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APPLICATION NO.	ISSUE DATE	PATENT NO.	ATTORNEY DOCKET NO.	CONFIRMATION NO.
17/105,576	08/30/2022	11431386	CBF-006.C3.2	5226

74284 7590 08/10/2022

Steven J Shattil
P.O. Box 17355
Boulder, CO 80308-0355

ISSUE NOTIFICATION

The projected patent number and issue date are specified above.

Determination of Patent Term Adjustment under 35 U.S.C. 154 (b)
(application filed on or after May 29, 2000)

The Patent Term Adjustment is 148 day(s). Any patent to issue from the above-identified application will include an indication of the adjustment on the front page.

If a Continued Prosecution Application (CPA) was filed in the above-identified application, the filing date that determines Patent Term Adjustment is the filing date of the most recent CPA.

Applicant will be able to obtain more detailed information by accessing the Patent Application Information Retrieval (PAIR) WEB site (http://pair.uspto.gov).

Any questions regarding the Patent Term Extension or Adjustment determination should be directed to the Office of Patent Legal Administration at (571)-272-7702. Questions relating to issue and publication fee payments should be directed to the Application Assistance Unit (AAU) of the Office of Patents Stakeholder Experience (OPSE), Stakeholder Support Division (SSD) at (571)-272-4200.

INVENTOR(s) (Please see PAIR WEB site http://pair.uspto.gov for additional inventors):

Steve Shattil, Cheyenne, WY;

APPLICANT(s) (Please see PAIR WEB site http://pair.uspto.gov for additional applicants):

Genghiscomm Holdings, LLC, Boulder, CO;

The United States represents the largest, most dynamic marketplace in the world and is an unparalleled location for business investment, innovation, and commercialization of new technologies. The USA offers tremendous resources and advantages for those who invest and manufacture goods here. Through SelectUSA, our nation works to encourage and facilitate business investment. To learn more about why the USA is the best country in the world to develop technology, manufacture products, and grow your business, visit SelectUSA.gov.

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NOTICE OF ALLOWANCE AND FEE(S) DUE

74284 7590 06/23/2022

Steven J Shattil
P.O. Box 17355
Boulder, CO 80308-0355

EXAMINER
CHOUDHRY, SAMINA F

ART UNIT	PAPER NUMBER
2462	

DATE MAILED: 06/23/2022

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
17/105,576	11/26/2020	Steve Shattil	CBF-006.C3.2	5226

TITLE OF INVENTION: Transmit Pre-Coding

APPLN. TYPE	ENTITY STATUS	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	SMALL	$600	$0.00	$0.00	$600	09/23/2022

THE APPLICATION IDENTIFIED ABOVE HAS BEEN EXAMINED AND IS ALLOWED FOR ISSUANCE AS A PATENT. PROSECUTION ON THE MERITS IS CLOSED. THIS NOTICE OF ALLOWANCE IS NOT A GRANT OF PATENT RIGHTS. THIS APPLICATION IS SUBJECT TO WITHDRAWAL FROM ISSUE AT THE INITIATIVE OF THE OFFICE OR UPON PETITION BY THE APPLICANT. SEE 37 CFR 1.313 AND MPEP 1308.

THE ISSUE FEE AND PUBLICATION FEE (IF REQUIRED) MUST BE PAID WITHIN THREE MONTHS FROM THE MAILING DATE OF THIS NOTICE OR THIS APPLICATION SHALL BE REGARDED AS ABANDONED. THIS STATUTORY PERIOD CANNOT BE EXTENDED. SEE 35 U.S.C. 151. THE ISSUE FEE DUE INDICATED ABOVE DOES NOT REFLECT A CREDIT FOR ANY PREVIOUSLY PAID ISSUE FEE IN THIS APPLICATION. IF AN ISSUE FEE HAS PREVIOUSLY BEEN PAID IN THIS APPLICATION (AS SHOWN ABOVE), THE RETURN OF PART B OF THIS FORM WILL BE CONSIDERED A REQUEST TO REAPPLY THE PREVIOUSLY PAID ISSUE FEE TOWARD THE ISSUE FEE NOW DUE.

HOW TO REPLY TO THIS NOTICE:

I. Review the ENTITY STATUS shown above. If the ENTITY STATUS is shown as SMALL or MICRO, verify whether entitlement to that entity status still applies.

If the ENTITY STATUS is the same as shown above, pay the TOTAL FEE(S) DUE shown above.

If the ENTITY STATUS is changed from that shown above, on PART B - FEE(S) TRANSMITTAL, complete section number 5 titled "Change in Entity Status (from status indicated above)".

For purposes of this notice, small entity fees are 1/2 the amount of undiscounted fees, and micro entity fees are 1/2 the amount of small entity fees.

II. PART B - FEE(S) TRANSMITTAL, or its equivalent, must be completed and returned to the United States Patent and Trademark Office (USPTO) with your ISSUE FEE and PUBLICATION FEE (if required). If you are charging the fee(s) to your deposit account, section "4b" of Part B - Fee(s) Transmittal should be completed. If an equivalent of Part B is filed, a request to reapply a previously paid issue fee must be clearly made, and delays in processing may occur due to the difficulty in recognizing the paper as an equivalent of Part B.

III. All communications regarding this application must give the application number. Please direct all communications prior to issuance to Mail Stop ISSUE FEE unless advised to the contrary.

IMPORTANT REMINDER: Maintenance fees are due in utility patents issuing on applications filed on or after Dec. 12, 1980. It is patentee's responsibility to ensure timely payment of maintenance fees when due. More information is available at www.uspto.gov/PatentMaintenanceFees.

Samsung Exhibit 1107, Page 2 of 401
Samsung Electronics Co., Ltd. et al. v. Genghiscomm Holdings LLC

PART B - FEE(S) TRANSMITTAL

Complete and send this form, together with applicable fee(s), by mail or fax, or via EFS-Web.

By mail, send to: Mail Stop ISSUE FEE
Commissioner for Patents
P.O. Box 1450
Alexandria, Virginia 22313-1450

By fax, send to: (571)-273-2885

INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE and PUBLICATION FEE (if required). Blocks 1 through 5 should be completed where appropriate. All further correspondence including the Patent, advance orders and notification of maintenance fees will be mailed to the current correspondence address as indicated unless corrected below or directed otherwise in Block 1, by (a) specifying a new correspondence address; and/or (b) indicating a separate "FEE ADDRESS" for maintenance fee notifications.

CURRENT CORRESPONDENCE ADDRESS (Note: Use Block 1 for any change of address)

74284 7590 06/23/2022

Steven J Shattil
P.O. Box 17355
Boulder, CO 80308-0355

Note: A certificate of mailing can only be used for domestic mailings of the Fee(s) Transmittal. This certificate cannot be used for any other accompanying papers. Each additional paper, such as an assignment or formal drawing, must have its own certificate of mailing or transmission.

Certificate of Mailing or Transmission

I hereby certify that this Fee(s) Transmittal is being deposited with the United States Postal Service with sufficient postage for first class mail in an envelope addressed to the Mail Stop ISSUE FEE address above, or being transmitted to the USPTO via EFS-Web or by facsimile to (571) 273-2885, on the date below.

(Typed or printed name)
(Signature)
(Date)

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
17/105,576	11/26/2020	Steve Shattil	CBF-006.C3.2	5226

TITLE OF INVENTION: Transmit Pre-Coding

APPLN. TYPE	ENTITY STATUS	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	SMALL	$600	$0.00	$0.00	$600	09/23/2022

EXAMINER	ART UNIT	CLASS-SUBCLASS
CHOUDHRY, SAMINA F	2462	370-329000

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363).

❑ Change of correspondence address (or Change of Correspondence Address form PTO/AIA/122 or PTO/SB/122) attached.

❑ "Fee Address" indication (or "Fee Address" Indication form PTO/AIA/47 or PTO/SB/47; Rev 03-02 or more recent) attached. **Use of a Customer Number is required.**

2. For printing on the patent front page, list
(1) The names of up to 3 registered patent attorneys or agents OR, alternatively,
(2) The name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed.

1 _____
2 _____
3 _____

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)

PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. If an assignee is identified below, the document must have been previously recorded, or filed for recordation, as set forth in 37 CFR 3.11 and 37 CFR 3.81(a). Completion of this form is NOT a substitute for filing an assignment.

(A) NAME OF ASSIGNEE (B) RESIDENCE: (CITY and STATE OR COUNTRY)

Please check the appropriate assignee category or categories (will not be printed on the patent) : ❑ Individual ❑ Corporation or other private group entity ❑ Government

4a. Fees submitted: ❑ Issue Fee ❑ Publication Fee (if required) ❑ Advance Order - # of Copies _____

4b. Method of Payment: *(Please first reapply any previously paid fee shown above)*

❑ Electronic Payment via EFS-Web ❑ Enclosed check ❑ Non-electronic payment by credit card (Attach form PTO-2038)

❑ The Director is hereby authorized to charge the required fee(s), any deficiency, or credit any overpayment to Deposit Account No. _____

5. **Change in Entity Status** (from status indicated above)

❑ Applicant certifying micro entity status. See 37 CFR 1.29

❑ Applicant asserting small entity status. See 37 CFR 1.27

❑ Applicant changing to regular undiscounted fee status.

NOTE: Absent a valid certification of Micro Entity Status (see forms PTO/SB/15A and 15B), issue fee payment in the micro entity amount will not be accepted at the risk of application abandonment.
NOTE: If the application was previously under micro entity status, checking this box will be taken to be a notification of loss of entitlement to micro entity status.
NOTE: Checking this box will be taken to be a notification of loss of entitlement to small or micro entity status, as applicable.

NOTE: This form must be signed in accordance with 37 CFR 1.31 and 1.33. See 37 CFR 1.4 for signature requirements and certifications.

Authorized Signature _____ Date _____

Typed or printed name _____ Registration No. _____

Samsung Electronics Co., Ltd. et al. v. Geneva Scientific Holdings LLC

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
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APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
17/105,576	11/26/2020	Steve Shattil	CBF-006.C3.2	5226

74284 7590 06/23/2022

Steven J Shattil
P.O. Box 17355
Boulder, CO 80308-0355

EXAMINER	
CHOUDHRY, SAMINA F	
ART UNIT	PAPER NUMBER
2462	

DATE MAILED: 06/23/2022

Determination of Patent Term Adjustment under 35 U.S.C. 154 (b)
(Applications filed on or after May 29, 2000)

The Office has discontinued providing a Patent Term Adjustment (PTA) calculation with the Notice of Allowance.

Section 1(h)(2) of the AIA Technical Corrections Act amended 35 U.S.C. 154(b)(3)(B)(i) to eliminate the requirement that the Office provide a patent term adjustment determination with the notice of allowance. See Revisions to Patent Term Adjustment, 78 Fed. Reg. 19416, 19417 (Apr. 1, 2013). Therefore, the Office is no longer providing an initial patent term adjustment determination with the notice of allowance. The Office will continue to provide a patent term adjustment determination with the Issue Notification Letter that is mailed to applicant approximately three weeks prior to the issue date of the patent, and will include the patent term adjustment on the patent. Any request for reconsideration of the patent term adjustment determination (or reinstatement of patent term adjustment) should follow the process outlined in 37 CFR 1.705.

Any questions regarding the Patent Term Extension or Adjustment determination should be directed to the Office of Patent Legal Administration at (571)-272-7702. Questions relating to issue and publication fee payments should be directed to the Customer Service Center of the Office of Patent Publication at 1-(888)-786-0101 or (571)-272-4200.

Samsung Exhibit 1107, Page 4 of 401
Samsung Electronics Co., Ltd. et al. v. Genghiscomm Holdings LLC

OMB Clearance and PRA Burden Statement for PTOL-85 Part B

The Paperwork Reduction Act (PRA) of 1995 requires Federal agencies to obtain Office of Management and Budget approval before requesting most types of information from the public. When OMB approves an agency request to collect information from the public, OMB (i) provides a valid OMB Control Number and expiration date for the agency to display on the instrument that will be used to collect the information and (ii) requires the agency to inform the public about the OMB Control Number's legal significance in accordance with 5 CFR 1320.5(b).

The information collected by PTOL-85 Part B is required by 37 CFR 1.311. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 30 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, Virginia 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, Virginia 22313-1450. Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

Notice of Allowability	Application No. 17/105,576	Applicant(s) Shattil, Steve	
	Examiner SAMINA F CHOUDHRY	Art Unit 2462	AIA (FITF) Status No

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address--

All claims being allowable, PROSECUTION ON THE MERITS IS (OR REMAINS) CLOSED in this application. If not included herewith (or previously mailed), a Notice of Allowance (PTOL-85) or other appropriate communication will be mailed in due course. **THIS NOTICE OF ALLOWABILITY IS NOT A GRANT OF PATENT RIGHTS.** This application is subject to withdrawal from issue at the initiative of the Office or upon petition by the applicant. See 37 CFR 1.313 and MPEP 1308.

1. ☑ This communication is responsive to 07/31/2021.
   ☐ A declaration(s)/affidavit(s) under **37 CFR 1.130(b)** was/were filed on _____.

2. ☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.

3. ☑ The allowed claim(s) is/are 1-27 . As a result of the allowed claim(s), you may be eligible to benefit from the **Patent Prosecution Highway** program at a participating intellectual property office for the corresponding application. For more information, please see **http://www.uspto.gov/patents/init_events/pph/index.jsp** or send an inquiry to **PPHfeedback@uspto.gov.**

4. ☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

   Certified copies:

   a) ☐ All b) ☐ Some* c) ☐ None of the:

   1. ☐ Certified copies of the priority documents have been received.
   2. ☐ Certified copies of the priority documents have been received in Application No. _____ .
   3. ☐ Copies of the certified copies of the priority documents have been received in this national stage application from the International Bureau (PCT Rule 17.2(a)).

   * Certified copies not received: _____ .

Applicant has THREE MONTHS FROM THE "MAILING DATE" of this communication to file a reply complying with the requirements noted below. Failure to timely comply will result in ABANDONMENT of this application.
THIS THREE-MONTH PERIOD IS NOT EXTENDABLE.

5. ☐ CORRECTED DRAWINGS (as "replacement sheets") must be submitted.
   ☐ including changes required by the attached Examiner's Amendment / Comment or in the Office action of Paper No./Mail Date _____ .

   Identifying indicia such as the application number (see 37 CFR 1.84(c)) should be written on the drawings in the front (not the back) of each sheet. Replacement sheet(s) should be labeled as such in the header according to 37 CFR 1.121(d).

6. ☐ DEPOSIT OF and/or INFORMATION about the deposit of BIOLOGICAL MATERIAL must be submitted. Note the attached Examiner's comment regarding REQUIREMENT FOR THE DEPOSIT OF BIOLOGICAL MATERIAL.

Attachment(s)

1. ☑ Notice of References Cited (PTO-892)
2. ☑ Information Disclosure Statements (PTO/SB/08), Paper No./Mail Date _____.
3. ☐ Examiner's Comment Regarding Requirement for Deposit of Biological Material _____.
4. ☐ Interview Summary (PTO-413), Paper No./Mail Date. _____.
5. ☐ Examiner's Amendment/Comment
6. ☑ Examiner's Statement of Reasons for Allowance
7. ☐ Other _____.

/SAMINA F CHOUDHRY/
Primary Examiner, Art Unit 2462

Notice of Pre-AIA or AIA Status

1. The present application, filed on or after March 16, 2013, is being examined under the first inventor to file provisions of the AIA.

Reason for Allowance

2. Claims 1-27 are allowed.

The following is an examiner's statement of reasons for allowance:

Closest prior art Medvedev et al. (US 2003/0161282) discloses "to transmit data over the available transmission channels in multi-channel communication systems such that higher overall system spectral efficiency and/or other benefits may be achieved. The transmission channels may correspond to the spatial subchannels of a MIMO system, the frequency subchannels of an OFDM system, or the spatial subchannels of the frequency subchannels in a MIMO-OFDM system" (para 0009). Another prior art Wallace et al. (US 2002/0193146) discloses "receiving antenna diversity status information for a first communication link, determining of a configuration of the first communication link in response to the antenna diversity status information, and applying a transmission scenario to the first communication link". The prior art alone or in combination with other references do not disclose or render obvious claim limitation of a claim 1 including "determining a plurality of subcarrier frequencies allocated to the user device; converting the OFDM signal to a plurality of frequency-domain values corresponding to the plurality of subcarrier frequencies; and decoding the plurality of frequency-domain values to recover a plurality of data symbols encoded by the user

device on the plurality of subcarrier frequencies; wherein decoding employs a plurality of codes that are inverse to, complex- conjugate of, or complementary to a set of complex-valued codes that the user device employs to shape the OFDM signal into a superposition of cyclic-shifted pulse waveforms that each has one of the plurality of data symbols modulated thereon..".

Any comments considered necessary by applicant must be submitted no later than the payment of the issue fee and, to avoid processing delays, should preferably accompany the issue fee. Such submissions should be clearly labeled "Comments on Statement of Reasons for Allowance."

