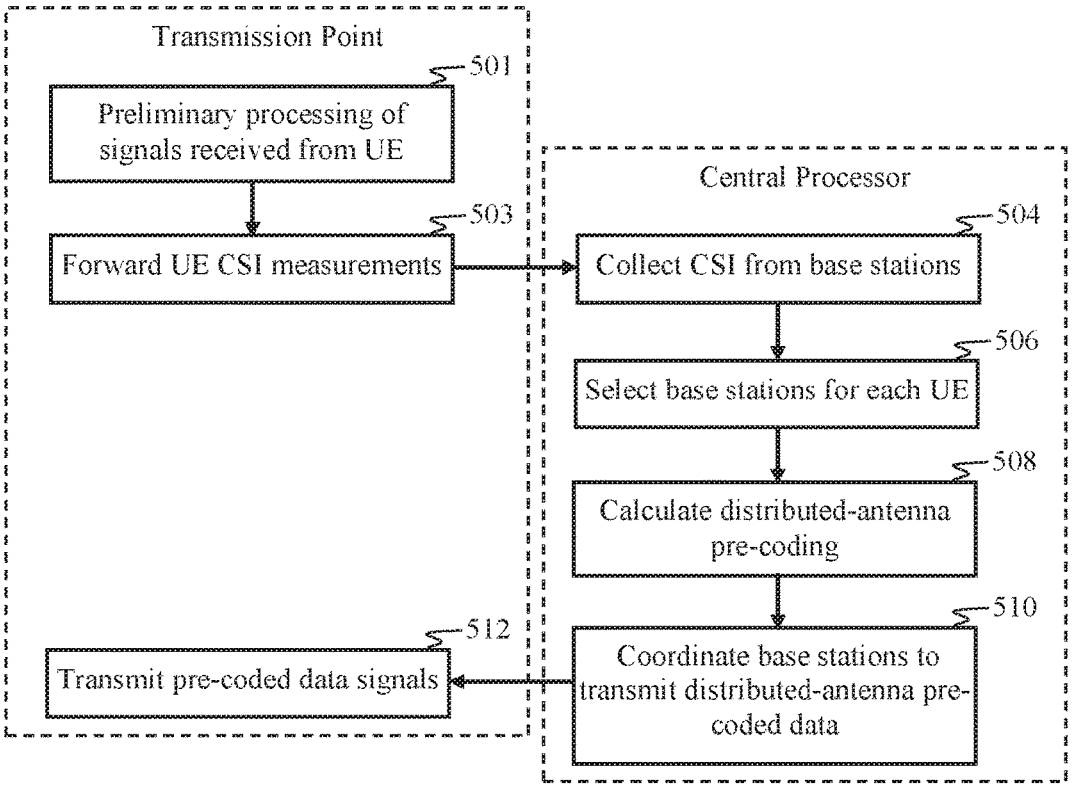
Transmission Point
501
Preliminary processing of signals received from UE
503
Forward UE CSI measurements
512
Transmit pre-coded data signals
Central Processor
504
Collect CSI from base stations
506
Select base stations for each UE
508
Calculate distributed-antenna pre-coding
510
Coordinate base stations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

Figure 5

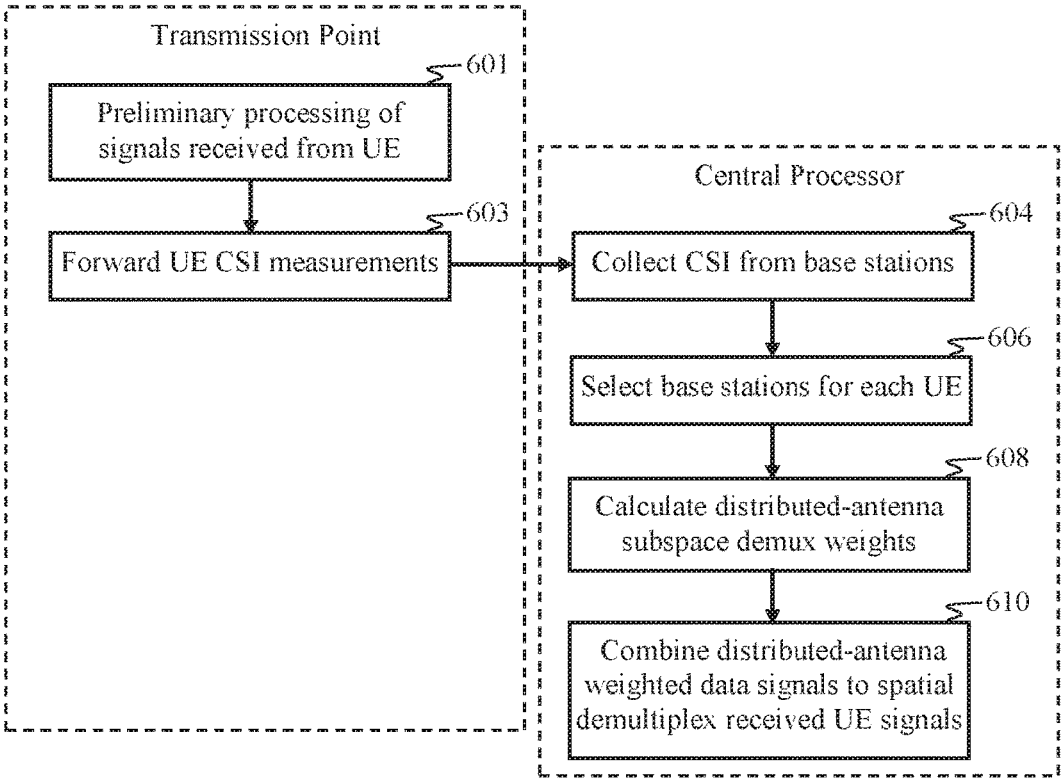
Transmission Point
601
Preliminary processing of signals received from UE
603
Forward UE CSI measurements
Central Processor
604
Collect CSI from base stations
606
Select base stations for each UE
608
Calculate distributed-antenna subspace demux weights
610
Combine distributed-antenna weighted data signals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

Figure 6

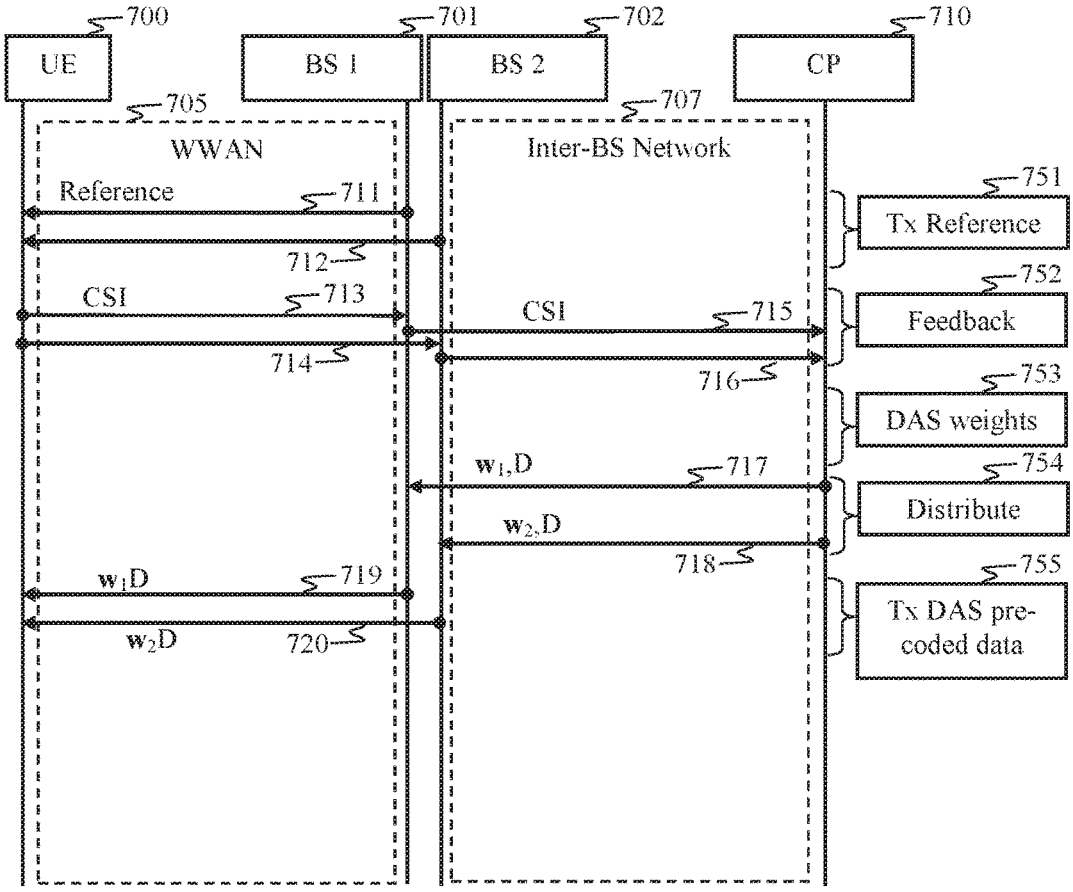
700
UE
701
BS 1
702
BS 2
710
CP
705
WWAN
707
Inter-BS Network
Reference
711
712
CSI
713
714
CSI
715
716
751
Tx Reference
752
Feedback
753
DAS weights
754
Distribute
755
Tx DAS pre-coded data
w1,D
717
w2,D
718
w1D
719
w2D
720

Figure 7

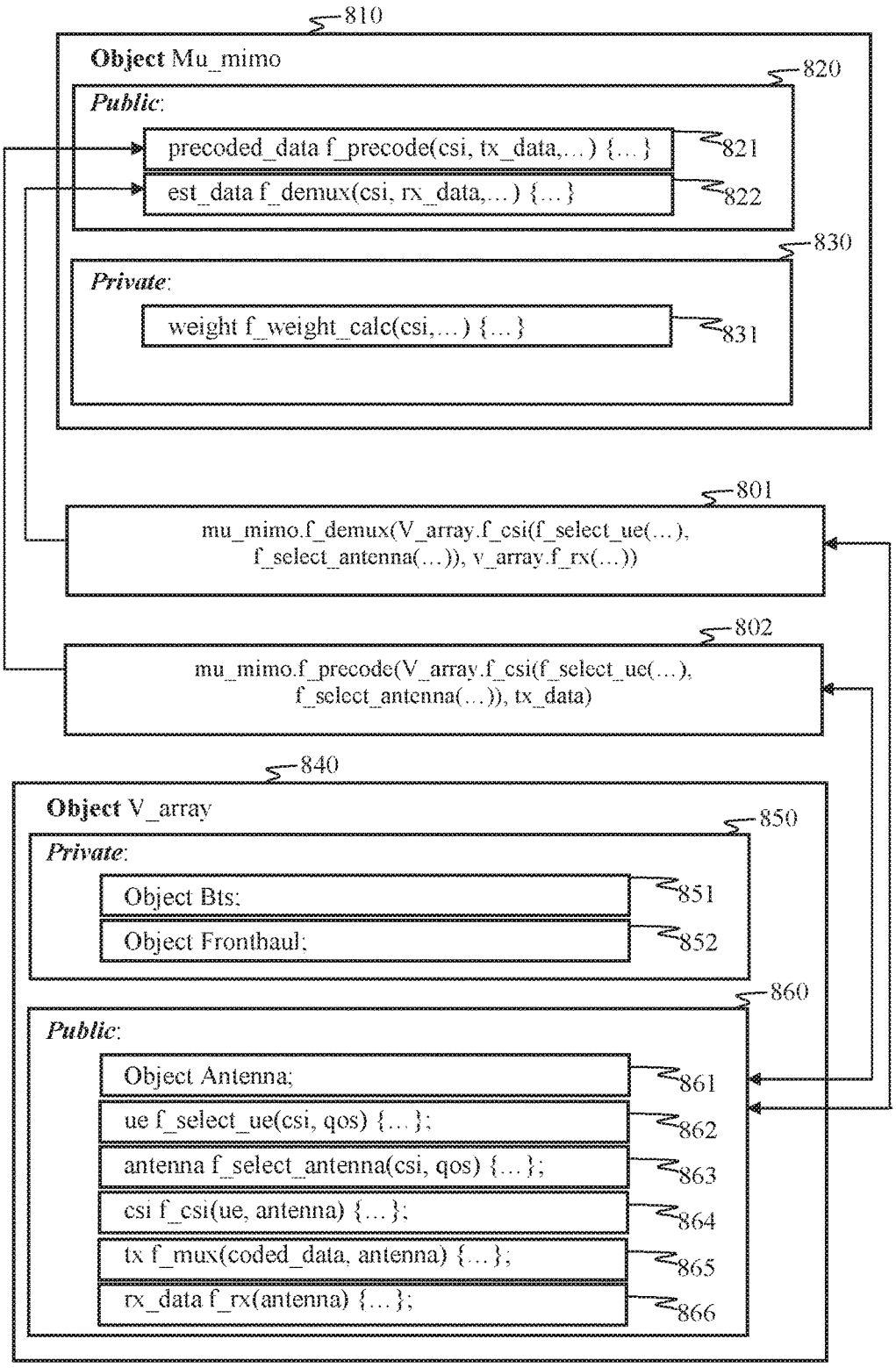
810
Object Mu_mimo
820
Public:
precoded_data f_precode(csi, tx_data,…) {…}
821
est_data f_demux(csi, rx_data,…) {…}
822
830
Private:
weight f_weight_calc(csi,…) {…}
831
801
mu_mimo.f_demux(V_array.f_csi(f_select_ue(…), f_select_antenna(…)), v_array.f_rx(…))
802
mu_mimo.f_precode(V_array.f_csi(f_select_ue(…), 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

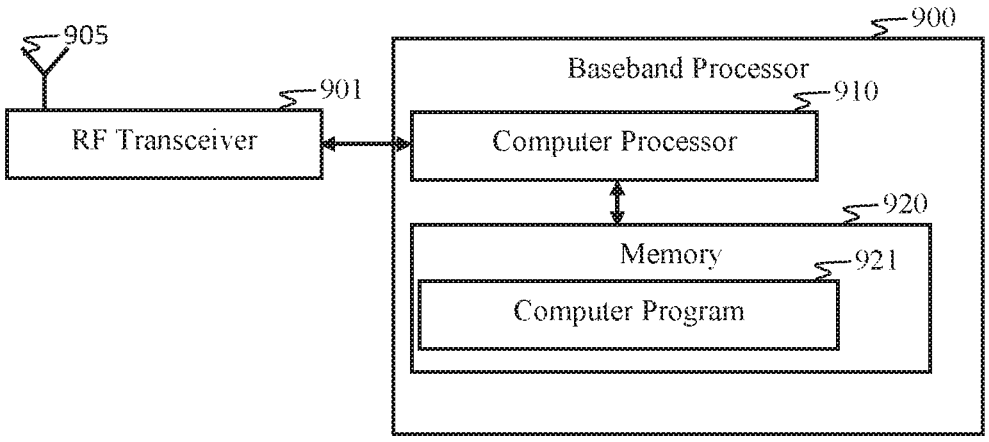
905
900
Baseband Processor
901
910
RF Transceiver
Computer Processor
920
Memory
921
Computer Program

Figure 9

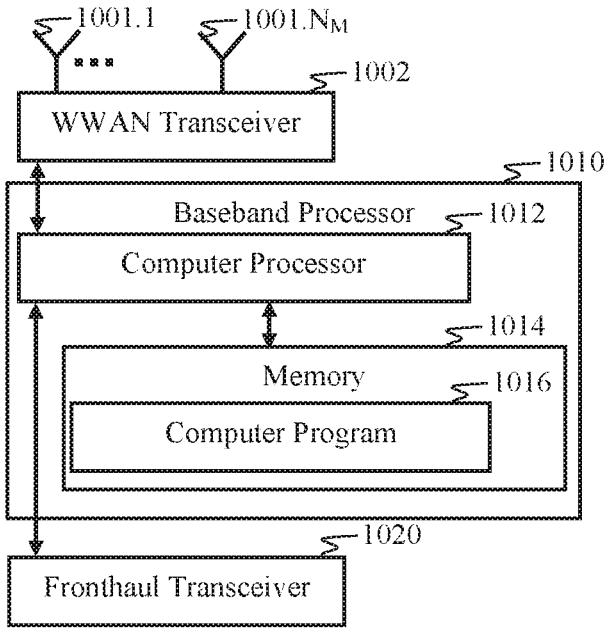
1001.1
1001.N_M
1002
WWAN Transceiver
1010
Baseband Processor
1012
Computer Processor
1014
Memory
1016
Computer Program
1020
Fronthaul Transceiver