Conclusion

3. Any inquiry concerning this communication or earlier communications from the examiner should be directed to SAMINA CHOUDHRY whose telephone number is (571)270-7102. The examiner can normally be reached on Monday to Thursday (7:30 a.m. to 5.00p.m.).

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Yemane Mesfin can be reached on (571)272-3927. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300. Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair direct.uspto.gov.

Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free). If you would like assistance from a USPTO Customer Service Representative or access to the automated information system, call 800-786-9199 (IN USA OR CANADA) or 571-272-1000.

/SAMINA F CHOUDHRY/
Primary Examiner, Art Unit 2462

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76.
This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.

Secrecy Order 37 CFR 5.2

☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)

Inventor Information:

Inventor 1 Remove

Legal Name

Prefix	Given Name	Middle Name	Family Name	Suffix
	Steve		Shattil	

Residence Information (Select One) ◉ US Residency ○ Non US Residency ○ Active US Military Service

City	Cheyenne	State/Province	WY	Country of Residence	US

Mailing Address of Inventor:

Address 1	PO Box 17355		
Address 2			
City	Boulder	State/Province	CO
Postal Code	80308	Country	US

All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the **Add** button. Add

Correspondence Information:

Enter either Customer Number or complete the Correspondence Information section below.
For further information see 37 CFR 1.33(a).

☐ **An Address is being provided for the correspondence Information of this application.**

Customer Number	74284		
Email Address	genghiscomm@gmail.com	Add Email	Remove Email

Application Information:

Title of the Invention	Transmit Pre-Coding		
Attorney Docket Number	CBF-006.C3.2	Small Entity Status Claimed	☒
Application Type	Nonprovisional		
Subject Matter	Utility		
Total Number of Drawing Sheets (if any)	17	Suggested Figure for Publication (if any)	8A

Filing By Reference :

PTO/AIA/14 (12-13)
Approved for use through 01/31/2014. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

Only complete this section when filing an application by reference under 35 U.S.C. 111(c) and 37 CFR 1.57(a). Do not complete this section if application papers including a specification and any drawings are being filed. Any domestic benefit or foreign priority information must be provided in the appropriate section(s) below (i.e., "Domestic Benefit/National Stage Information" and "Foreign Priority Information").

For the purposes of a filing date under 37 CFR 1.53(b), the description and any drawings of the present application are replaced by this reference to the previously filed application, subject to conditions and requirements of 37 CFR 1.57(a).

Application number of the previously filed application	Filing date (YYYY-MM-DD)	Intellectual Property Authority or Country

Publication Information:

☐ Request Early Publication (Fee required at time of Request 37 CFR 1.219)

☒ **Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32).
Either enter Customer Number or complete the Representative Name section below. If both sections are completed the customer Number will be used for the Representative Information during processing.

Please Select One:	◉ Customer Number	○ US Patent Practitioner	○ Limited Recognition (37 CFR 11.9)
Customer Number	74284		

Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78.
When referring to the current application, please leave the application number blank.

Prior Application Status	Pending		Remove
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
	Division of	14727769	2015-06-01
Prior Application Status	Patented		Remove

Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)	Patent Number	Issue Date (YYYY-MM-DD)
14727769	Continuation of	14276309	2014-05-13	9048897	2015-06-02

Prior Application Status	Patented	Remove

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)	Patent Number	Issue Date (YYYY-MM-DD)
14276309	Continuation of	12545572	2009-08-21	~~9042333~~ 8750264	~~2015-05-26~~ 2014-06-10
Prior Application Status	Patented			Remove	

Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)	Patent Number	Issue Date (YYYY-MM-DD)
12545572	Division of	11187107	2005-07-22	8670390	2014-03-11
Prior Application Status	Expired			Remove	

Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
11187107	Claims benefit of provisional	60598187	2004-08-02

Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the **Add** button.

Foreign Priority Information:

This section allows for the applicant to claim priority to a foreign application. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(d). When priority is claimed to a foreign application that is eligible for retrieval under the priority document exchange program (PDX)[i] the information will be used by the Office to automatically attempt retrieval pursuant to 37 CFR 1.55(h)(1) and (2). Under the PDX program, applicant bears the ultimate responsibility for ensuring that a copy of the foreign application is received by the Office from the participating foreign intellectual property office, or a certified copy of the foreign priority application is filed, within the time period specified in 37 CFR 1.55(g)(1).

Remove

Application Number	Country[i]	Filing Date (YYYY-MM-DD)	Access Code[i] (if applicable)

Additional Foreign Priority Data may be generated within this form by selecting the **Add** button.

Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications

☐ This application (1) claims priority to or the benefit of an application filed before March 16, 2013 and (2) also contains, or contained at any time, a claim to a claimed invention that has an effective filing date on or after March 16, 2013.
NOTE: By providing this statement under 37 CFR 1.55 or 1.78, this application, with a filing date on or after March 16, 2013, will be examined under the first inventor to file provisions of the AIA.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

Authorization to Permit Access:

☐ Authorization to Permit Access to the Instant Application by the Participating Offices

If checked, the undersigned hereby grants the USPTO authority to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the World Intellectual Property Office (WIPO), and any other intellectual property offices in which a foreign application claiming priority to the instant patent application is filed access to the instant patent application. See 37 CFR 1.14(c) and (h). This box should not be checked if the applicant does not wish the EPO, JPO, KIPO, WIPO, or other intellectual property office in which a foreign application claiming priority to the instant patent application is filed to have access to the instant patent application.

In accordance with 37 CFR 1.14(h)(3), access will be provided to a copy of the instant patent application with respect to: 1) the instant patent application-as-filed; 2) any foreign application to which the instant patent application claims priority under 35 U.S.C. 119(a)-(d) if a copy of the foreign application that satisfies the certified copy requirement of 37 CFR 1.55 has been filed in the instant patent application; and 3) any U.S. application-as-filed from which benefit is sought in the instant patent application.

In accordance with 37 CFR 1.14(c), access may be provided to information concerning the date o f filing this Authorization.

Applicant Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Applicant 1

If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.

Clear

◉ Assignee	○ Legal Representative under 35 U.S.C. 117	○ Joint Inventor
○ Person to whom the inventor is obligated to assign.	○ Person who shows sufficient proprietary interest	

If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:

Name of the Deceased or Legally Incapacitated Inventor :

If the Applicant is an Organization check here. ☒

Organization Name	Genghiscomm Holdings, LLC

PTO/AIA/14 (12-13)
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U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

Mailing Address Information For Applicant:			
Address 1	PO Box 17355		
Address 2			
City	Boulder	**State/Province**	CO
Country	US	Postal Code	80308
Phone Number	7202344351	Fax Number	
Email Address	genghiscomm@gmail.com		

Additional Applicant Data may be generated within this form by selecting the Add button.

Assignee Information including Non-Applicant Assignee Information:

Providing assignment information in this section does not subsitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Assignee 1

Complete this section if assignee information, including non-applicant assignee information, is desired to be included on the patent application publication . An assignee-applicant identified in the "Applicant Information" section will appear on the patent application publication as an applicant. For an assignee-applicant, complete this section only if identification as an assignee is also desired on the patent application publication.

If the Assignee or Non-Applicant Assignee is an Organization check here. ☒

Organization Name	Genghiscomm Holdings, LLC

Mailing Address Information For Assignee including Non-Applicant Assignee:			
Address 1	PO Box 17355		
Address 2			
City	Boulder	**State/Province**	CO
Country	US	Postal Code	80308
Phone Number	7202344351	Fax Number	
Email Address	genghiscomm@gmail.com		

Additional Assignee or Non-Applicant Assignee Data may be generated within this form by selecting the Add button.

Signature:

NOTE: This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4 for signature requirements and certifications.

Signature	/Steven J Shattil/	Date (YYYY-MM-DD)	2020-11-26

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

First Name	Steven	Last Name	Shattil	Registration Number	40170
Additional Signature may be generated within this form by selecting the Add button.					

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these records.

2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.

3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent C o o p eration Treaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.

8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.

9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76.
This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.

Secrecy Order 37 CFR 5.2

☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)

Inventor Information:

Inventor 1 — Remove

Legal Name

Prefix	Given Name	Middle Name	Family Name	Suffix
	Steve		Shattil	

Residence Information (Select One) ● US Residency Non US Residency Active US Military Service

City	Cheyenne	State/Province	WY	Country of Residence	US

Mailing Address of Inventor:

Address 1	PO Box 17355		
Address 2			
City	Boulder	State/Province	CO
Postal Code	80308	Country	US

All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the **Add** button. Add

Correspondence Information:

Enter either Customer Number or complete the Correspondence Information section below.
For further information see 37 CFR 1.33(a).

☐ **An Address is being provided for the correspondence Information of this application.**

Customer Number	74284		
Email Address	genghiscomm@gmail.com	Add Email	Remove Email

Application Information:

Title of the Invention	Transmit Pre-Coding		
Attorney Docket Number	CBF-006.C3.2	Small Entity Status Claimed	☒
Application Type	Nonprovisional		
Subject Matter	Utility		
Total Number of Drawing Sheets (if any)	17	Suggested Figure for Publication (if any)	8A

Filing By Reference :

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

Only complete this section when filing an application by reference under 35 U.S.C. 111(c) and 37 CFR 1.57(a). Do not complete this section if application papers including a specification and any drawings are being filed. Any domestic benefit or foreign priority information must be provided in the appropriate section(s) below (i.e., "Domestic Benefit/National Stage Information" and "Foreign Priority Information").

For the purposes of a filing date under 37 CFR 1.53(b), the description and any drawings of the present application are replaced by this reference to the previously filed application, subject to conditions and requirements of 37 CFR 1.57(a).

Application number of the previously filed application	Filing date (YYYY-MM-DD)	Intellectual Property Authority or Country

Publication Information:

☐ Request Early Publication (Fee required at time of Request 37 CFR 1.219)

☒ **Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32).
Either enter Customer Number or complete the Representative Name section below. If both sections are completed the customer Number will be used for the Representative Information during processing.

Please Select One:	● Customer Number	US Patent Practitioner	○ Limited Recognition (37 CFR 11.9)
Customer Number	74284		

Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78.
When referring to the current application, please leave the application number blank.

Prior Application Status	Pending		Remove
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
	Division of	14727769	2015-06-01
Prior Application Status	Patented		Remove

Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)	Patent Number	Issue Date (YYYY-MM-DD)
14727769	Continuation of	14276309	2014-05-13	9048897	2015-06-02

Prior Application Status	Patented	Remove

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)	Patent Number	Issue Date (YYYY-MM-DD)
14276309	Continuation of	12545572	2009-08-21	8750264	2014-06-10
Prior Application Status	Patented			Remove	
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)	Patent Number	Issue Date (YYYY-MM-DD)
12545572	Division of	11187107	2005-07-22	8670390	2014-03-11
Prior Application Status	Expired			Remove	
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)		
11187107	Claims benefit of provisional	60598187	2004-08-02		

Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the **Add** button. Add

Foreign Priority Information:

This section allows for the applicant to claim priority to a foreign application. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(d). When priority is claimed to a foreign application that is eligible for retrieval under the priority document exchange program (PDX)[i] the information will be used by the Office to automatically attempt retrieval pursuant to 37 CFR 1.55(h)(1) and (2). Under the PDX program, applicant bears the ultimate responsibility for ensuring that a copy of the foreign application is received by the Office from the participating foreign intellectual property office, or a certified copy of the foreign priority application is filed, within the time period specified in 37 CFR 1.55(g)(1).

Remove

Application Number	Country[i]	Filing Date (YYYY-MM-DD)	Access Code[i] (if applicable)

Additional Foreign Priority Data may be generated within this form by selecting the **Add** button. Add

Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications

☐ This application (1) claims priority to or the benefit of an application filed before March 16, 2013 and (2) also contains, or contained at any time, a claim to a claimed invention that has an effective filing date on or after March 16, 2013.
NOTE: By providing this statement under 37 CFR 1.55 or 1.78, this application, with a filing date on or after March 16, 2013, will be examined under the first inventor to file provisions of the AIA.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

Authorization to Permit Access:

☐ Authorization to Permit Access to the Instant Application by the Participating Offices

If checked, the undersigned hereby grants the USPTO authority to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the World Intellectual Property Office (WIPO), and any other intellectual property offices in which a foreign application claiming priority to the instant patent application is filed access to the instant patent application. See 37 CFR 1.14(c) and (h). This box should not be checked if the applicant does not wish the EPO, JPO, KIPO, WIPO, or other intellectual property office in which a foreign application claiming priority to the instant patent application is filed to have access to the instant patent application.

In accordance with 37 CFR 1.14(h)(3), access will be provided to a copy of the instant patent application with respect to: 1) the instant patent application-as-filed; 2) any foreign application to which the instant patent application claims priority under 35 U.S.C. 119(a)-(d) if a copy of the foreign application that satisfies the certified copy requirement of 37 CFR 1.55 has been filed in the instant patent application; and 3) any U.S. application-as-filed from which benefit is sought in the instant patent application.

In accordance with 37 CFR 1.14(c), access may be provided to information concerning the date o f filing this Authorization.

Applicant Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Applicant 1 Remove

If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.

Clear

● Assignee	Legal Representative under 35 U.S.C. 117	Joint Inventor
Person to whom the inventor is obligated to assign.	Person who shows sufficient proprietary interest	

If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:

Name of the Deceased or Legally Incapacitated Inventor :	
If the Applicant is an Organization check here. ☒	
Organization Name	Genghiscomm Holdings, LLC

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U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

Mailing Address Information For Applicant:			
Address 1	PO Box 17355		
Address 2			
City	Boulder	**State/Province**	CO
Country i	US	Postal Code	80308
Phone Number	7202344351	Fax Number	
Email Address	genghiscomm@gmail.com		

Additional Applicant Data may be generated within this form by selecting the Add button. Add

Assignee Information including Non-Applicant Assignee Information:

Providing assignment information in this section does not subsitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Assignee 1

Complete this section if assignee information, including non-applicant assignee information, is desired to be included on the patent application publication . An assignee-applicant identified in the "Applicant Information" section will appear on the patent application publication as an applicant. For an assignee-applicant, complete this section only if identification as an assignee is also desired on the patent application publication.

Remove

If the Assignee or Non-Applicant Assignee is an Organization check here. ☒

Organization Name	Genghiscomm Holdings, LLC

Mailing Address Information For Assignee including Non-Applicant Assignee:			
Address 1	PO Box 17355		
Address 2			
City	Boulder	**State/Province**	CO
Country i	US	Postal Code	80308
Phone Number	7202344351	Fax Number	
Email Address	genghiscomm@gmail.com		

Additional Assignee or Non-Applicant Assignee Data may be generated within this form by selecting the Add button. Add

Signature:

Remove

NOTE: This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4 for signature requirements and certifications.

Signature	/Steven J Shattil/	Date (YYYY-MM-DD)	2020-11-26

PTO/AIA/14 (12-13)
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U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

First Name	Steven	Last Name	Shattil	Registration Number	40170

Additional Signature may be generated within this form by selecting the Add button. Add

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these records.

2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.

3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent C o o p eration Treaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.

8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.

9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Patent Application of:	Docket No.: CBF-006.C3.2
Steve Shattil	Confirmation No.: 5226
Application No.: 17105576	Group Art Unit:
Filed: 26-NOV-2020	Examiner:

For: **TRANSMIT PRE-CODING**

Commissioner for Patents
P.O. BOX 1700
Alexandria, VA 22313-1700

PRELIMINARY AMENDMENT

Sir:

Prior to examination on the merits, please amend the above-identified application as follows.

Amendments to the Specification begin on page 2.

The listing of **Claims** begins on page 3.

Amendments to the **Drawings** begin on page 11 and include Replacement drawing sheets 1, 2, 22, 26, and 29.

Remarks begin on page 12.

AMENDMENTS TO THE SPECIFICATION

Please REPLACE the first paragraph on Page 1 under the heading -- RELATED APPLICATIONS—with the following paragraph.

-- This application is a Continuation of U.S. Pat. Appl. No. 14/727,769, filed June 1, 2015, which is a Continuation of U.S. Pat. Appl. No. 14/276,309, filed May 13, 2014, now U.S. Pat. No. 9,048,897, which is a Continuation of U.S. Pat. Appl. No. 12/545,572, filed August 21, 2009, now U.S. Pat. No. 8,750,264 ~~9,042,333~~, which is a Divisional of U.S. Pat. Appl. No. 11/187,107, filed on July 22, 2005, now U.S. Pat. No. 8,670,390, which claims priority to Provisional Appl. No. 60/598,187, filed August 2, 2004, all of which are incorporated by reference in their entireties. –

The clean version of the above paragraph is as follows:

-- This application is a Continuation of U.S. Pat. Appl. No. 14/727,769, filed June 1, 2015, which is a Continuation of U.S. Pat. Appl. No. 14/276,309, filed May 13, 2014, now U.S. Pat. No. 9,048,897, which is a Continuation of U.S. Pat. Appl. No. 12/545,572, filed August 21, 2009, now U.S. Pat. No. 8,750,264, which is a Divisional of U.S. Pat. Appl. No. 11/187,107, filed on July 22, 2005, now U.S. Pat. No. 8,670,390, which claims priority to Provisional Appl. No. 60/598,187, filed August 2, 2004, all of which are incorporated by reference in their entireties. --

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CLAIMS

The following is a complete list of all claims in this application.

1. (Original) A method for receiving an Orthogonal Frequency Division Multiplexing (OFDM) signal transmitted by a user device in a wireless network, the method comprising:

determining a plurality of subcarrier frequencies allocated to the user device;

converting the OFDM signal to a plurality of frequency-domain values corresponding to the plurality of subcarrier frequencies; and

decoding the plurality of frequency-domain values to recover a plurality of data symbols encoded by the user device on the plurality of subcarrier frequencies;

wherein decoding employs a plurality of codes that are inverse to, complex-conjugate of, or complementary to a set of complex-valued codes that the user device employs to shape the OFDM signal into a superposition of cyclic-shifted pulse waveforms that each has one of the plurality of data symbols modulated thereon.

2. (Original) The method of claim 1, wherein each of the plurality of codes employed for decoding comprises a different vector of linear phase offsets.

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3. (Original) The method of claim 1, wherein the cyclic-shifted waveforms have cyclic shifts that cause the cyclic-shifted waveforms to be orthogonal, and each of the plurality of codes employed for decoding comprises a set of linear phase offsets that corresponds to one of the cyclic shifts.

4. (Original) The method of claim 1, wherein the complex-valued codes cause the cyclic-shifted waveforms to be Sinc waveforms, and the plurality of codes is configured to decode the Sinc waveforms.

5. (Original) The method of claim 1, wherein the plurality of subcarrier frequencies has a frequency spacing f_s, and the plurality of cyclic-shifted waveforms are periodic over a symbol interval $T_s = 1/f_s$.

6. (Original) The method of claim 1, wherein converting the OFDM signal to a plurality of frequency-domain values uses a discrete Fourier transform.

7. (Original) The method of claim 1, further comprising removing at least one of a guard interval, a cyclic prefix, and a cyclic postfix from the OFDM signal before converting the OFDM signal to the plurality of frequency-domain values.

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8. (Original) The method of claim 1, wherein converting the OFDM signal to the plurality of frequency-domain values provides for orthogonal frequency division multiple access for the user device and at least one other user device.

9. (Original) The method of claim 1, wherein an mth one of the plurality of codes is expressed as a set of N code chips for a set of integers n = {0,..., N-1}, wherein each code chip is expressed by $e^{i2\pi nm/N}$, wherein *i* is the square root of -1, and π is Pi.

10. (Original) An apparatus for receiving an Orthogonal Frequency Division Multiplexing (OFDM) signal transmitted by a user device in a wireless network, the apparatus comprising:

at least one processor; and

a non-transitory computer-readable memory communicatively coupled to the at least one processor, the non-transitory computer-readable memory including a set of instructions stored thereon and executable by the at least one processor for:

determining a plurality of subcarrier frequencies allocated to the user device;

converting the OFDM signal to a plurality of frequency-domain values corresponding to the plurality of subcarrier frequencies; and

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Samsung Electronics Co., Ltd. et al. v. Genghiscomm Holdings LLC

decoding the plurality of frequency-domain values to recover a plurality of data symbols encoded by the user device on the plurality of subcarrier frequencies;

wherein decoding employs a plurality of codes that are inverse to, complex-conjugate of, or complementary to a set of complex-valued codes that the user device employs to shape the OFDM signal into a superposition of cyclic-shifted pulse waveforms that each has one of the plurality of data symbols modulated thereon.

11. (Original) The apparatus of claim 10, wherein each of the plurality of codes employed for decoding comprises a different vector of linear phase offsets.

12. (Original) The apparatus of claim 10, wherein the cyclic-shifted waveforms have cyclic shifts that cause the cyclic-shifted waveforms to be orthogonal, and each of the plurality of codes employed for decoding comprises a set of linear phase offsets that corresponds to one of the cyclic shifts.

13. (Original) The apparatus of claim 10, wherein the complex-valued codes cause the cyclic-shifted waveforms to be Sinc waveforms, and the plurality of codes is configured to decode the Sinc waveforms.

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Samsung Electronics Co., Ltd. et al. v. Genghiscomm Holdings LLC

14. (Original) The apparatus of claim 10, wherein the plurality of subcarrier frequencies has a frequency spacing f_s, and the plurality of cyclic-shifted waveforms are periodic over a symbol interval $T_s = 1/f_s$.

15. (Original) The apparatus of claim 10, wherein converting the OFDM signal to a plurality of frequency-domain values uses a discrete Fourier transform.

16. (Original) The apparatus of claim 10, wherein the non-transitory computer-readable memory further includes instructions stored thereon and executable by the at least one processor for removing at least one of a guard interval, a cyclic prefix, and a cyclic postfix from the OFDM signal before converting the OFDM signal to the plurality of frequency-domain values.

17. (Original) The apparatus of claim 10, wherein converting the OFDM signal to the plurality of frequency-domain values provides for orthogonal frequency division multiple access for the user device and at least one other user device.

18. (Original) The apparatus of claim 10, wherein an mth one of the plurality of codes is expressed as a set of N code chips for a set of integers n = {0,..., N-1}, wherein each code chip is expressed by $e^{i2\pi nm/N}$, wherein *i* is the square root of -1, and π is Pi.

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19. (Original) A computer program product for receiving an Orthogonal Frequency Division Multiplexing (OFDM) signal transmitted by a user device in a wireless network, the computer program product comprising a non-transitory computer readable storage device having computer readable program code stored therein, said program code containing instructions executable by one or more processors of a computer system for:

determining a plurality of subcarrier frequencies allocated to the user device;

converting the OFDM signal to a plurality of frequency-domain values corresponding to the plurality of subcarrier frequencies; and

decoding the plurality of frequency-domain values to recover a plurality of data symbols encoded by the user device on the plurality of subcarrier frequencies;

wherein decoding employs a plurality of codes that are inverse to, complex-conjugate of, or complementary to a set of complex-valued codes that the user device employs to shape the OFDM signal into a superposition of cyclic-shifted pulse waveforms that each has one of the plurality of data symbols modulated thereon.

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20. (Original) The computer program product of claim 19, wherein each of the plurality of codes employed for decoding comprises a different vector of linear phase offsets.

21. (Original) The computer program product of claim 19, wherein the cyclic-shifted waveforms have cyclic shifts that cause the cyclic-shifted waveforms to be orthogonal, and each of the plurality of codes employed for decoding comprises a set of linear phase offsets that corresponds to one of the cyclic shifts.

22. (Original) The computer program product of claim 19, wherein the complex-valued codes cause the cyclic-shifted waveforms to be Sinc waveforms, and the plurality of codes is configured to decode the Sinc waveforms.

23. (Original) The computer program product of claim 19, wherein the plurality of subcarrier frequencies has a frequency spacing f_s, and the plurality of cyclic-shifted waveforms are periodic over a symbol interval $T_s = 1/f_s$.

24. (Original) The computer program product of claim 19, wherein converting the OFDM signal to a plurality of frequency-domain values uses a discrete Fourier transform.

25. (Original) The computer program product of claim 19, wherein the non-transitory computer-readable storage device further includes instructions stored therein and

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executable by the one or more processors for removing at least one of a guard interval, a cyclic prefix, and a cyclic postfix from the OFDM signal before converting the OFDM signal to the plurality of frequency-domain values.

26. (Original) The computer program product of claim 19, wherein converting the OFDM signal to the plurality of frequency-domain values provides for orthogonal frequency division multiple access for the user device and at least one other user device.

27. (Original) The computer program product of claim 19, wherein an mth one of the plurality of codes is expressed as a set of N code chips for a set of integers n = {0,…, N-1}, wherein each code chip is expressed by $e^{i2\pi nm/N}$, wherein *i* is the square root of -1, and π is Pi.

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Samsung Electronics Co., Ltd. et al. v. Genghiscomm Holdings LLC

AMENDMENTS TO THE DRAWINGS

In FIG. 1B, three instances of the label – c_n – were amended to increase font size.

In FIG. 1C, labels – f_1 --, – f_2 --, and – f_3 – were amended to increase font size.

In FIG. 1D, labels – c_1 --, – c_2 --, and – c_3 – were amended to increase font size.

In FIG. 22A, labels – f_1 --, – f_2 --, and – f_N – and the text inside labeled boxes 2211, 2212, and 2219 was amended to increase font size.

In FIG. 22B, text inside boxes 2210, 2201, 2209, 2221, 2222, and 2229 was amended to increase font size.

In FIG. 22B, text inside boxes 2502, 2504.1, 2504.2, and 2504.N was amended to increase font size.

FIG. 29B is being resubmitted to clear up portions of the original submitted figure that were blurry.

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REMARKS

By this amendment, a clerical error is corrected in the RELATED APPLICATIONS section of the Specification and in the Domestic Benefit / National Stage Information section of the Application Data Sheet. This correction does not constitute any addition of a benefit claim or any change to a claim of benefit to an earlier filing date.

Drawing figures were amended to increase the size of some text, and FIG. 29B is resubmitted to fix a portion of the figure that was blurry in the originally submitted figure.

No amendment was made to the claims.

Applicant respectfully contends that no issue of new matter has been added by this amendment.

If the Examiner believes, for any reason, that personal communication will expedite prosecution of this application, the Examiner is invited to telephone the undersigned at the number provided.

Prompt and favorable consideration of this Reply is respectfully requested.

Respectfully Submitted,

/Steven J Shattil/

Steven J Shattil
Reg. No. 40170

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Samsung Electronics Co., Ltd. et al. v. Genghiscomm Holdings LLC