Figure 10

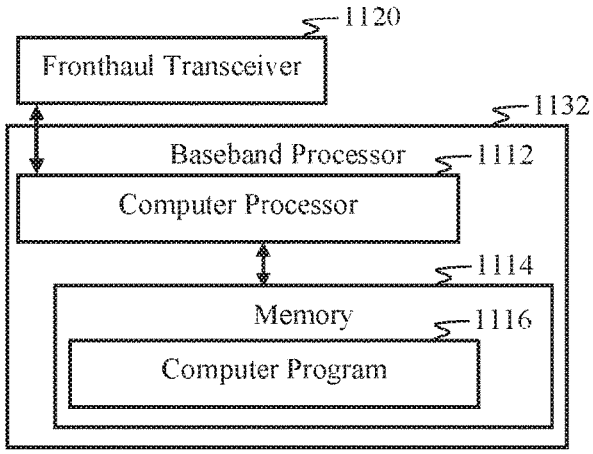

Figure 11A

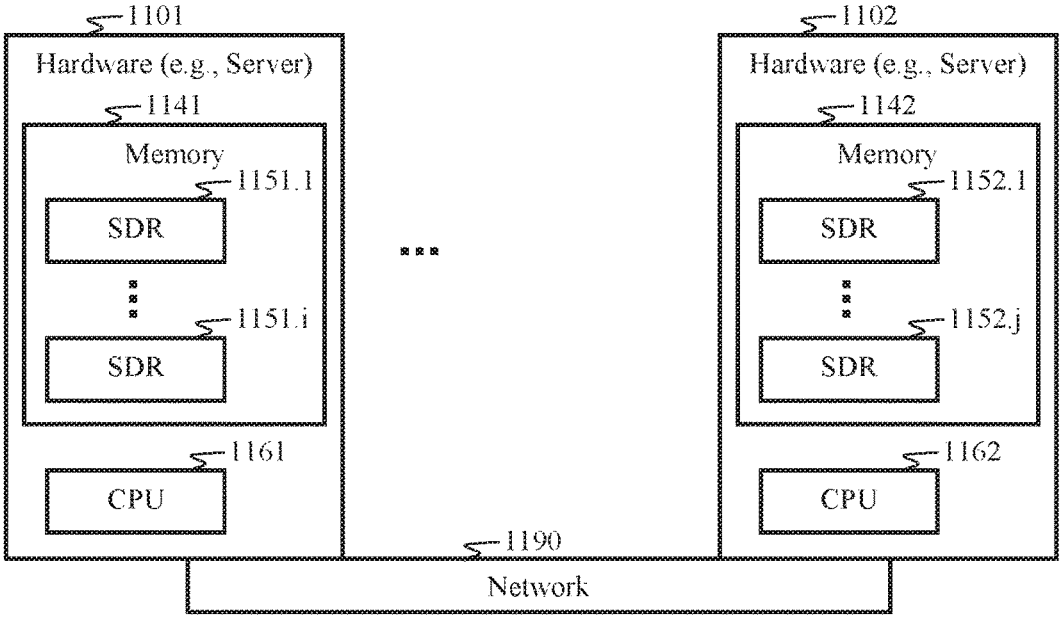

Figure 11B

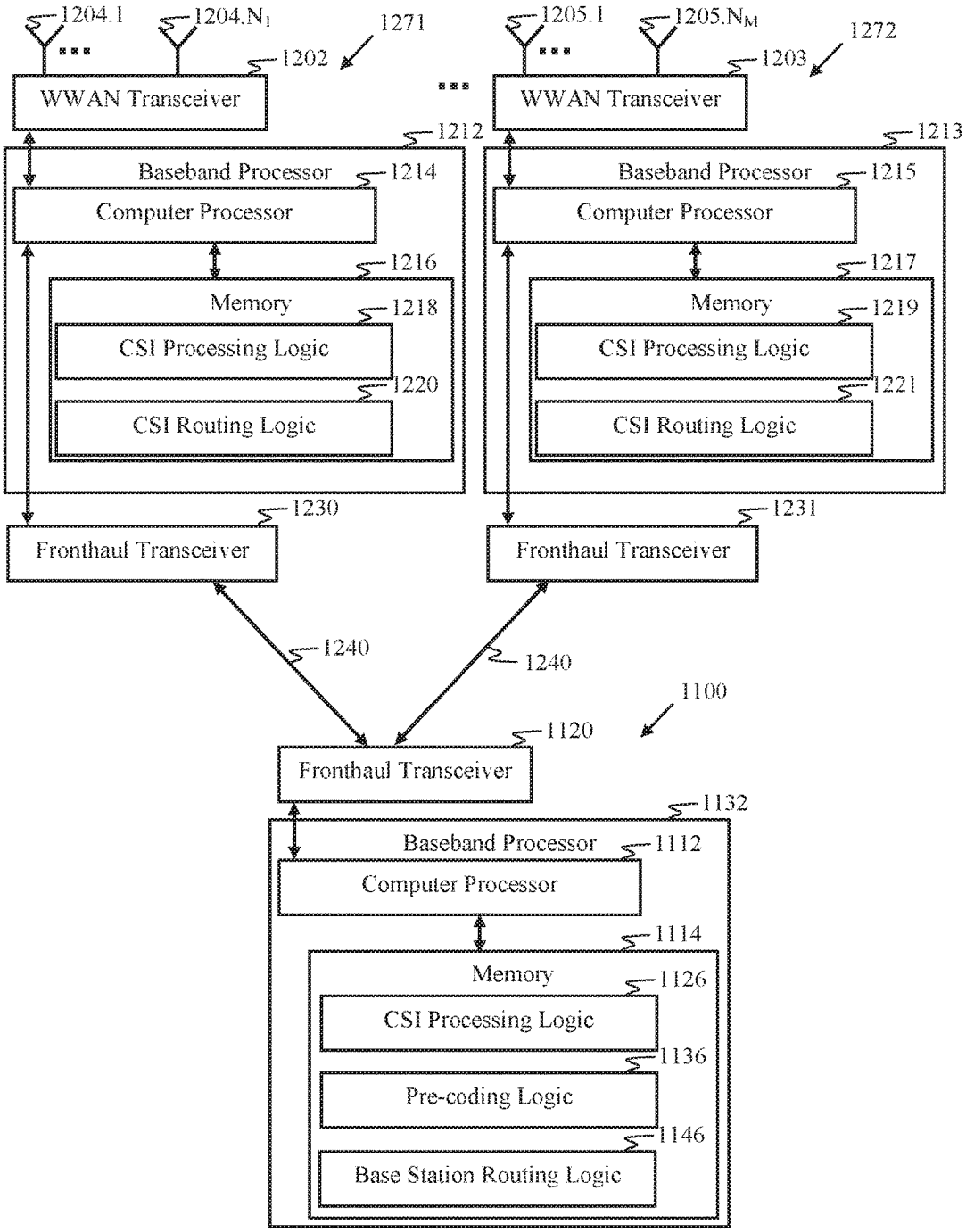
1204.1
1204.N1
1271
1205.1
1205.NM
1272
1202
1203
WWAN Transceiver
WWAN Transceiver
1212
1213
Baseband Processor
1214
Baseband Processor
1215
Computer Processor
Computer Processor
1216
1217
Memory
1218
Memory
1219
CSI Processing Logic
CSI Processing Logic
1220
1221
CSI Routing Logic
CSI Routing Logic
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