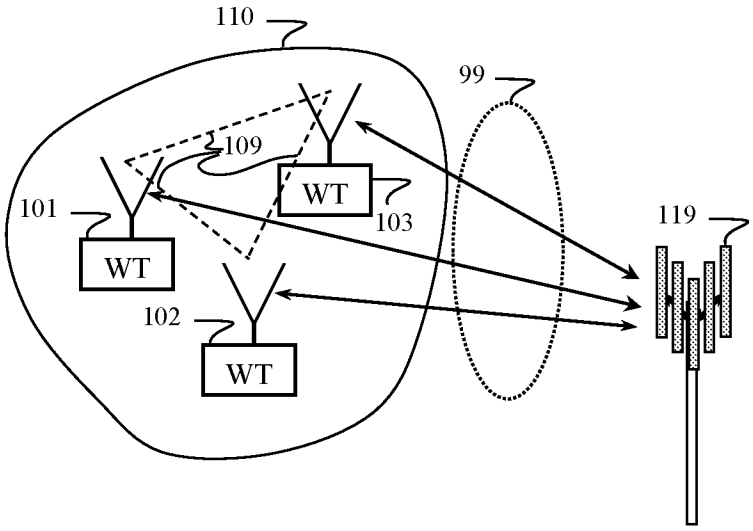


FIGURE 1A

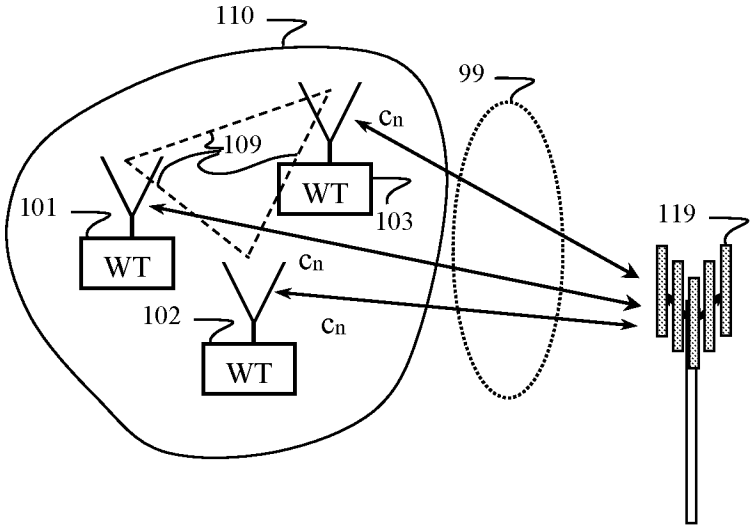


FIGURE 1B

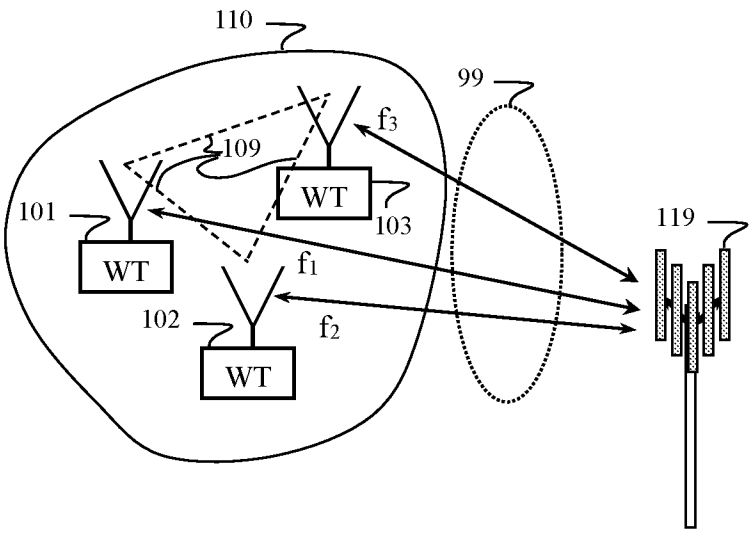


FIGURE 1C

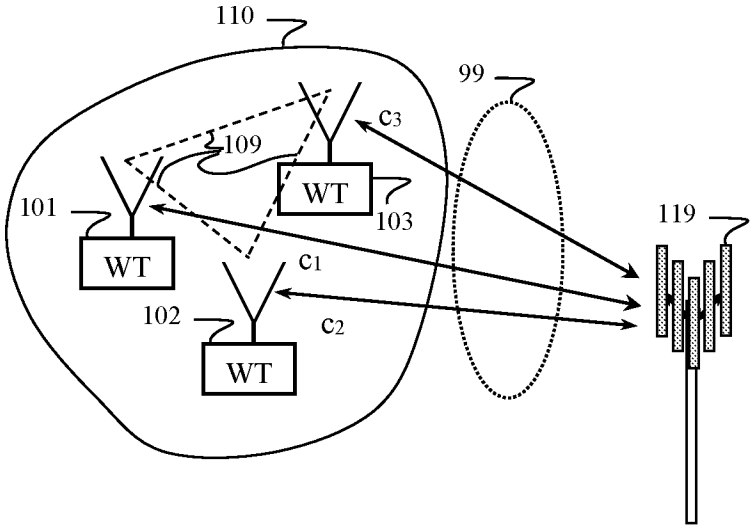


FIGURE 1D

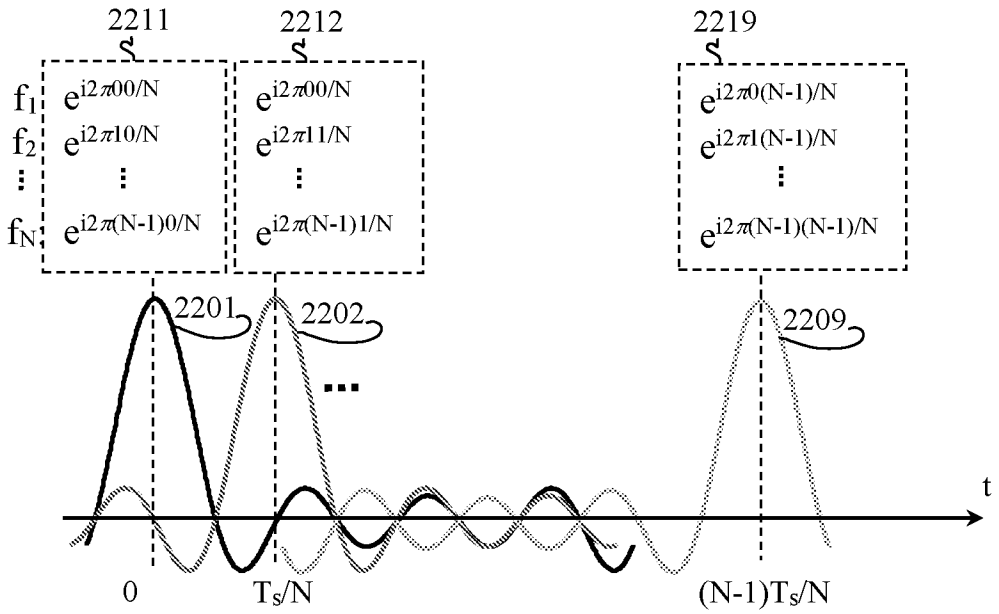


FIGURE 22A

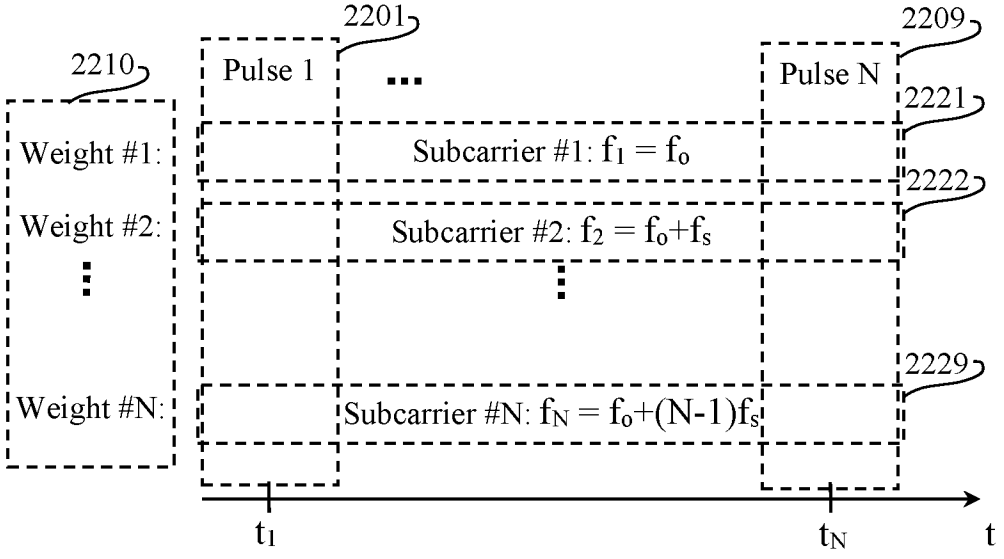


FIGURE 22B

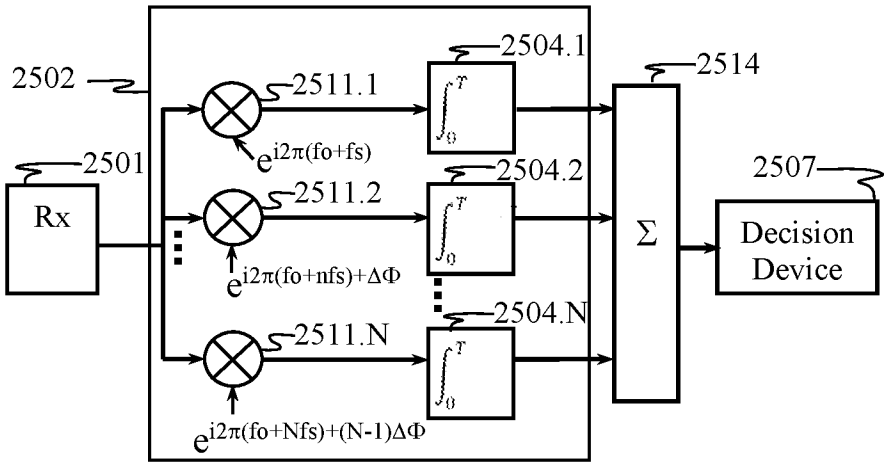


FIGURE 26A

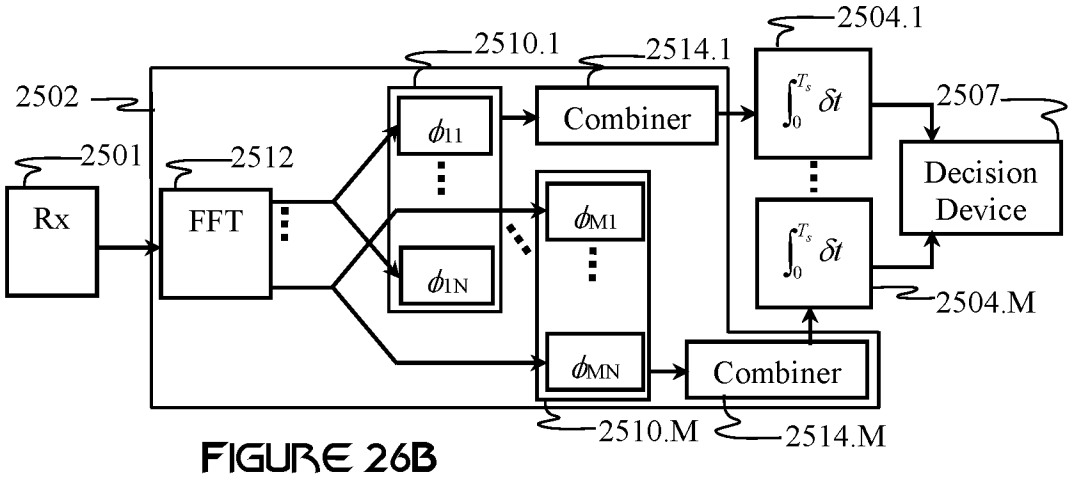


FIGURE 26B

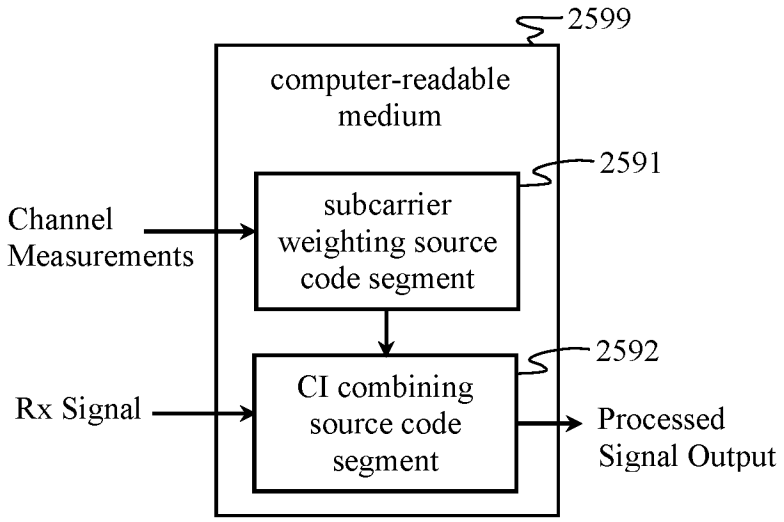


FIGURE 26C

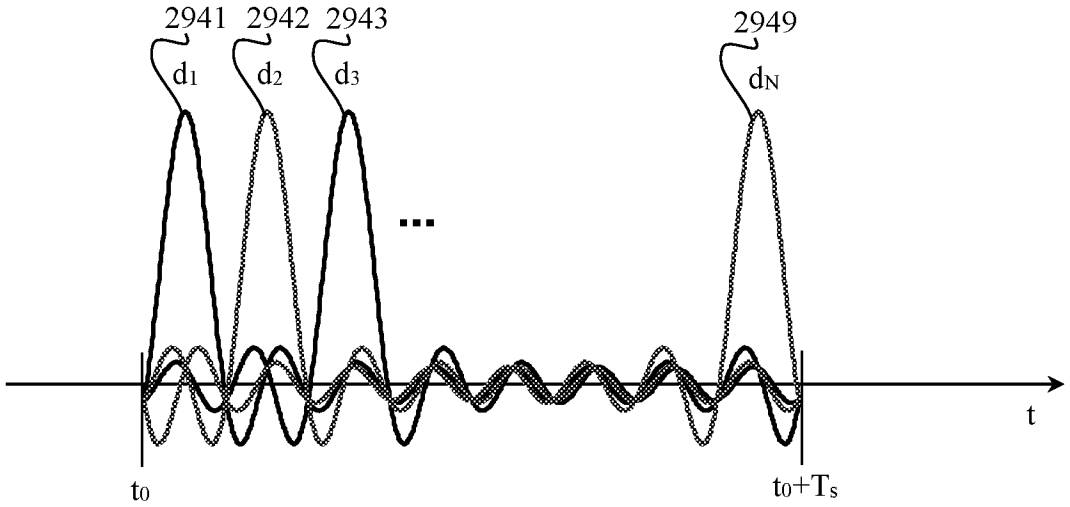


FIGURE 29A

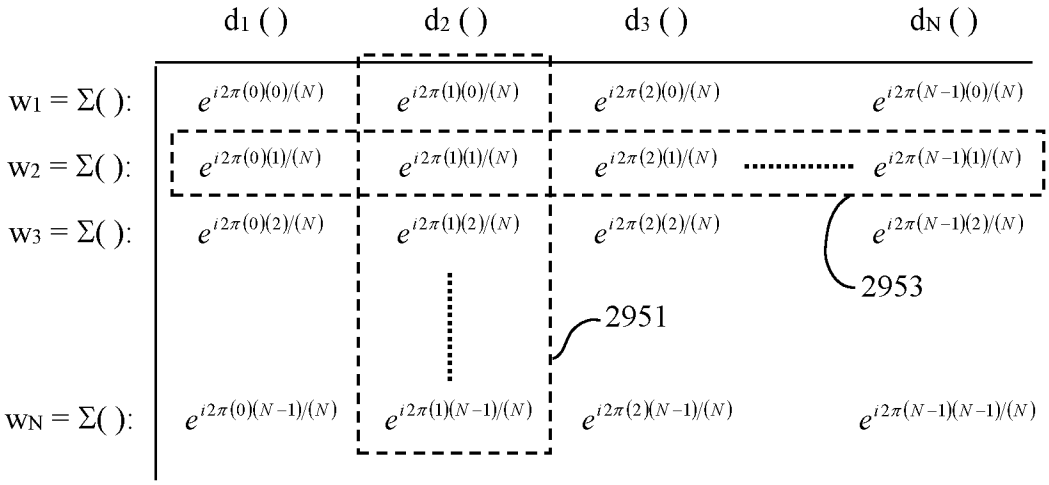


FIGURE 29B

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United States Patent and Trademark Office
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APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
17/105,576	11/26/2020	Steve Shattil	CBF-006.C3.2	5226

74284 7590 12/29/2020

Steven J Shattil
P.O. Box 17355
Boulder, CO 80308-0355

EXAMINER	

ART UNIT	PAPER NUMBER
2462	

MAIL DATE	DELIVERY MODE
12/29/2020	PAPER

Please find below and/or attached an Office communication concerning this application or proceeding.

The time period for reply, if any, is set in the attached communication.

Decision Dismissing Request for Prioritized Examination (Track I)	Application No. 17/105,576	Applicant(s) Shattil, Steve	
	Examiner JoAnne L Burke	Art Unit OPET	AIA (FITF) Status No

1. THE REQUEST FILED 26 November 2020 IS **DISMISSED** BECAUSE:

A. ☐ The application is not a utility application under 35 U.S.C. 111(a) filed by EFS-Web or a plant application under 35 U.S.C. 111(a) filed by paper:
   i. ☐ The application is a utility application that was not filed by EFS-Web.
   ii. ☐ The application is neither a utility application nor a plant application, but rather is a _____ , which is excluded from the Track I program.

B. ☐ The request was not filed with the application or on the same date of the application.

C. ☑ One or more of the following fees were not filed with the application:
   i. ☑ Basic filing fee, as set forth in 37 CFR 1.16(a), or for a plant application, 37 CFR 1.16(c).
   ii. ☑ Search fee, as set forth in 37 CFR 1.16(k), or for a plant application, 37 CFR 1.16(m).
   iii. ☑ Examination fee, as set forth in 37 CFR 1.16(o), or for a plant application, 37 CFR 1.16(q).
   iv. ☐ Publication fee, as set forth in 37 CFR 1.18(d).
   v. ☑ Track I processing fee, as set forth in 37 CFR 1.17(i).
   vi. ☑ Track I prioritized examination fee, as set forth in 37 CFR 1.17(c).
   vii. ☑ Application size fee, due because the specification and drawings exceed 100 sheets of paper, as set forth in 37 CFR 1.16(s).
   viii. ☐ Excess independent claim fee, due because the number of independent claims exceeds three, as set forth in 37 CFR 1.16(h).
   ix. ☑ Excess claim fee, due because the number of claims exceeds twenty, as set forth in 37 CFR 1.16(i).

D. ☐ The executed inventor's oath or declaration, or an application data sheet meeting the conditions specified in 37 CFR 1.53(f)(3)(i) was not filed with the application or on the same date the application was filed.

E. ☐ The application contains or has been amended to contain:
   i. ☐ More than four independent claims.
   ii. ☐ More than thirty total claims.
   iii. ☐ One or more multiple dependent claims.

F. ☐ The Track I program has exceeded its limit of 10,000 requests for the current fiscal year.

G. ☐ Other: _____

2. CONCLUSION

☐ **ALL of the above defect(s) consist only of one or more of items E (i-iii). Applicant is hereby accorded a non-extendable ONE MONTH time period from the mailing date of this Decision to (1) correct the subject defect(s) and (2) file a petition under 37 CFR 1.181 requesting reconsideration of prioritized examination. If no such petition is timely filed, the application will not undergo prioritized examination.**

- OR -

☑ **The application will not undergo prioritized examination, because the request was not accompanied by all of the required items.**

Telephone inquiries with regard to this decision should be directed to JoAnne Burke at (571)272-4584 . In his/her absence, calls may be directed to Petition Help Desk at (571) 272-3282.

/JOANNE L BURKE/ Lead Paralegal Specialist, OPET	

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APPLICATION NUMBER	FILING OR 371(C) DATE	FIRST NAMED APPLICANT	ATTY. DOCKET NO./TITLE
17/105,576	11/26/2020	Steve Shattil	CBF-006.C3.2

CONFIRMATION NO. 5226

74284
Steven J Shattil
P.O. Box 17355
Boulder, CO 80308-0355

FORMALITIES LETTER

OC000000121843098

Date Mailed: 12/07/2020

NOTICE TO FILE MISSING PARTS OF NONPROVISIONAL APPLICATION

FILED UNDER 37 CFR 1.53(b)

Filing Date Granted

Items Required To Avoid Abandonment:

An application number and filing date have been accorded to this application. The item(s) indicated below, however, are missing. Applicant is given **TWO MONTHS** from the date of this Notice within which to file all required items below to avoid abandonment. Extensions of time may be obtained by filing a petition accompanied by the extension fee under the provisions of 37 CFR 1.136(a).

The application is informal since it does not comply with the regulations for the reason(s) indicated below.

The required item(s) identified below must be timely submitted to avoid abandonment:

- Replacement drawings in compliance with 37 CFR 1.84 and 37 CFR 1.121(d) are required. The drawings submitted are not acceptable because:
  - Numbers, letters, and reference characters on the drawings must measure at least 0.32 cm (1/8 inch) in height. See Figure(s) 1B-1D, 22A, 22B, 26A.
  - The drawings submitted to the Office are not electronically reproducible because portions of figures 29B are missing and/or blurry.

Applicant is cautioned that correction of the above items may cause the specification and drawings page count to exceed 100 pages. If the specification and drawings exceed 100 pages, applicant will need to submit the required application size fee.

SUMMARY OF FEES DUE:

The fee(s) required within **TWO MONTHS** from the date of this Notice to avoid abandonment is/are itemized below. Small entity discount is in effect. If applicant is qualified for micro entity status, an acceptable Certification of Micro Entity Status must be submitted to establish micro entity status. (See 37 CFR 1.29 and forms PTO/SB/15A and 15B.)

- $ **420** for **30** electronically equivalent pages in excess of **150** application size fee.
- $(**210**) previous unapplied payment amount.
- $ **210** TOTAL FEE BALANCE DUE.

Replies must be received in the USPTO within the set time period or must include a proper Certificate of Mailing or Transmission under 37 CFR 1.8 with a mailing or transmission date within the set time period. For more information and a suggested format, see Form PTO/SB/92 and MPEP 512.

Replies should be mailed to:

Mail Stop Missing Parts
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Alexandria VA 22313-1450

Registered users of EFS-Web may alternatively submit their reply to this notice via EFS-Web, including a copy of this Notice and selecting the document description "Applicant response to Pre-Exam Formalities Notice". https://sportal.uspto.gov/authenticate/AuthenticateUserLocalEPF.html

For more information about EFS-Web please call the USPTO Electronic Business Center at 1-866-217-9197 or visit our website at http://www.uspto.gov/ebc.

If you are not using EFS-Web to submit your reply, you must include a copy of this notice.

Questions about the contents of this notice and the requirements it sets forth should be directed to the Office of Data Management, Application Assistance Unit, at **(571) 272-4000** or **(571) 272-4200** or **1-888-786-0101**.

/ldvan/

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APPLICATION NUMBER	FILING OR 371(C) DATE	FIRST NAMED APPLICANT	ATTY. DOCKET NO./TITLE
17/105,576	11/26/2020	Steve Shattil	CBF-006.C3.2

CONFIRMATION NO. 5226

74284
Steven J Shattil
P.O. Box 17355
Boulder, CO 80308-0355

FORMALITIES LETTER

OC000000121843098

Date Mailed: 12/07/2020

NOTICE TO FILE MISSING PARTS OF NONPROVISIONAL APPLICATION

FILED UNDER 37 CFR 1.53(b)

Filing Date Granted

Items Required To Avoid Abandonment:

An application number and filing date have been accorded to this application. The item(s) indicated below, however, are missing. Applicant is given **TWO MONTHS** from the date of this Notice within which to file all required items below to avoid abandonment. Extensions of time may be obtained by filing a petition accompanied by the extension fee under the provisions of 37 CFR 1.136(a).

The application is informal since it does not comply with the regulations for the reason(s) indicated below.