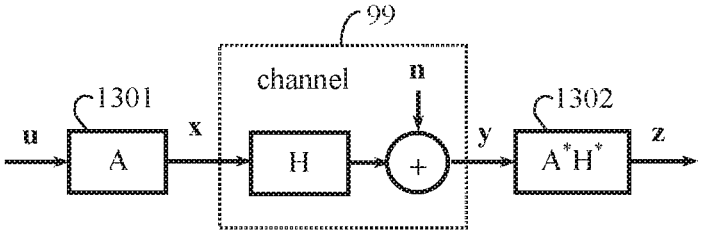

Figure 13A

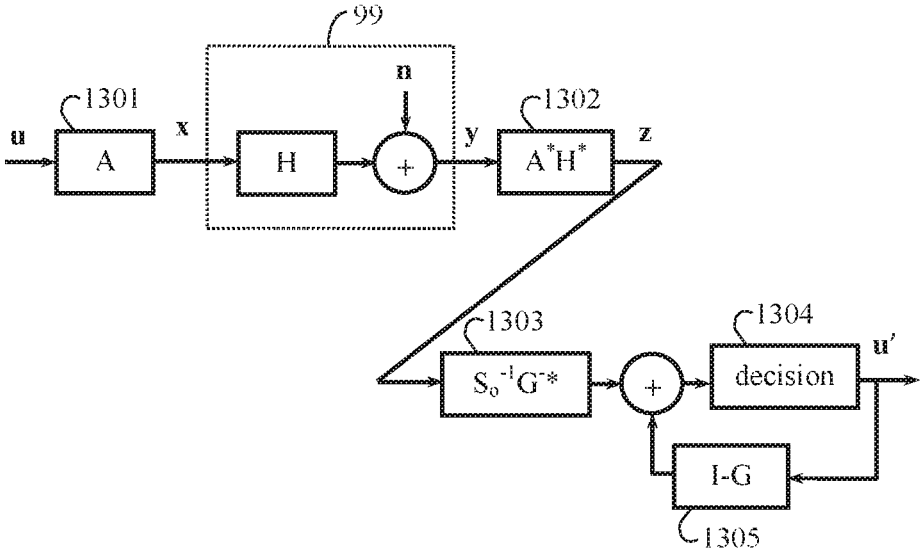

Figure 13B

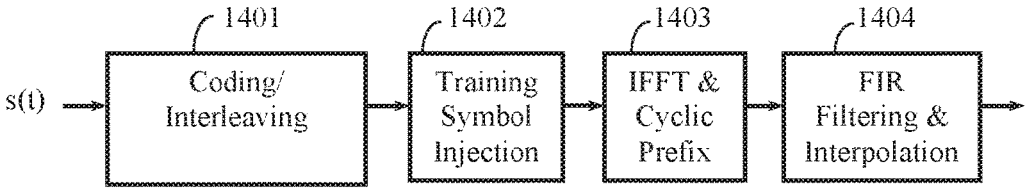

Figure 14A

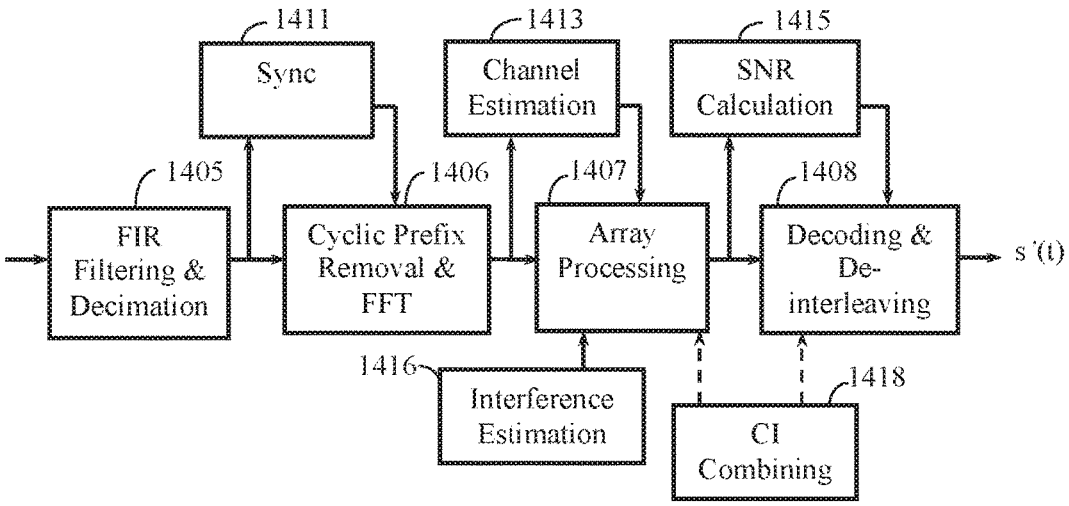

Figure 14B

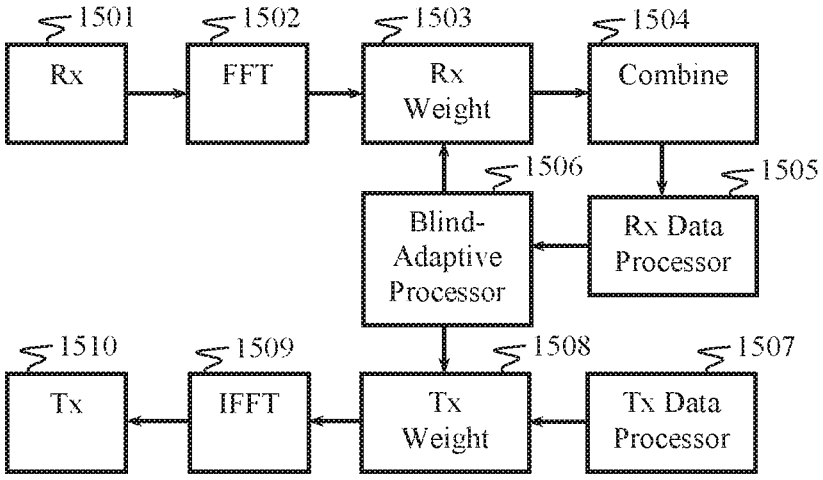
1501
Rx
1502
FFT
1503
Rx Weight
1504
Combine
1506
Blind-Adaptive Processor
1505
Rx Data Processor
1510
Tx
1509
IFFT
1508
Tx Weight
1507
Tx Data Processor

Figure 15

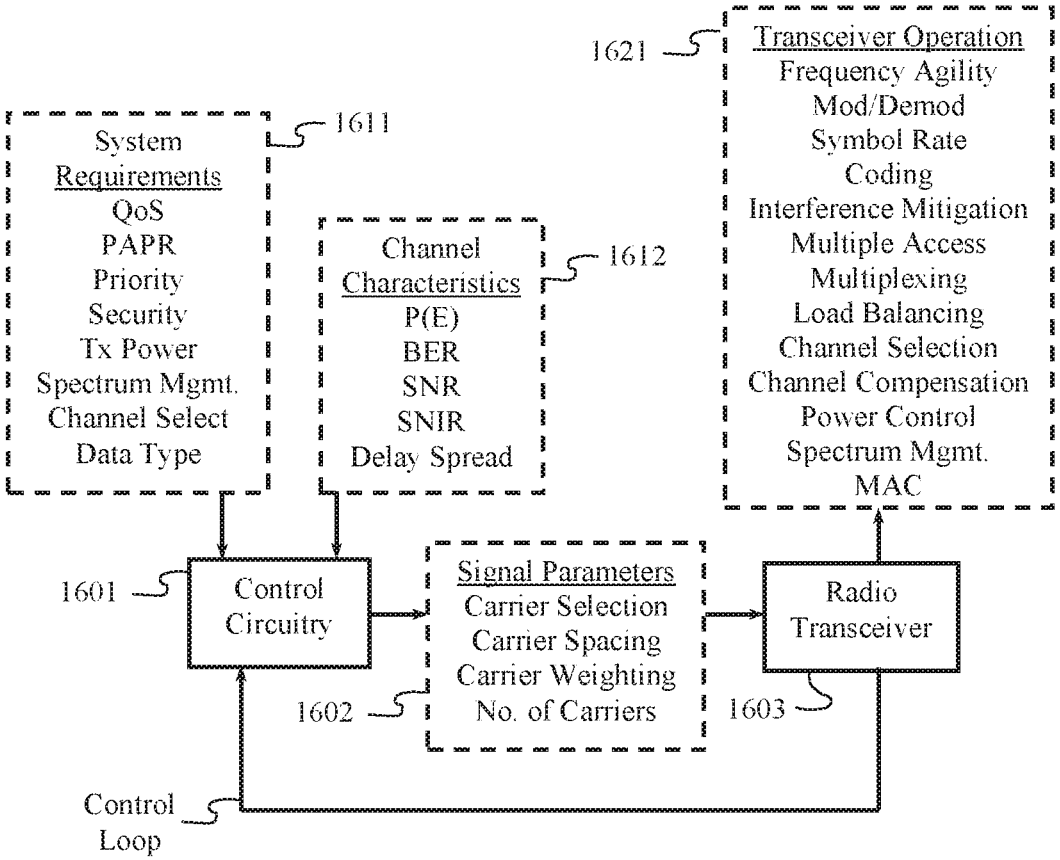
1621
Transceiver Operation
Frequency Agility
Mod/Demod
Symbol Rate
Coding
Interference Mitigation
Multiple Access
Multiplexing
Load Balancing
Channel Selection
Channel Compensation
Power Control
Spectrum Mgmt.
MAC
1611
System
Requirements
QoS
PAPR
Priority
Security
Tx Power
Spectrum Mgmt.
Channel Select
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

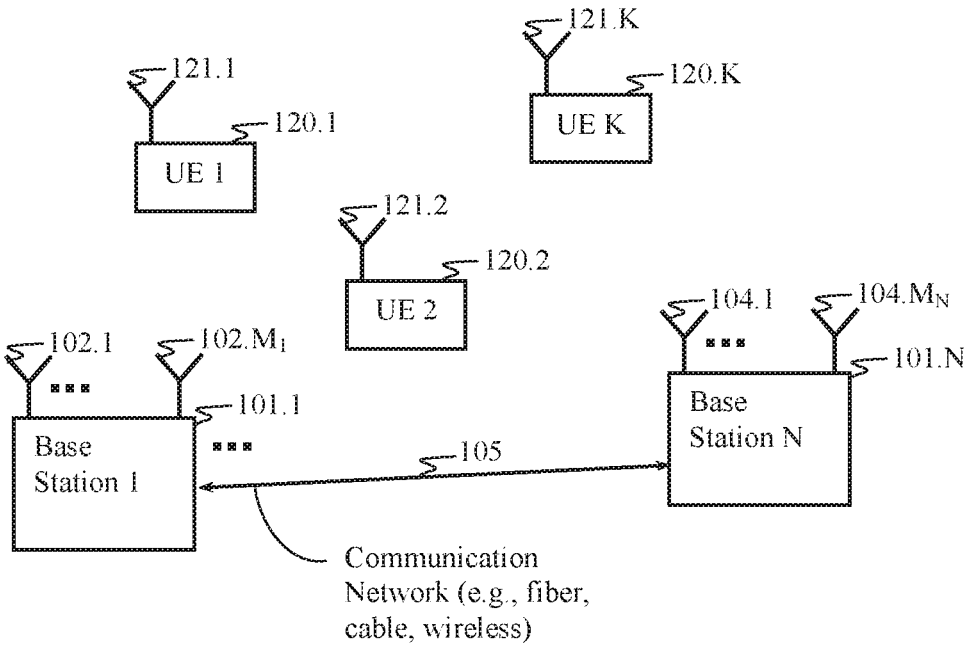
121.K
120.K
UE K
121.1
120.1
UE 1
121.2
120.2
UE 2
104.1
104.M_N
101.N
102.1
102.M_1
101.1
Base Station 1
Base Station N
105
Communication Network (e.g., fiber, cable, wireless)

Figure 17

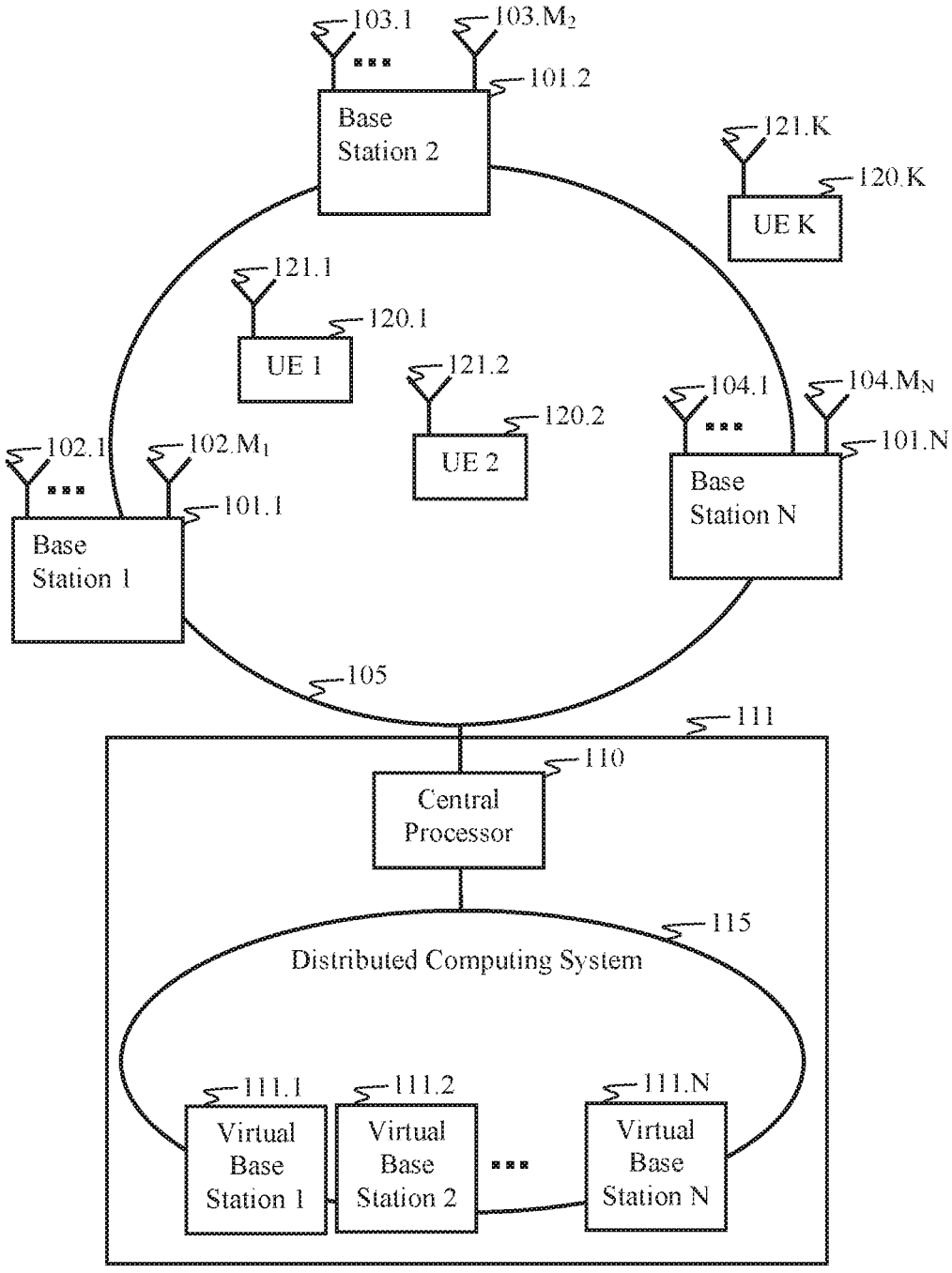
103.1
103.M2
101.2
Base Station 2
121.K
120.K
UE K
121.1
120.1
UE 1
121.2
120.2
UE 2
104.1
104.MN
101.N
Base Station N
102.1
102.M1
101.1
Base Station 1
105
111
110
Central Processor
115
Distributed Computing System
111.1
111.2
111.N
Virtual Base Station 1
Virtual Base Station 2
Virtual Base Station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