The required item(s) identified below must be timely submitted to avoid abandonment:

- Replacement drawings in compliance with 37 CFR 1.84 and 37 CFR 1.121(d) are required. The drawings submitted are not acceptable because:
  - Numbers, letters, and reference characters on the drawings must measure at least 0.32 cm (1/8 inch) in height. See Figure(s) 1B-1D, 22A, 22B, 26A.
  - The drawings submitted to the Office are not electronically reproducible because portions of figures 29B are missing and/or blurry.

Applicant is cautioned that correction of the above items may cause the specification and drawings page count to exceed 100 pages. If the specification and drawings exceed 100 pages, applicant will need to submit the required application size fee.

SUMMARY OF FEES DUE:

The fee(s) required within **TWO MONTHS** from the date of this Notice to avoid abandonment is/are itemized below. Small entity discount is in effect. If applicant is qualified for micro entity status, an acceptable Certification of Micro Entity Status must be submitted to establish micro entity status. (See 37 CFR 1.29 and forms PTO/SB/15A and 15B.)

- $ **420** for **30** electronically equivalent pages in excess of **150** application size fee.
- $(**210**) previous unapplied payment amount.
- $ **210** TOTAL FEE BALANCE DUE.

Replies must be received in the USPTO within the set time period or must include a proper Certificate of Mailing or Transmission under 37 CFR 1.8 with a mailing or transmission date within the set time period. For more information and a suggested format, see Form PTO/SB/92 and MPEP 512.

Replies should be mailed to:

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Commissioner for Patents
P.O. Box 1450
Alexandria VA 22313-1450

Registered users of EFS-Web may alternatively submit their reply to this notice via EFS-Web, including a copy of this Notice and selecting the document description "Applicant response to Pre-Exam Formalities Notice". https://sportal.uspto.gov/authenticate/AuthenticateUserLocalEPF.html

For more information about EFS-Web please call the USPTO Electronic Business Center at 1-866-217-9197 or visit our website at http://www.uspto.gov/ebc.

If you are not using EFS-Web to submit your reply, you must include a copy of this notice.

Questions about the contents of this notice and the requirements it sets forth should be directed to the Office of Data Management, Application Assistance Unit, at **(571) 272-4000** or **(571) 272-4200** or **1-888-786-0101**.

/ldvan/

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Alexandria, Virginia 22313-1450
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APPLICATION NUMBER	FILING or 371(c) DATE	GRP ART UNIT	FIL FEE REC'D	ATTY.DOCKET.NO	TOT CLAIMS	IND CLAIMS
17/105,576	11/26/2020	2414	1390	CBF-006.C3.2	27	3

CONFIRMATION NO. 5226

74284
Steven J Shattil
P.O. Box 17355
Boulder, CO 80308-0355

FILING RECEIPT

OC000000121843097

Date Mailed: 12/07/2020

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Inventor(s)

Steve Shattil, Cheyenne, WY;

Applicant(s)

Genghiscomm Holdings, LLC, Boulder, CO;

Assignment For Published Patent Application

Genghiscomm Holdings, LLC, Boulder, CO

Power of Attorney: None

Domestic Priority data as claimed by applicant

This application is a DIV of 14/727,769 06/01/2015
which is a CON of 14/276,309 05/13/2014 PAT 9048897
which is a CON of 12/545,572 08/21/2009 PAT 8750264
which is a DIV of 11/187,107 07/22/2005 PAT 8670390
which claims benefit of 60/598,187 08/02/2004

Foreign Applications for which priority is claimed (You may be eligible to benefit from the **Patent Prosecution Highway** program at the USPTO. Please see http://www.uspto.gov for more information.) - None.
Foreign application information must be provided in an Application Data Sheet in order to constitute a claim to foreign priority. See 37 CFR 1.55 and 1.76.

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Projected Publication Date: Request for Non-Publication Acknowledged
Non-Publication Request: Yes
Early Publication Request: No
**** SMALL ENTITY ****
Title

Transmit Pre-Coding

Preliminary Class

370

Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications: No

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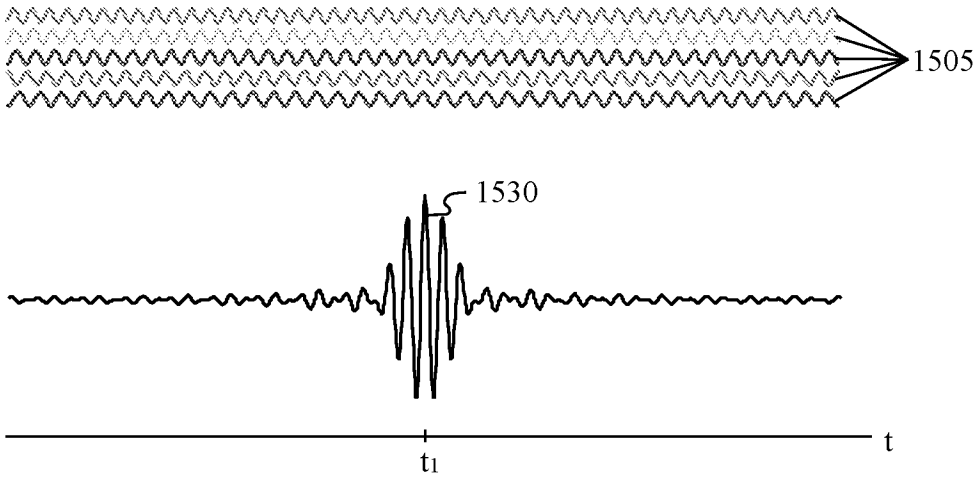


FIGURE 15

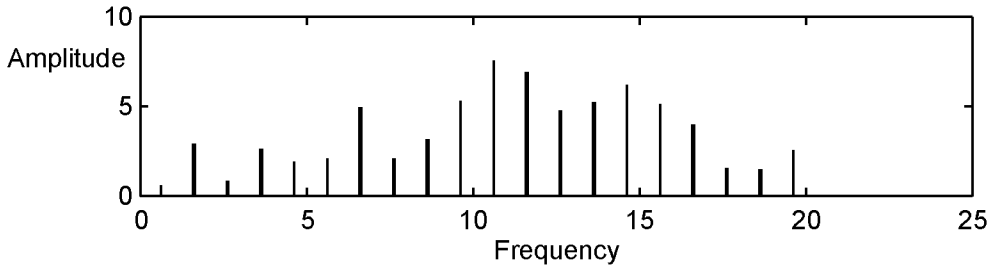


FIGURE 16A

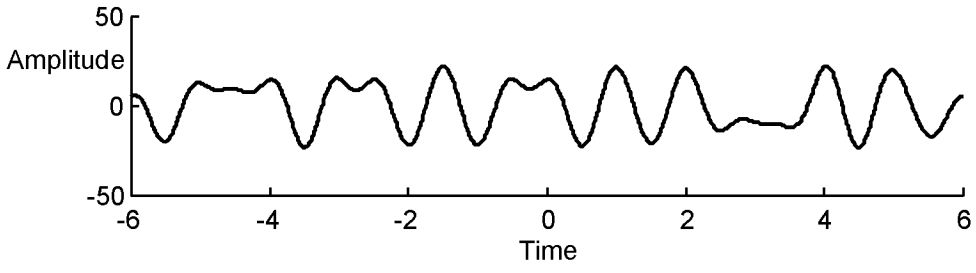


FIGURE 16B

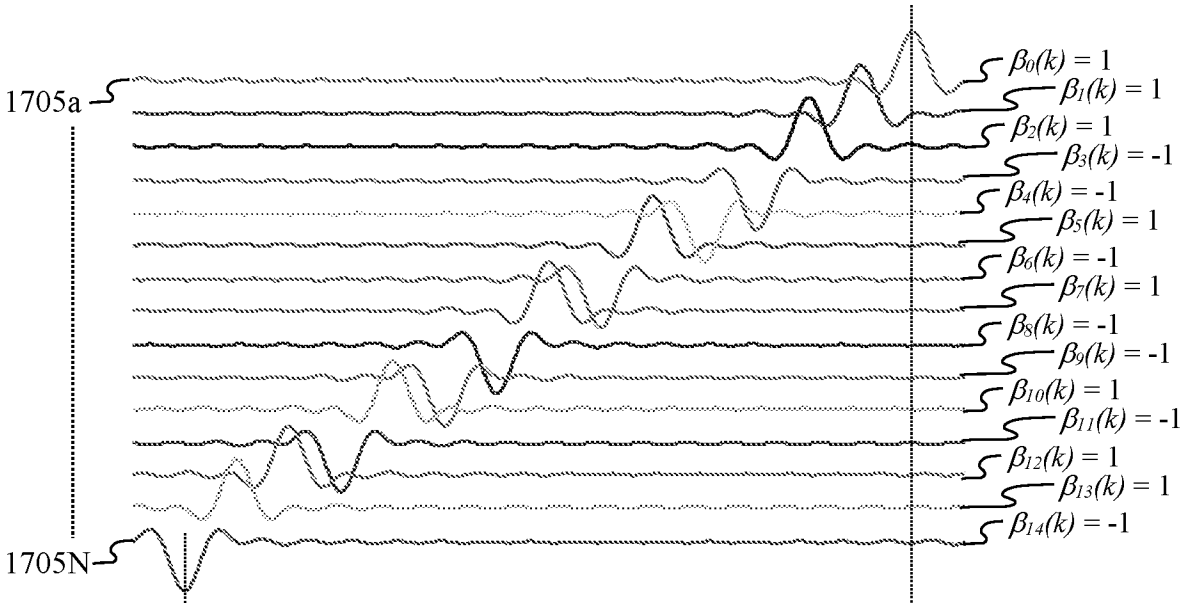


FIGURE 17A

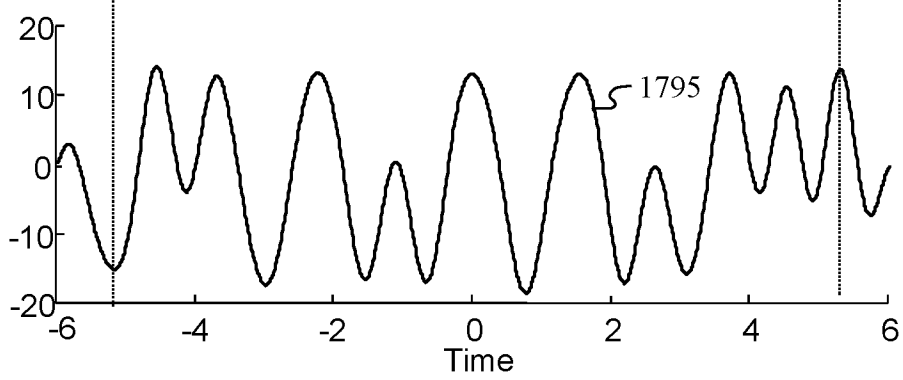


FIGURE 17B

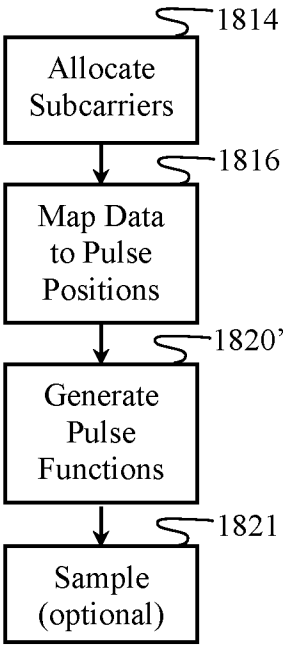


FIGURE 18A

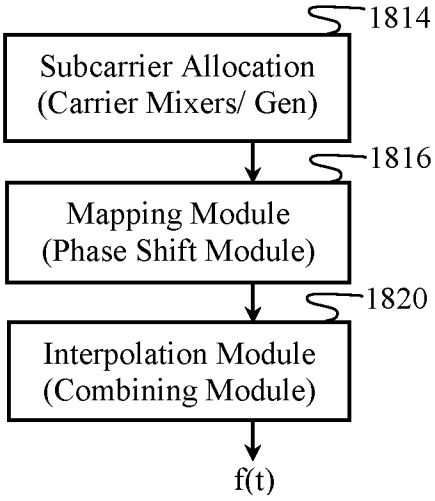


FIGURE 18B

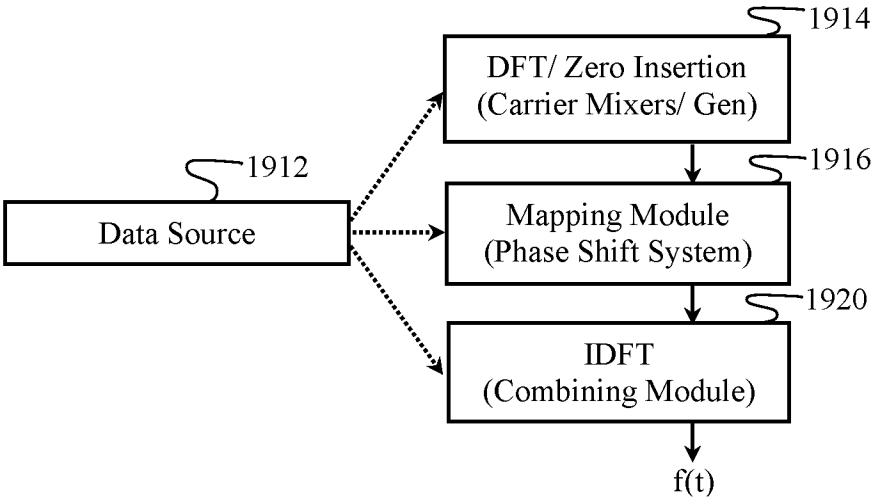


FIGURE 19

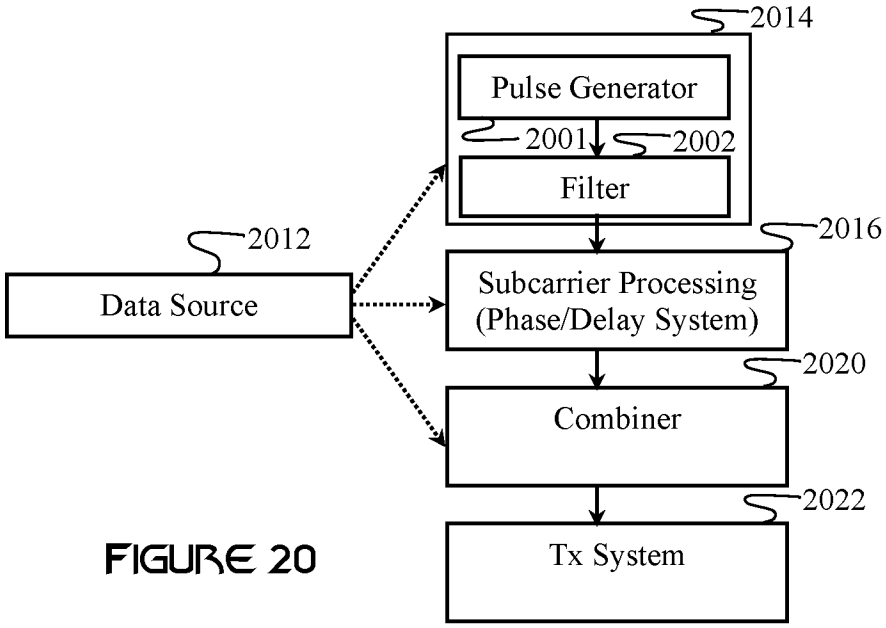


FIGURE 20

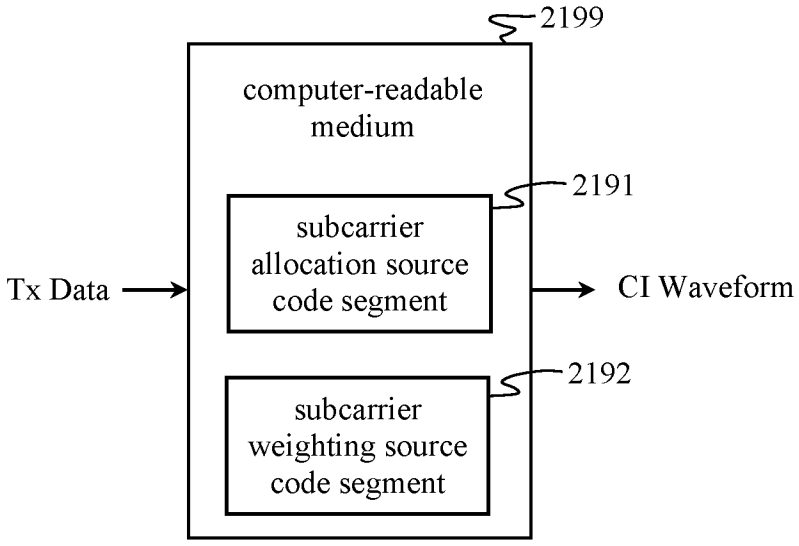


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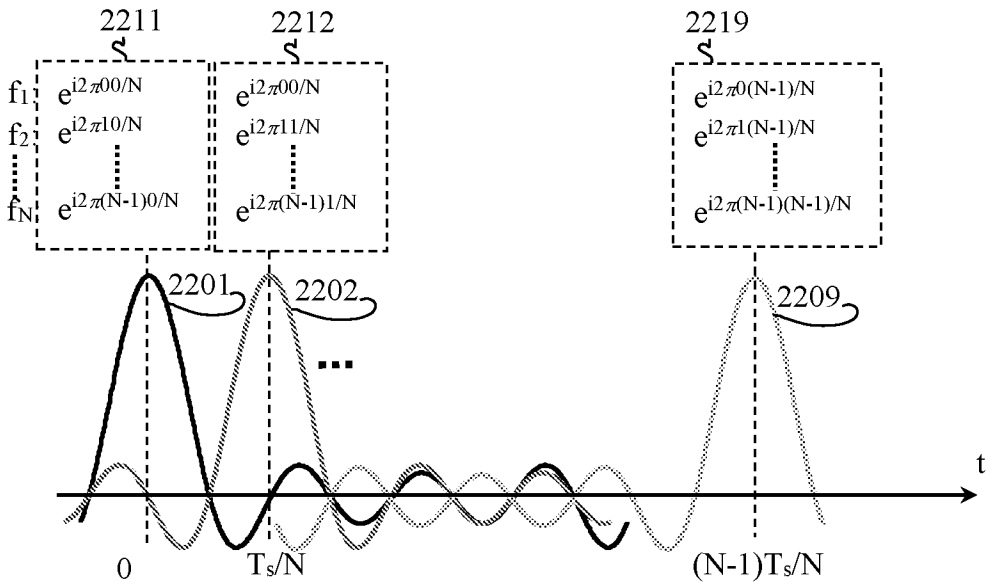


FIGURE 22A

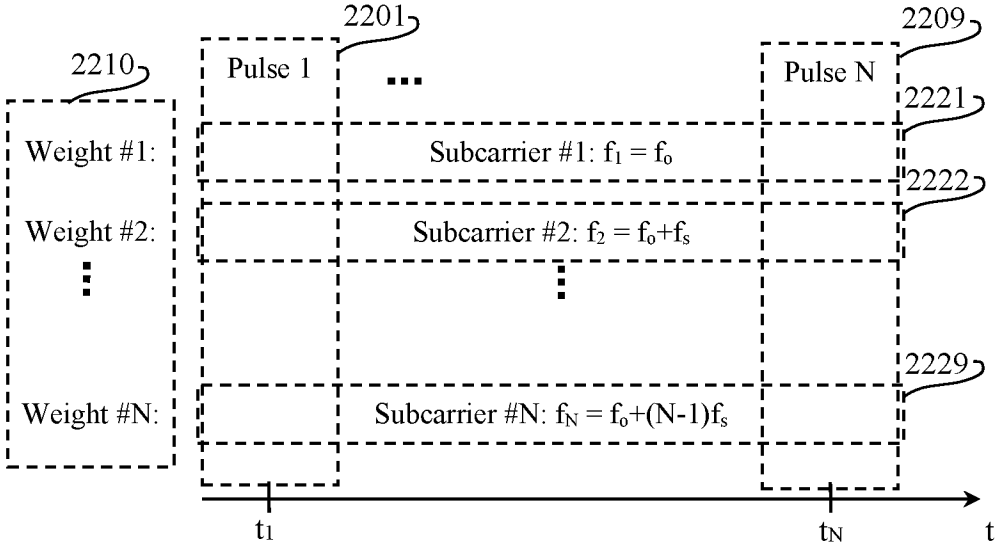


FIGURE 22B

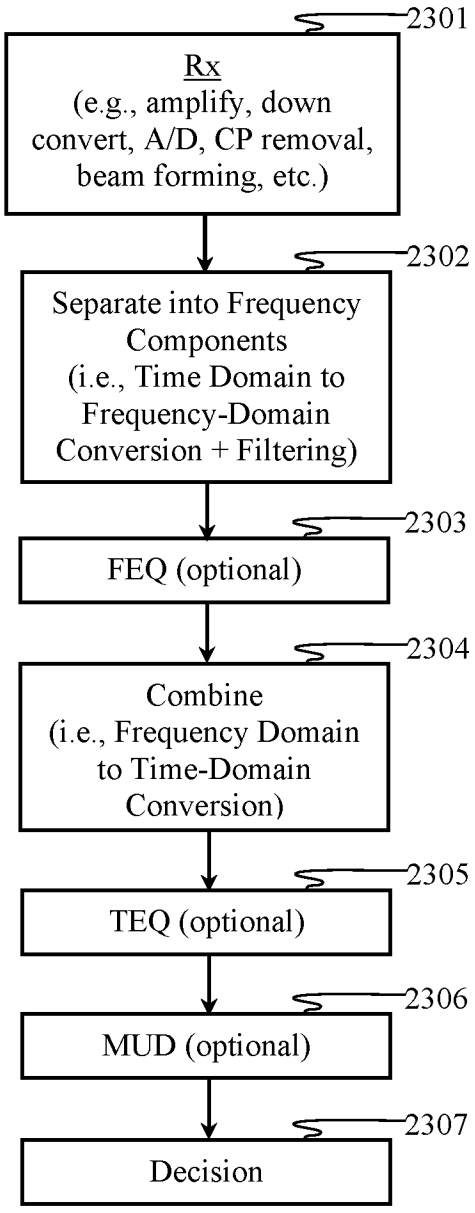


FIGURE 23A

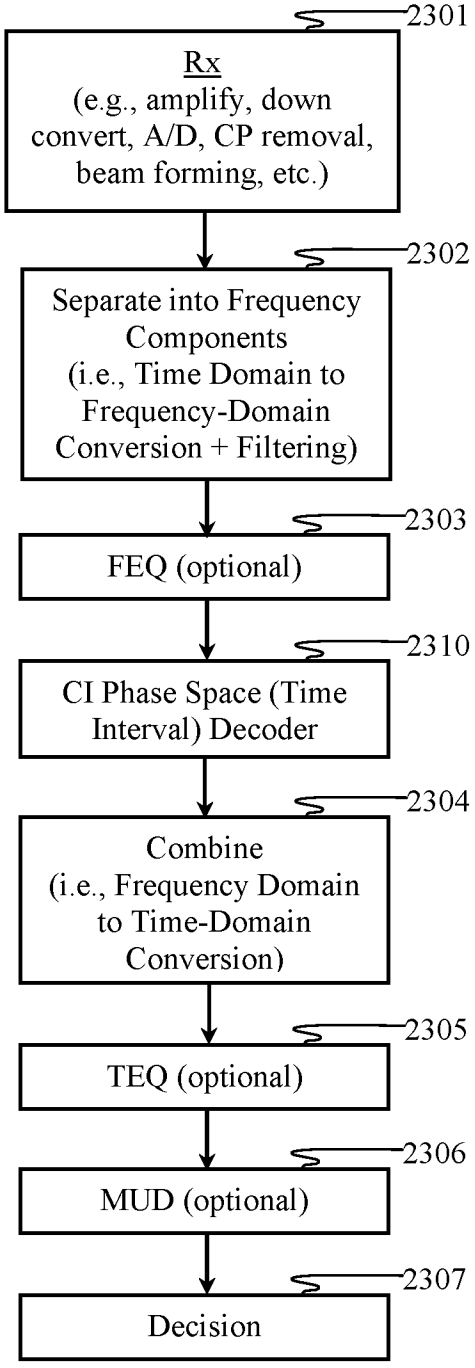


FIGURE 23B

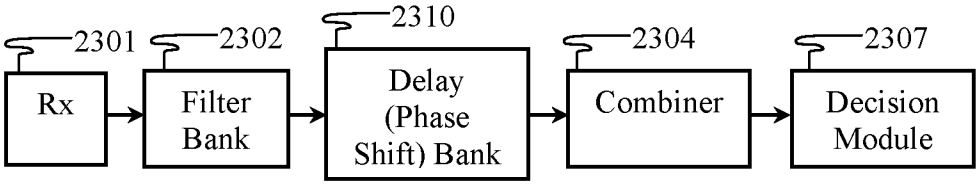


FIGURE 24A

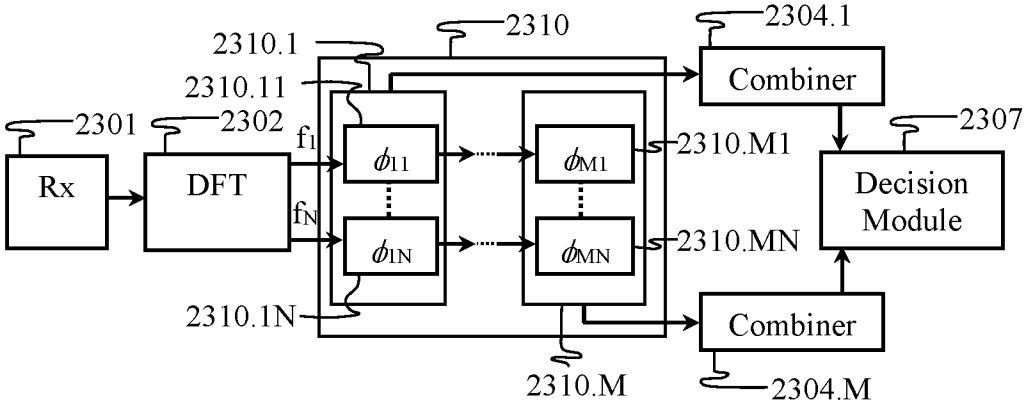


FIGURE 24B

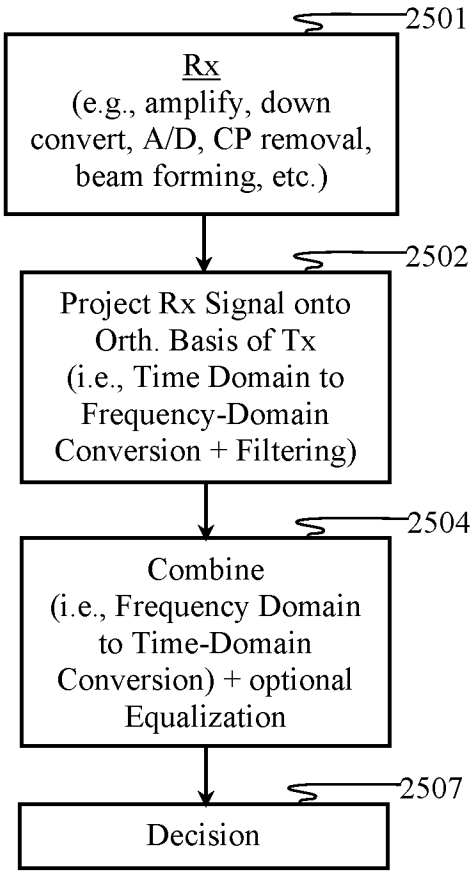


FIGURE 25A

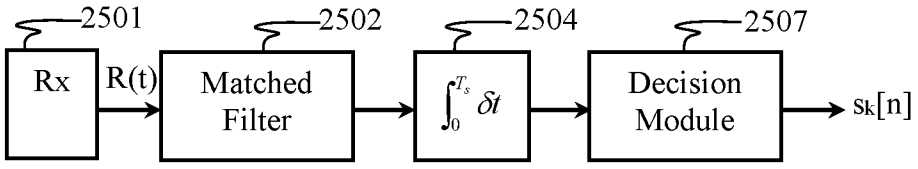


FIGURE 25B

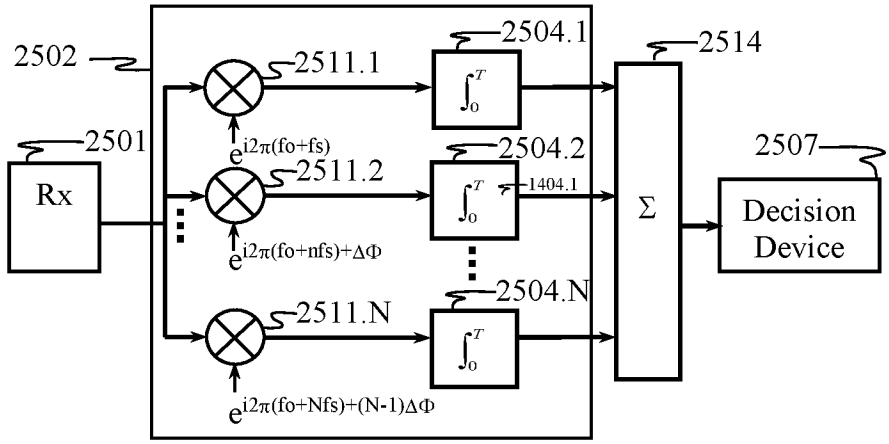


FIGURE 26A

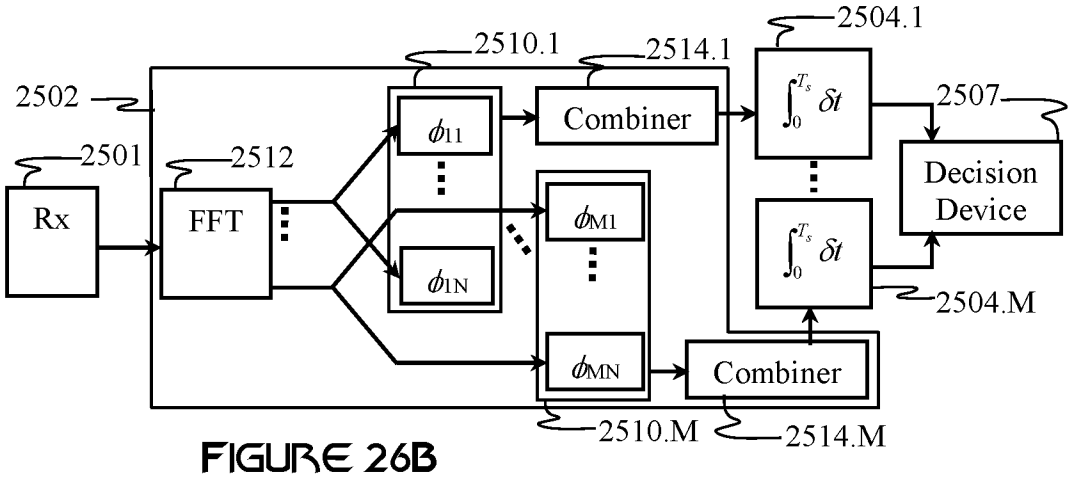


FIGURE 26B

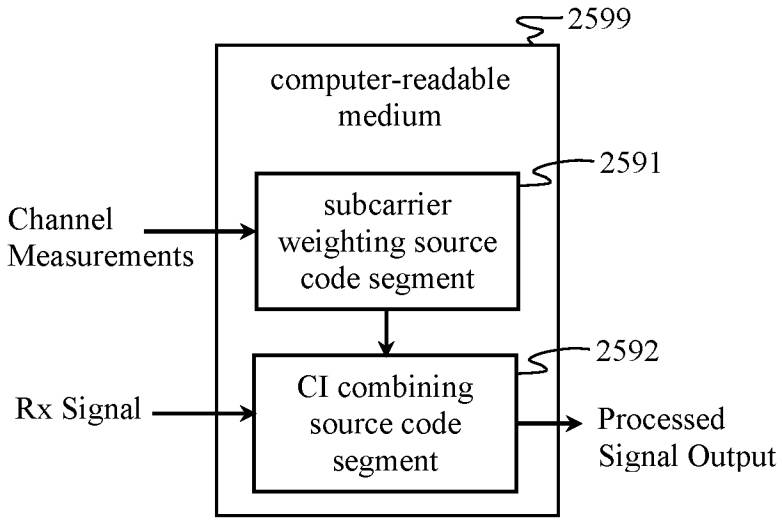


FIGURE 26C

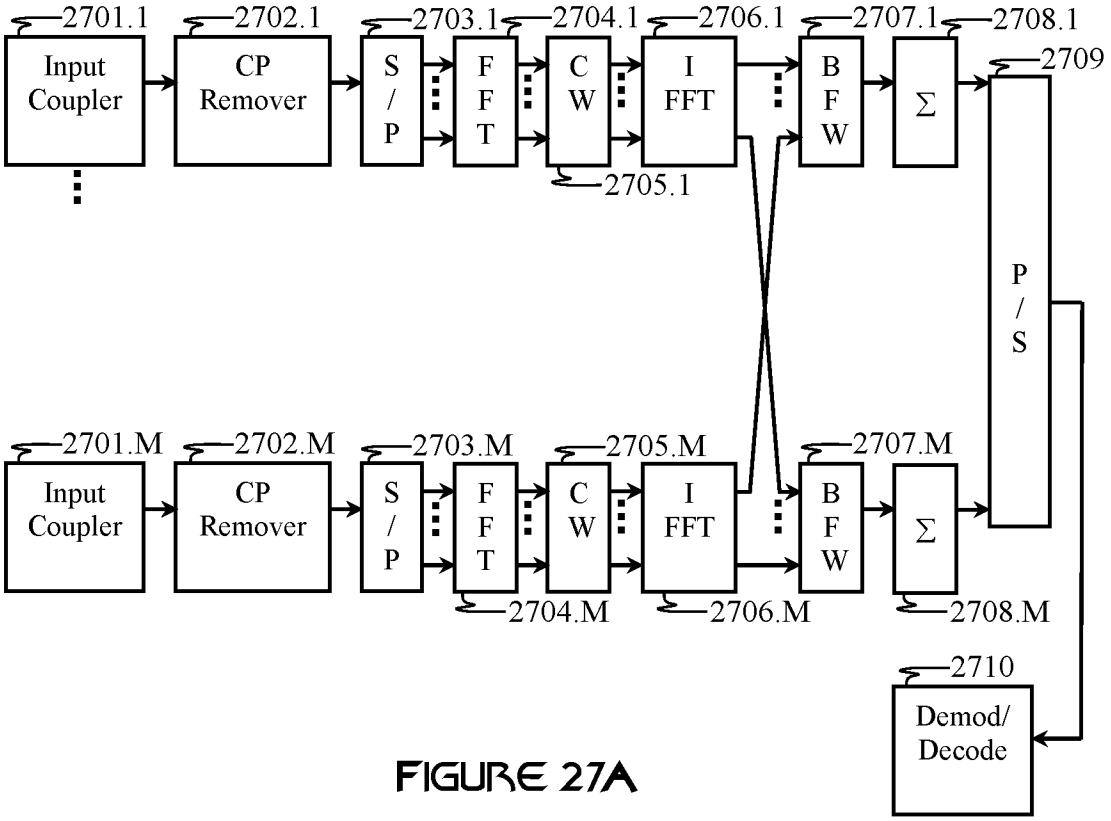


FIGURE 27A

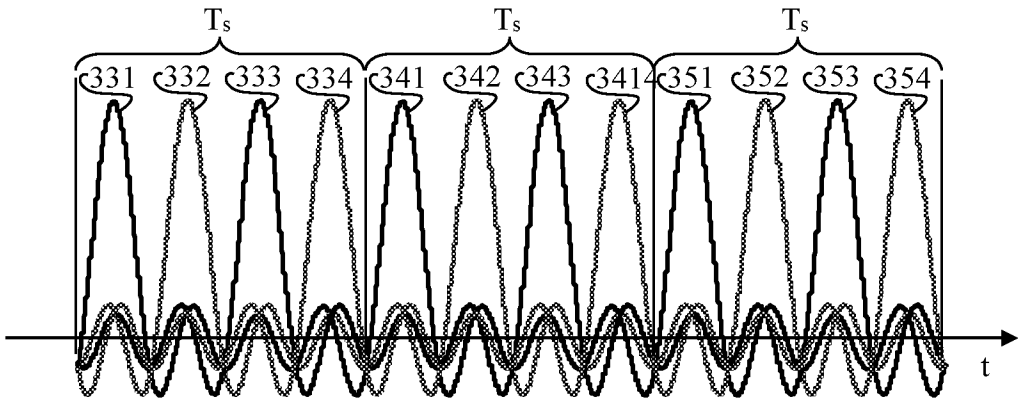


FIGURE 27B

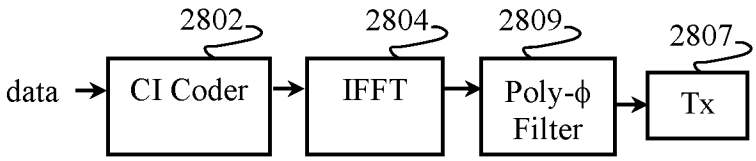


FIGURE 28A

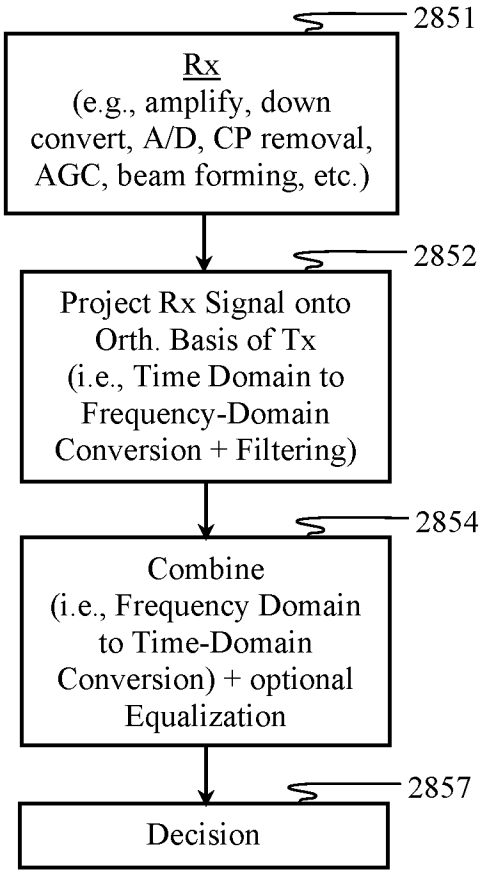


FIGURE 28B

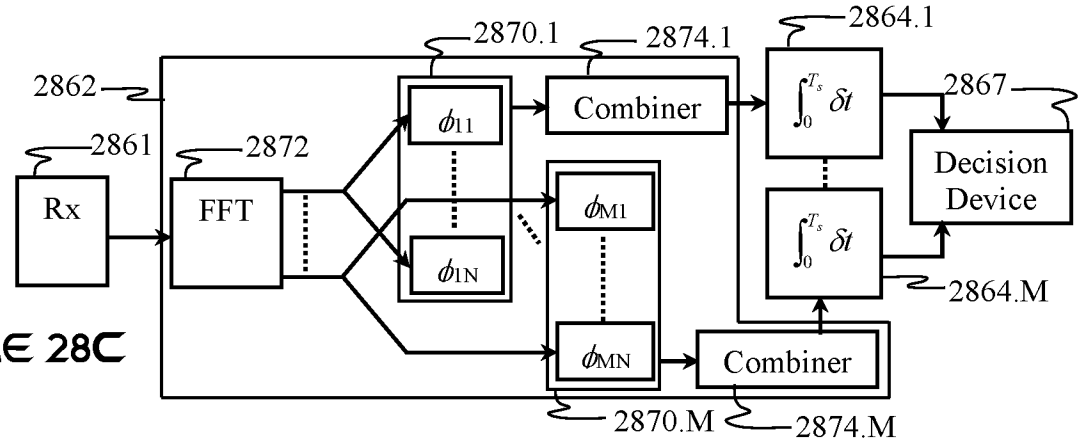


FIGURE 28C

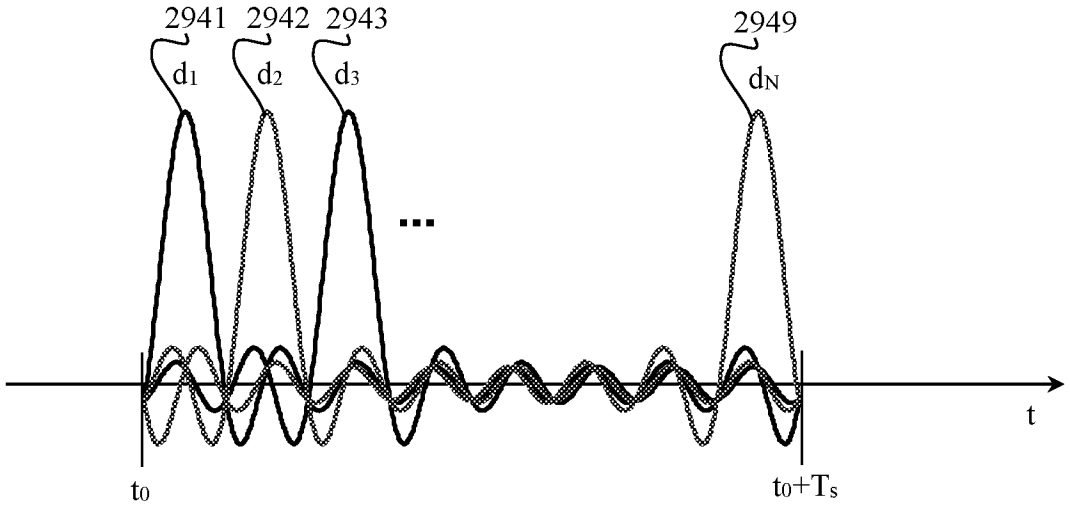


FIGURE 29A

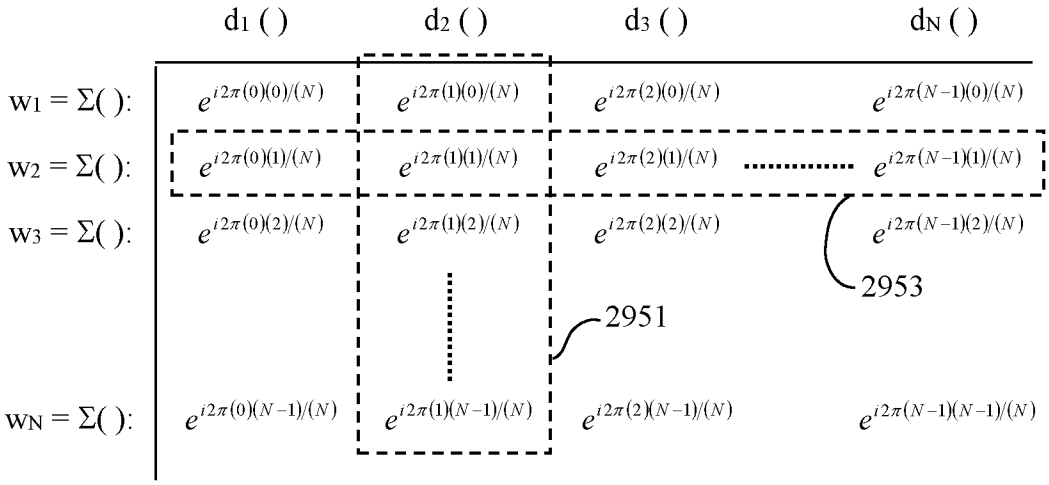


FIGURE 29B

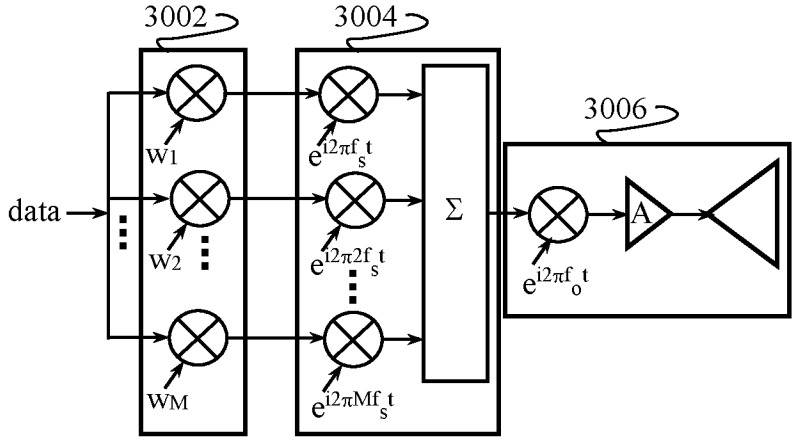


FIGURE 30A

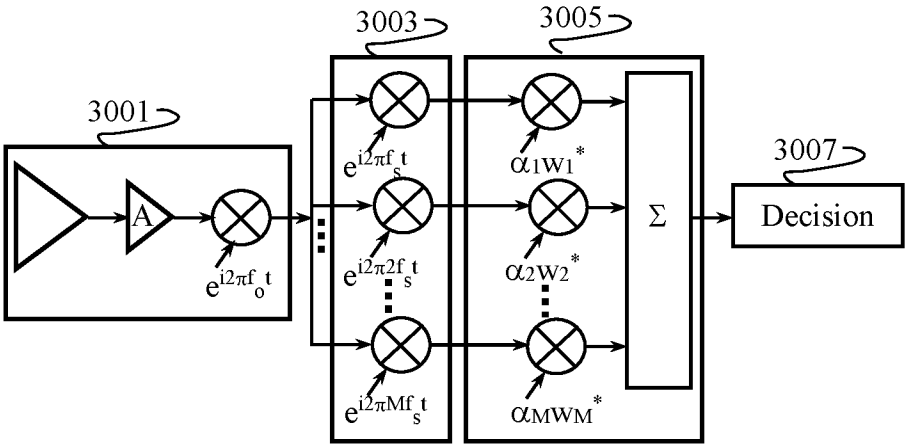


FIGURE 30B

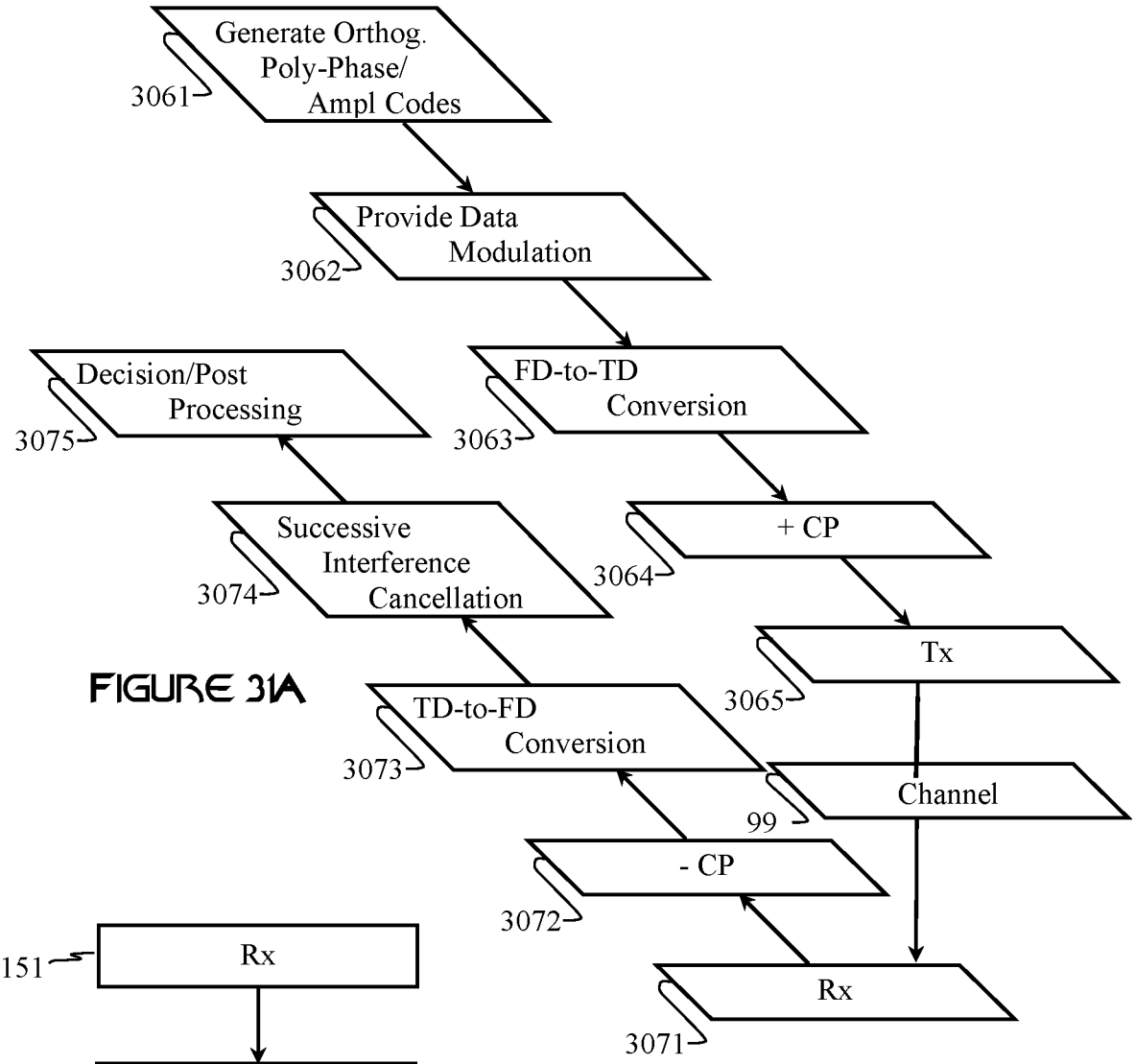


FIGURE 31A

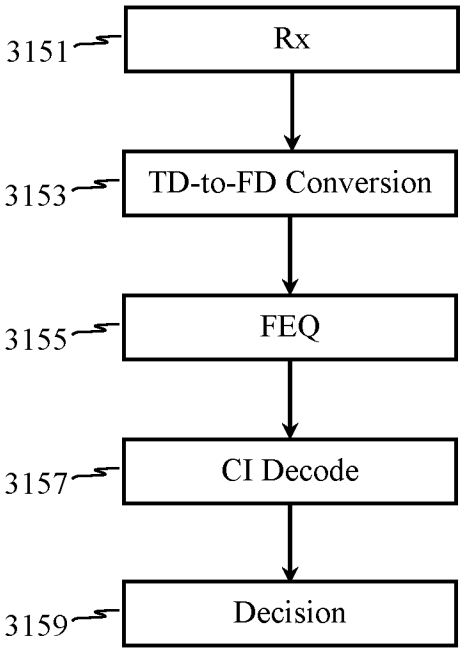


FIGURE 31B

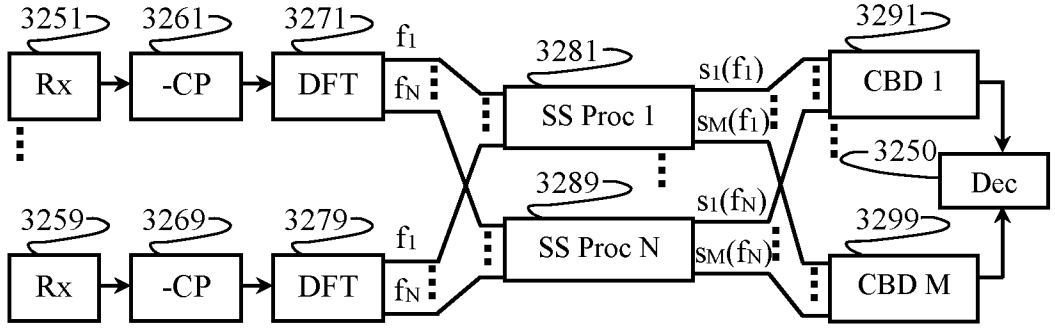


FIGURE 32

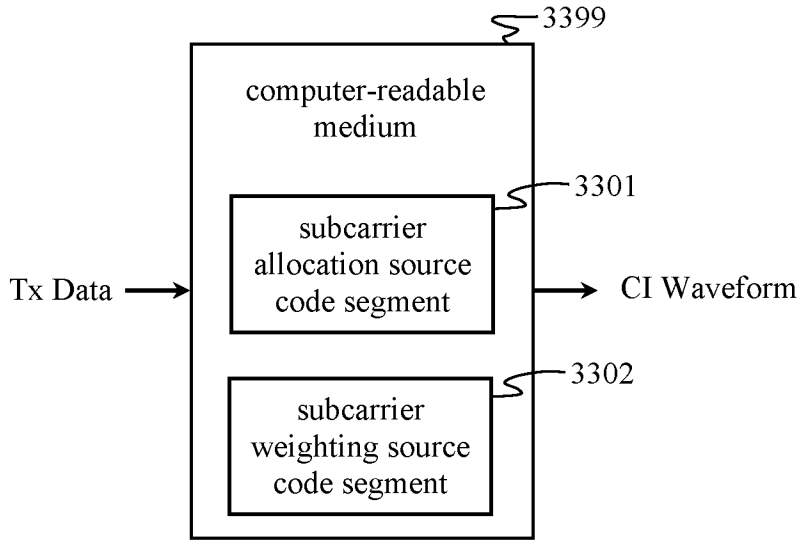


FIGURE 33A

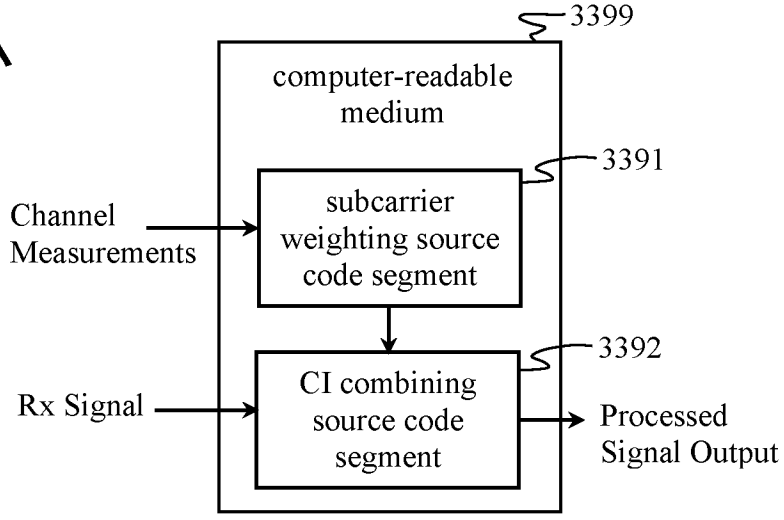


FIGURE 33B

Patent Application

of

Steve Shattil

for

Transmit Pre-Coding

RELATED APPLICATIONS

This application is a Continuation of U.S. Pat. Appl. No. 14/727,769, filed June 1, 2015, which is a Continuation of U.S. Pat. Appl. No. 14/276,309, filed May 13, 2014, now U.S. Pat. No. 9,048,897, which is a Continuation of U.S. Pat. Appl. No. 12/545,572, filed August 21, 2009, now U.S. Pat. No. 9,042,333, which is a Divisional of U.S. Pat. Appl. No. 11/187,107, filed on July 22, 2005, now U.S. Pat. No. 8,670,390, which claims priority to Provisional Appl. No. 60/598,187, filed August 2, 2004, all of which are incorporated by reference in their entireties.

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BACKGROUND

I. Field

Disclosed aspects relate generally to antenna-array processing and ad-hoc networking, and particularly to providing cooperative signal processing between a plurality of wireless terminal devices, such as to improve network access.

II. Background

Wireless data service is an emerging market with high growth potential. However, market growth requires higher bandwidth and better coverage than cellular technologies can provide. Furthermore, state-of-the-art wireless network technologies are mainly focused on the server side, rather than using mobile wireless terminals to extend the network infrastructure.

A peer-to-peer mode of communication is expected to offer distinct performance benefits over the conventional cellular model, including better spatial-reuse characteristics, lower energy consumption, and extended coverage areas. The key advantage of the peer-to-peer network model is the increase in spatial reuse due to its short-range transmissions. Although peer-to-peer networking shows some promise, there are significant drawbacks that prevent conventional peer-to-peer networks from being a technically and commercially viable solution.

Recent analyses of multi-hop networks compared to cellular networks have indicated that the spatial reuse improvement in the peer-to-peer network model does not translate into greater throughput. Rather, the throughput is lower than that observed in the cellular network model. This observation is explained in three parts:

- *Multi-hop Routes:* Although the spatial reuse is increased, since a flow traverses multiple hops in the peer-to-peer network model, the end-to-end throughput of a flow, while directly proportional to the spatial reuse, is also inversely proportional to the hop-length. Moreover, since the expected hop-length in a dense network is of the order of $O(\sqrt{n})$, a tighter bound on the expected per-flow throughput is $O(1/\sqrt{n})$. While this bound is still higher than that of the dense cellular network model ($O(1/n)$), the following two reasons degrade the performance even more.
- *Base-Station Bottleneck:* The degree of spatial reuse and expected per-flow throughput of the peer-to-peer network model is valid for a network where all flows

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have destinations within the same cell. In this case, the base station is the destination for all flows (e.g., it is the destination of the wireless path). Thus, any increase in spatial reuse cannot be fully realized as the channel around the base-station becomes a bottleneck and has to be shared by all the flows in the network. Note that this is not an artifact of the single-channel model. As long as the resources around the base-station are shared by all the flows in the network (irrespective of the number of channels), the performance of the flows will be limited to that of the cellular network model.

- *Protocol Inefficiencies:* The protocols used in the cellular network model are both simple and centralized, with the base station performing most of the coordination. Cellular protocols operate over a single hop, leading to very minimal performance degradation because of protocol inefficiencies. However, in the peer-to-peer network model, the protocols (such as IEEE 802.11 and DSR) are distributed, and they operate over multiple hops. The multi-hop path results in more variation in latency, losses, and throughput for TCP. These inefficiencies (which arise because of the distributed operation of the medium access and routing layers) and the multi-hop operation at the transport layer translate into a further degraded performance.

Similarly, antenna-array processing has demonstrated impressive improvements in coverage and spatial reuse. Array-processing systems typically employ multiple antennas at base stations to focus transmitted and received radio energy and thereby improve signal quality. In cellular communications, improvements in signal quality lead to system-wide benefits with respect to coverage, service quality and, ultimately, the economics of cellular service. Furthermore, the implementation of antenna arrays at both ends of a communication link can greatly increase the capacity and performance benefits via Multiple Input Multiple Output (MIMO) processing. However, power, cost, and size constraints typically make the implementation of antenna arrays on mobile wireless terminals, such as handsets or PDAs, impractical.