Figure 18

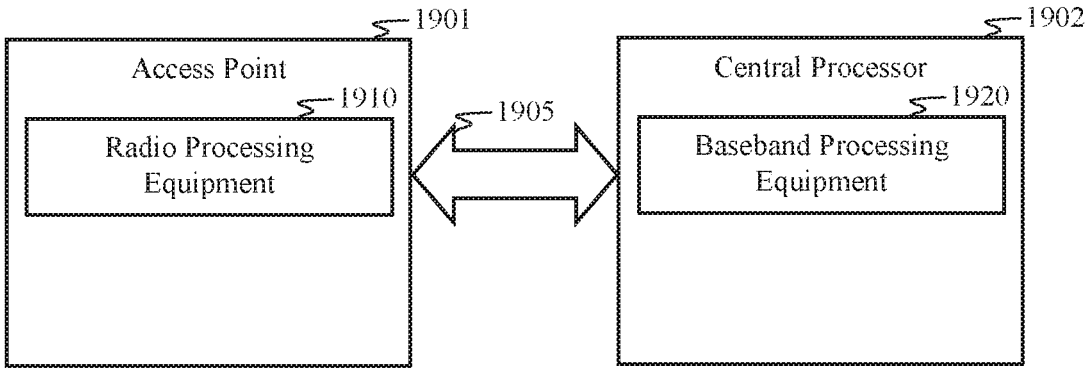
1901
Access Point
1910
Radio Processing Equipment
1905
1902
Central Processor
1920
Baseband Processing Equipment

Figure 19

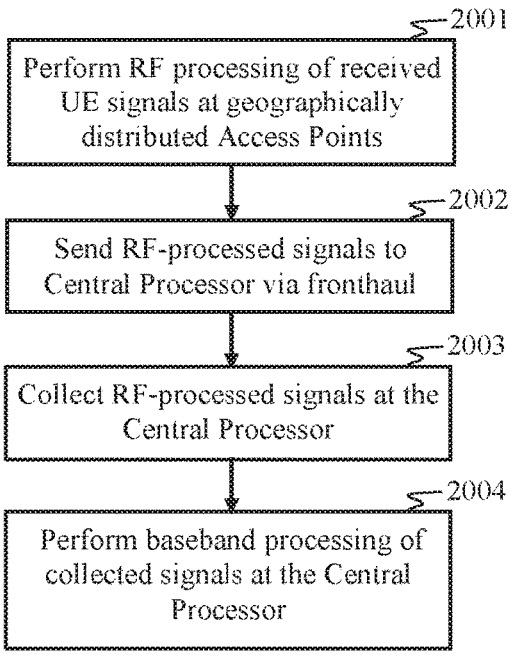

Figure 20A

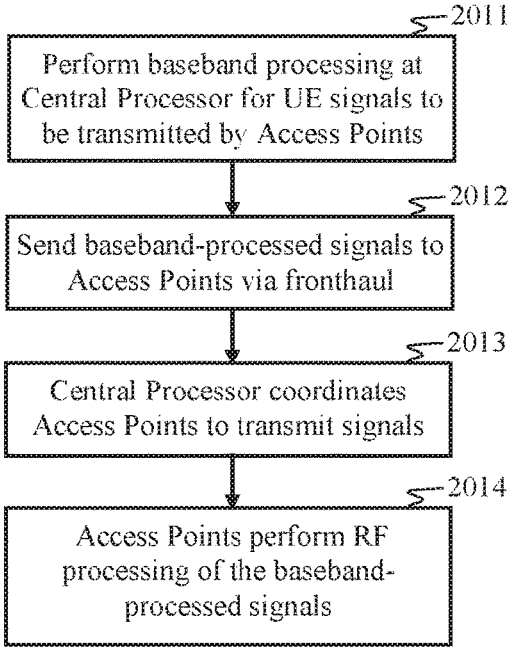

Figure 20B

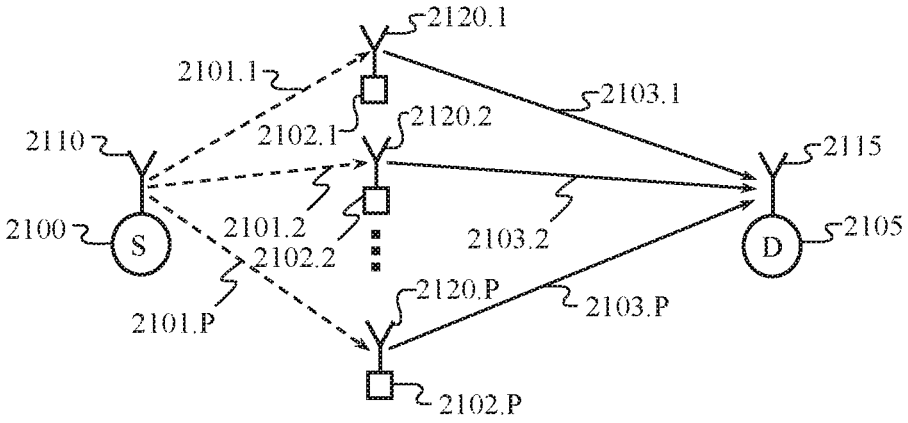
2120.1
2101.1
2103.1
2102.1
2120.2
2110
2115
2100
S
2101.2
2102.2
2103.2
D
2105
2120.P
2103.P
2101.P
2102.P