In cooperative diversity, each wireless terminal is assigned an orthogonal signal space relative to the other terminals for transmission and/or reception. In particular, both multiplexing and multiple access in cooperative diversity are orthogonal. In antenna-array processing, either or both multiplexing and multiple access are non-orthogonal.

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Specifically, some form of interference cancellation is required to separate signals in an array-processing system because transmitted and/or received information occupies the same signal space.

Applications and embodiments relate to ad-hoc networking and antenna-array processing. Embodiments may address general and/or specific needs that are not adequately serviced by the prior art, including (but not limited to) improving network access (e.g., enhancing range, coverage, throughput, connectivity, and/or reliability). Applications of certain embodiments may include tactical, emergency response, and consumer wireless communications. Due to the breadth and scope of the present invention, embodiments may be provided for achieving a large number of objectives and applications, which are too numerous to list herein. Therefore, only some of the objects and advantages of specific embodiments are discussed in the Summary and in the Detailed Description.

SUMMARY

Some of the exemplary embodiments of the disclosure are summarized as follows. Embodiments include beam-forming systems configured to enable spatially separated wireless terminals (WTs) to perform beam-forming operations in a wireless wide area network (WWAN). A wireless local area network (WLAN) couples together the WTs, which may be configured to share WWAN data, access, and control information. A beam-forming system may comprise the WTs, which function as elements of an antenna array. WWAN network access functions (such as monitoring control channels and exchanging control messages with the WWAN) may be provided in a centralized or a distributed manner with respect to the WTs.

Embodiments also include systems and methods configured for allocating network resources among the WTs, load balancing, distributed computing, antenna-switching diversity, WWAN diversity, interference mitigation, hand off, power control, authentication, session management, ad-hoc network control, error correction coding, and interference mitigation. Other embodiments and variations thereof are described in the Detailed Description.

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In one embodiment, a computer program comprises a beam-forming weight calculation source code segment adapted to calculate at least one set of beam-forming weights for signaling between at least one group of WTs and at least one WWAN, and a WLAN information-distribution source code segment adapted to distribute at least one of a set of signals between the at least one group of WTs, the set of signals including a plurality of received WWAN signals, a plurality of WWAN transmission data, and the at least one set of beam-forming weights.

In another embodiment. a computer program comprises a beam-forming weight source code segment adapted to calculate at least one set of beam-forming weights for signaling between at least one group of WTs and at least one WWAN, and a MIMO combining source code segment adapted to combine a plurality of weighted received WWAN signals, at least one of the beam-forming weight source code segment and the MIMO combining source code segment including WLAN information-distribution source code adapted to distribute at least one of a set of signals between the at least one group of wireless terminals, the set of signals including a plurality of received WWAN signals, a plurality of WWAN transmission data, at least one channel estimate, and the at least one set of beam-forming weights.

A receiver embodiment of the invention comprises a plurality of WWAN interfaces, wherein each WWAN interface is adapted to receive at least one transmitted WWAN signal; a plurality of baseband processors wherein each baseband processor is coupled to at least one WWAN interface in the plurality of WWAN interfaces, the plurality of baseband processors adapted to generate a plurality of WWAN baseband signals; at least one WLAN coupled to the plurality of baseband processors; and at least one MIMO combiner adapted to receive at least one WWAN baseband signal from the WLAN, the at least one MIMO combiner adapted to perform MIMO combining of a plurality of WWAN baseband signals.

A transmitter embodiment of the invention comprises a plurality of WWAN interfaces wherein each WWAN interface is adapted to transmit at least one WWAN signal; at least one data source adapted to generate at least one data signal for transmission into at least one WWAN; at least one WLAN adapted to couple the at least one data signal to the plurality of WWAN interfaces for generating a plurality of WWAN

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data signals; and at least one MIMO processor adapted to generate a plurality of complex weights for weighting the plurality of WWAN data signals.

A wireless terminal according to one aspect of the invention comprises at least one WWAN interface; at least one WLAN interface; and at least one cooperative beam-forming system coupled between the WWAN interface and the WLAN interface and adapted to perform beamforming with information received from the WLAN interface.