Figure 21

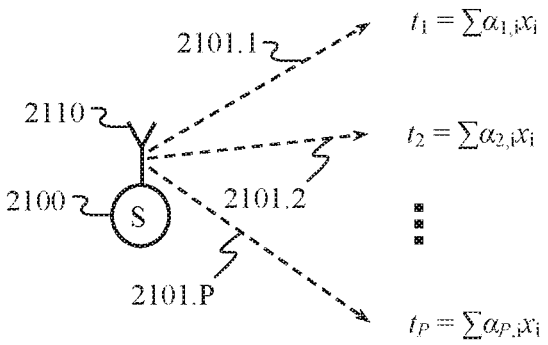

Figure 22A

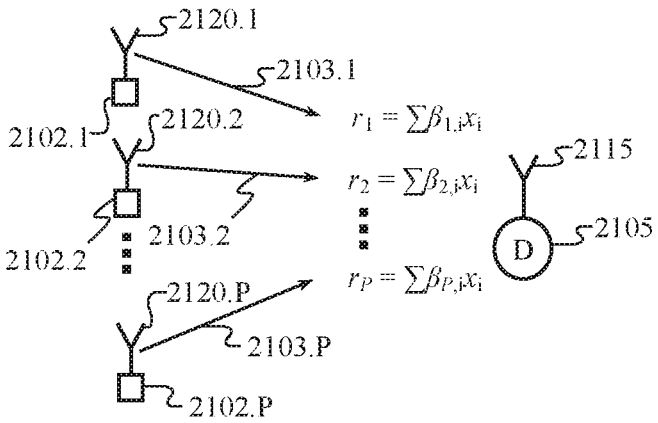

Figure 22B

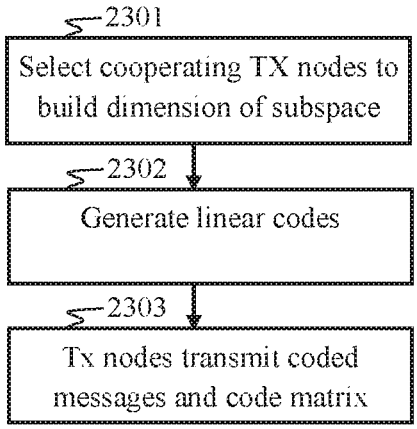

Figure 23A

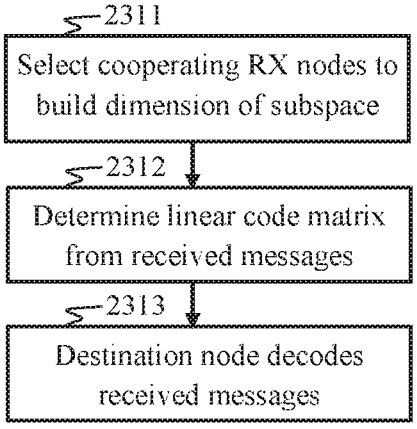

Figure 23B

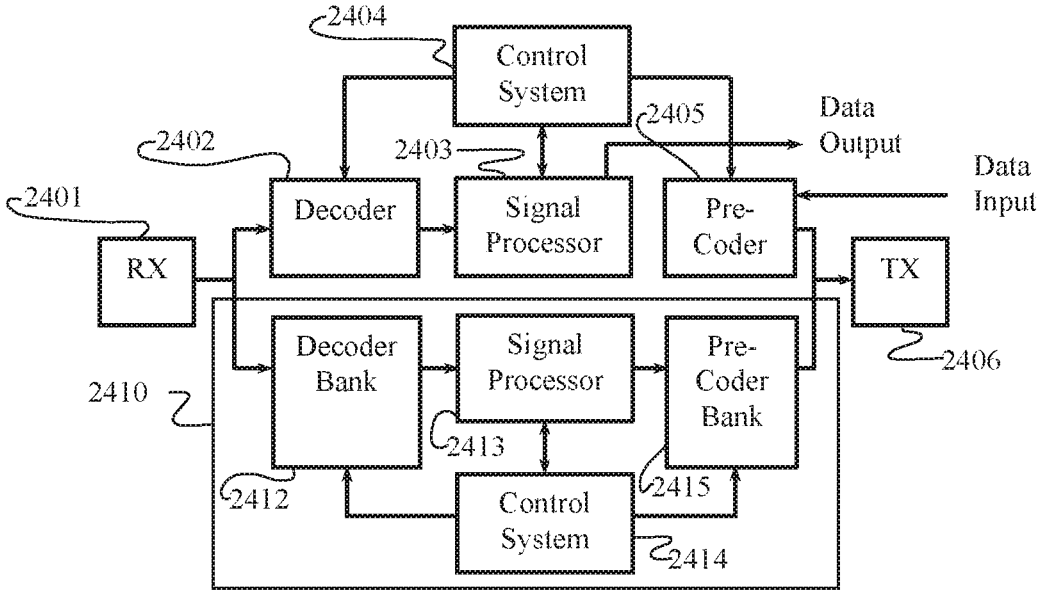

Figure 24A

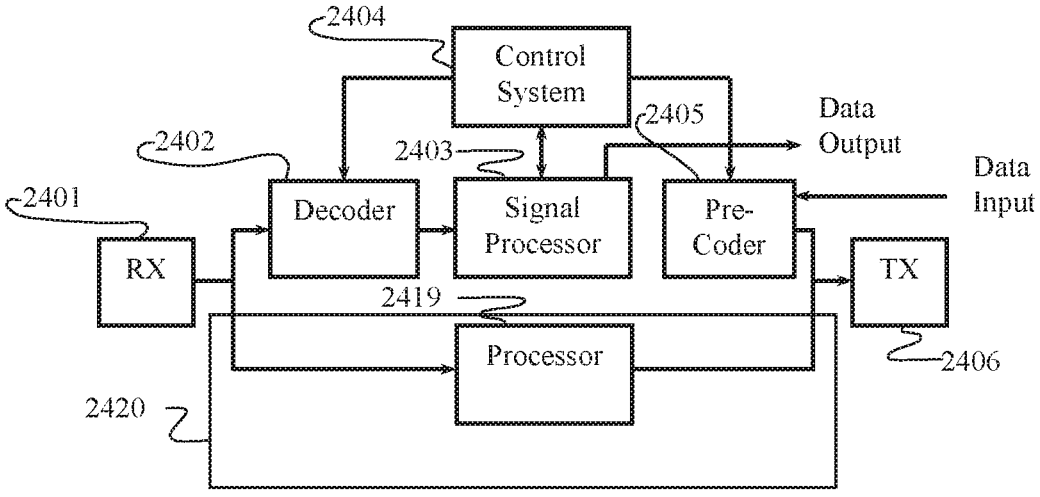

Figure 24B

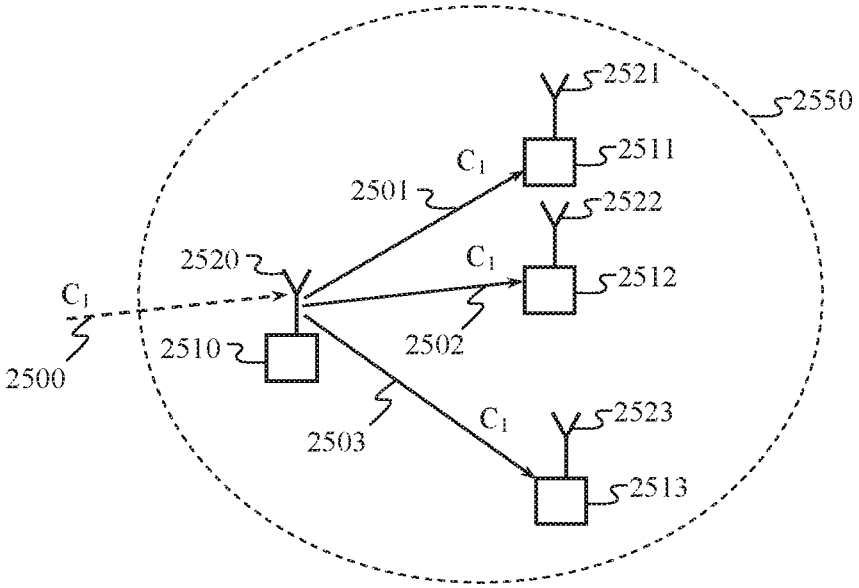

Figure 25A

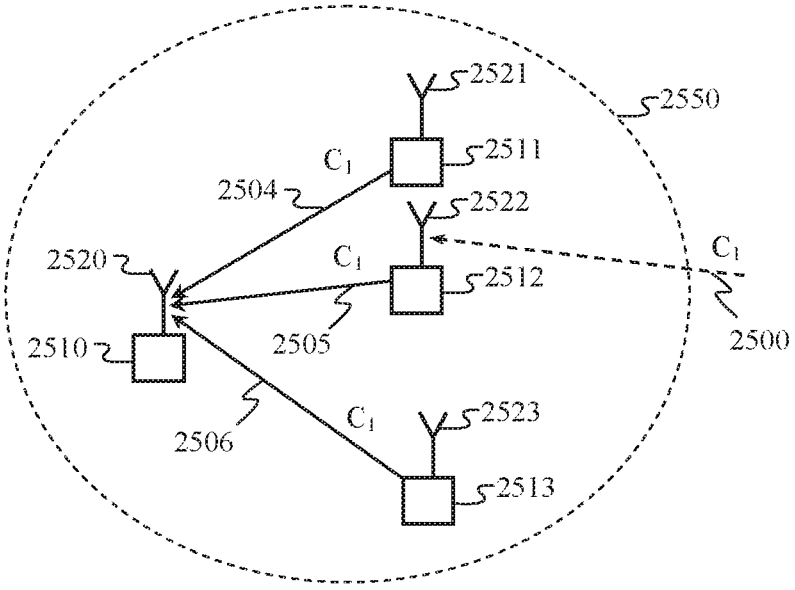

Figure 25B

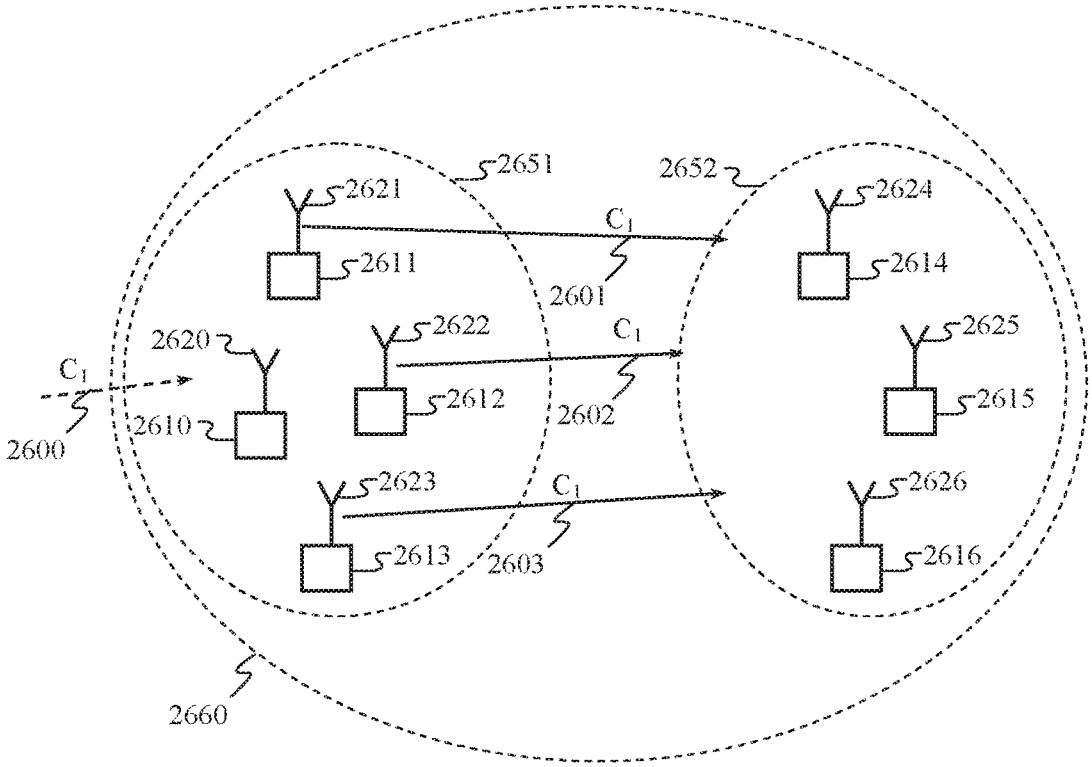
2651
2652
2621
2624
C1
2611
2601
2614
2620
2622
C1
2625
C1
2612
2602
2615
2610
2600
2623
C1
2626
2613
2603
2616
2660

Figure 26

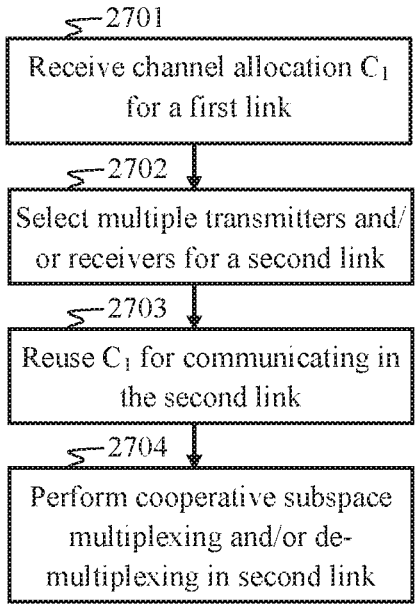
2701
Receive channel allocation C_1 for a first link
2702
Select multiple transmitters and/or receivers for a second link
2703
Reuse C_1 for communicating in the second link
2704
Perform cooperative subspace multiplexing and/or de-multiplexing in second link

Figure 27

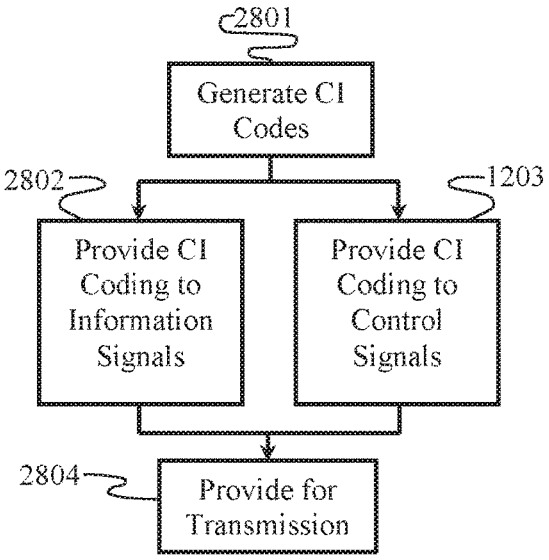

FIG. 28A

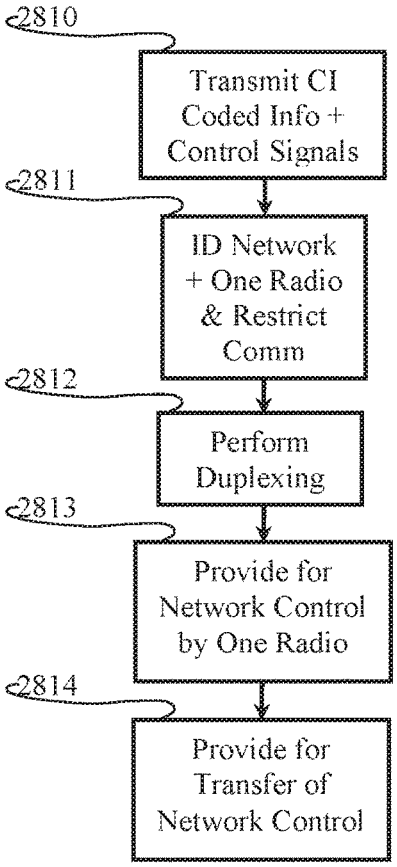

FIG. 28B

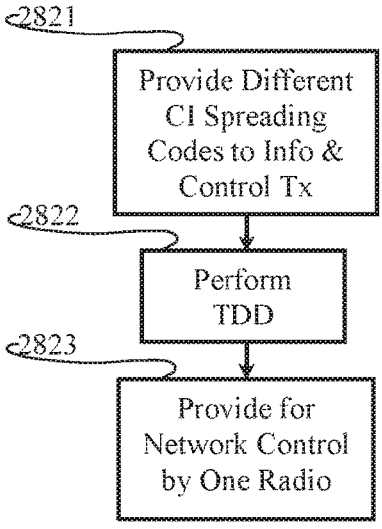

FIG. 28C

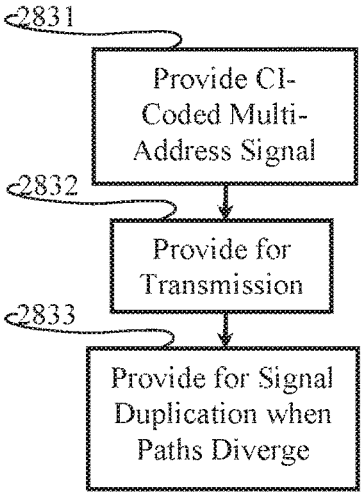

FIG. 28D

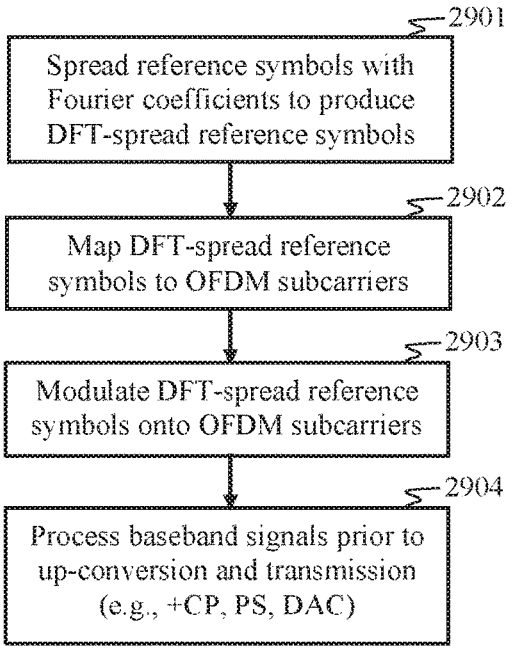

Figure 29A

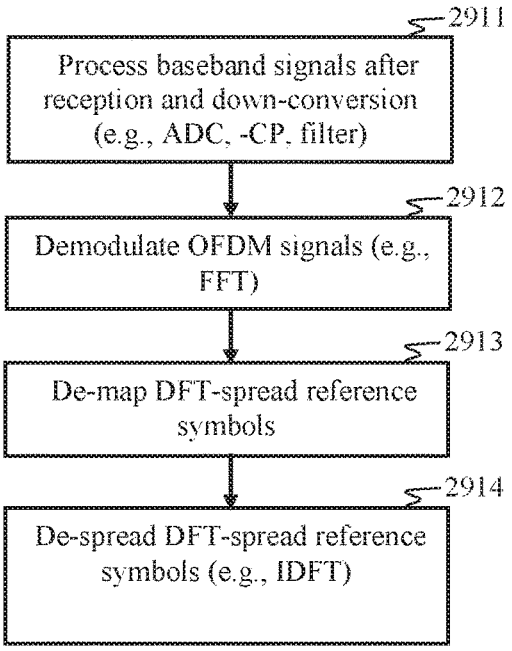

Figure 29B

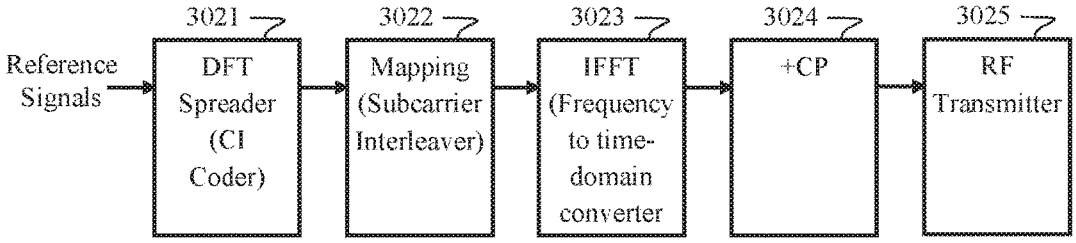

Figure 30A

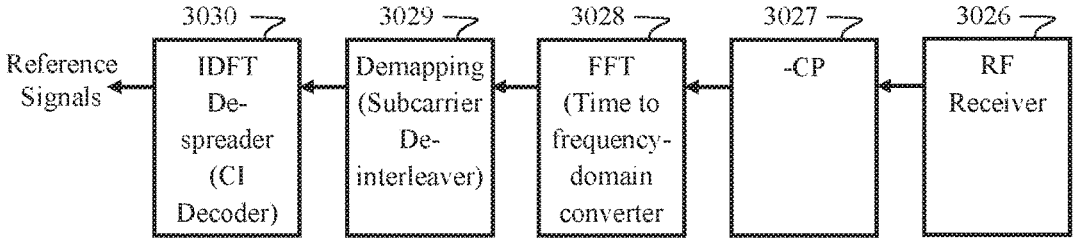

Figure 30B

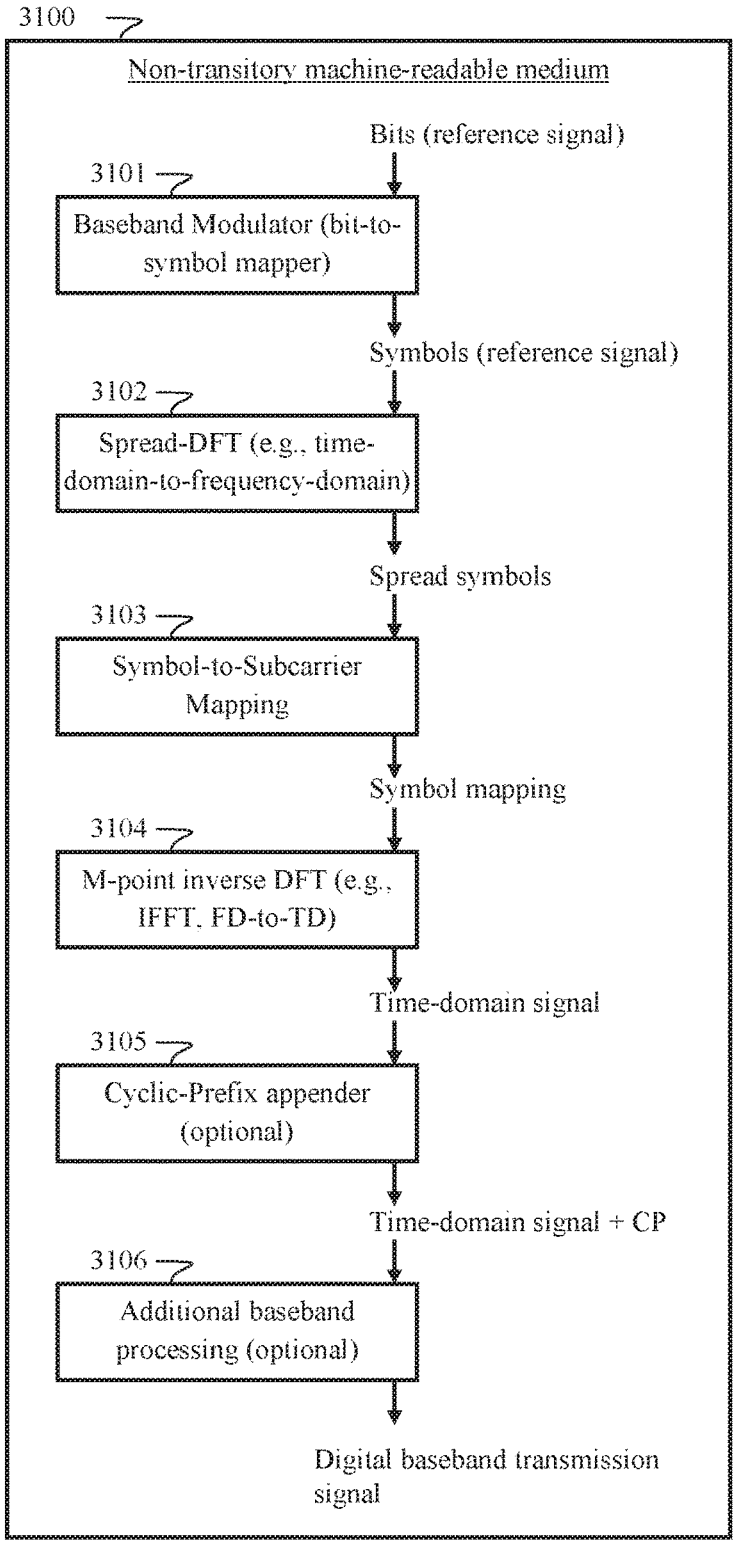
3100
Non-transitory machine-readable medium
Bits (reference signal)
3101
Baseband Modulator (bit-to-symbol mapper)
Symbols (reference signal)
3102
Spread-DFT (e.g., time-domain-to-frequency-domain)
Spread symbols
3103
Symbol-to-Subcarrier Mapping
Symbol mapping
3104
M-point inverse DFT (e.g., IFFT, FD-to-TD)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

Figure 31

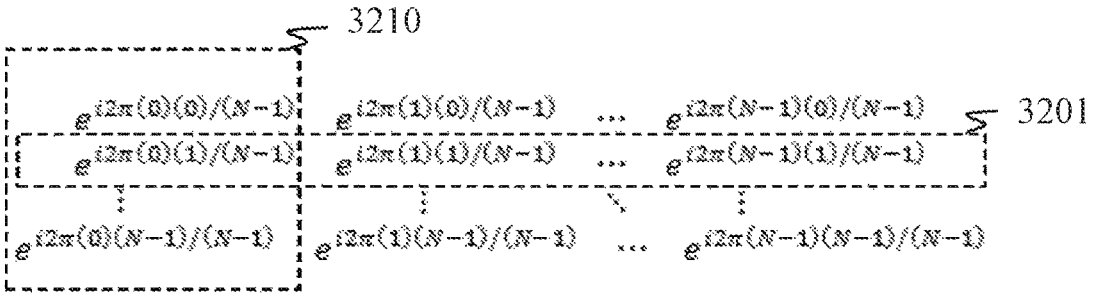
3210
3201
$e^{i2\pi(0)(0)/(N-1)}$ $e^{i2\pi(1)(0)/(N-1)}$ ... $e^{i2\pi(N-1)(0)/(N-1)}$
$e^{i2\pi(0)(1)/(N-1)}$ $e^{i2\pi(1)(1)/(N-1)}$ ... $e^{i2\pi(N-1)(1)/(N-1)}$
$e^{i2\pi(0)(N-1)/(N-1)}$ $e^{i2\pi(1)(N-1)/(N-1)}$ ... $e^{i2\pi(N-1)(N-1)/(N-1)}$

Figure 32

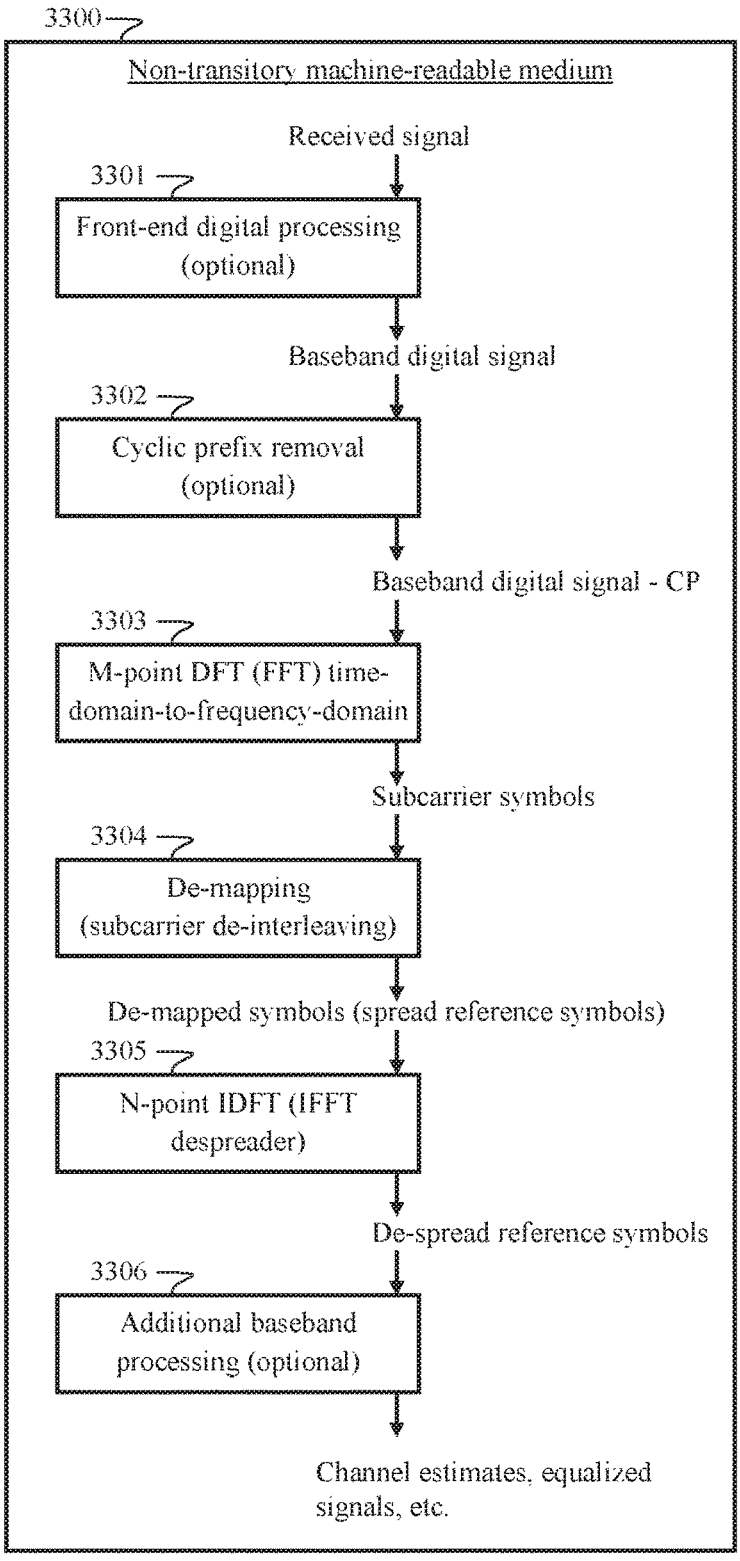
3300
Non-transitory machine-readable medium
Received signal
3301
Front-end digital processing (optional)
Baseband digital signal
3302
Cyclic prefix removal (optional)
Baseband digital signal - CP
3303
M-point DFT (FFT) time-domain-to-frequency-domain
Subcarrier symbols
3304
De-mapping (subcarrier de-interleaving)
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 N^{th} base station **101**.N may comprise an N^{th} 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 N^{th} 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 n^{th} 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 k^{th} 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 k^{th} 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 k^{th} 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-

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 p^{th} 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 p^{th} 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 k^{th} 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 j^{th} 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 k^{th} 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, . . . , 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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