Receivers and cancellation systems described herein may be employed in subscriber-side devices (e.g., cellular handsets, wireless modems, and consumer premises equipment) and/or server-side devices (e.g., cellular base stations, wireless access points, wireless routers, wireless relays, and repeaters). Chipsets for subscriber-side and/or server-side devices may be configured to perform at least some of the receiver and/or cancellation functionality of the embodiments described herein.

Additional embodiments, objects, and advantages are described and inferred from the following detailed descriptions and figures. Although particular embodiments are described herein, many variations and permutations of these embodiments fall within the scope and spirit of the invention. Although some benefits and advantages of the preferred embodiments are mentioned, the scope of the invention is not intended to be limited to particular benefits, uses, or objectives. Rather, embodiments of the invention are intended to be broadly applicable to different wireless technologies, system configurations, networks, and transmission protocols, some of which are illustrated by way of example in the figures and in the following detailed description. The detailed description and drawings are merely illustrative of the invention rather than limiting, the scope of the invention being defined by the appended claims and equivalents thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A illustrates an application of various embodiments of the invention to a cellular network.

Figure 1B illustrates an embodiment of the invention in which transmitted and/or received data between a WLAN group and a WWAN terminal occupies parallel, redundant channels c_n.

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Figure 1C illustrates an embodiment of the invention in which a WLAN group comprising a plurality of Wireless Terminals (WTs) is adapted to communicate with at least one WWAN node.

Figure 1D illustrates an embodiment of the invention in which communications between a WWAN node and a plurality of WTs are characterized by different, yet complementary, code spaces c_1, c_2, and c_3.

Figure 1E illustrates an embodiment of the invention in which a first WLAN group is adapted to communicate with a second WLAN group via at least one WWAN channel or network.

Figure 1F shows an embodiment of the invention wherein a WLAN group includes a plurality of WWAN-active WTs and at least one WWAN-inactive WT.

Figure 1G illustrates a cooperative beam-forming embodiment of the invention that functions in the presence of a desired WWAN terminal and a jamming source.

Figure 1H illustrates a cooperative beam-forming embodiment of the invention that functions in the presence of a plurality of desired WWAN terminals.

Figure 1I illustrates an embodiment of the invention adapted to provide a plurality of WTs in a WLAN group with access to a plurality of WWAN services.

Figure 1J illustrates an embodiment of the invention in which a WLAN group includes at least one WWAN terminal.

Figure 2A illustrates a functional receiver embodiment of the invention that may be realized in both method and apparatus embodiments.

Figure 2B illustrates a functional receiver embodiment of the invention that may be realized in both method and apparatus embodiments.

Figure 3A illustrates an embodiment of the invention in which a WLAN controller for a WLAN group allocates processing resources based on WWAN-link performance.

Figure 3B illustrates an alternative embodiment of the invention in which a WLAN controller for a WLAN group allocates processing resources based on WWAN-link performance.

Figure 4A illustrates a MIMO receiver embodiment of the invention.

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Figure 4B illustrates a functional embodiment of the invention in which MIMO processing operations are distributed over two or more WTs.

Figure 4C illustrates a functional embodiment of the invention for transmission and reception of WWAN signals in a distributed network of WTs.

Figure 4D illustrates a functional embodiment of the invention adapted to perform cooperative beamforming.

Figure 5A illustrates a receiver embodiment of the invention that may be implemented by hardware and/or software.

Figure 5B illustrates an alternative receiver embodiment of the invention.

Figure 6A illustrates functional and apparatus embodiments of the present invention pertaining to one or more WTs coupled to at least one WWAN and at least one WLAN.

Figure 6B illustrates a preferred embodiment of the invention that may be employed as either or both apparatus and functional embodiments of one or more WTs.

Figure 7A illustrates a functional embodiment of the invention related to calculating MIMO weights in a cooperative-beamforming network.

Figure 7B illustrates a functional embodiment of the invention adapted to calculate transmitted data symbols received by a cooperative-beamforming network.

Figure 8A illustrates a preferred transmitter embodiment of the invention.

Figure 8B illustrates a preferred receiver embodiment of the invention.

Figure 8C illustrates an embodiment of the invention in which a plurality of WTs is adapted to perform time-domain processing.

Figure 9A illustrates an optional transmission embodiment of the present invention.

Figure 9B illustrates a functional flow chart that pertains to transmitter apparatus and method embodiments of the invention.

Figure 10A illustrates software components of a transmission embodiment of the invention residing on a computer-readable memory.

Figure 10B illustrates software components of a receiver embodiment of the invention residing on a computer-readable memory.

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Figure 11 shows a WWAN comprising a WWAN access point (e.g., a base station) and a local group comprising a plurality of wireless terminals communicatively coupled together via a WLAN. A network-management operator is configured to handle WWAN-control operations within the local group.

Figure 12 is a block diagram of a communication system comprising a WLAN for communicatively coupling a plurality of mobile wireless terminals to a WLAN controller, and a network-management operator for cooperatively processing WWAN-control messages for the mobile wireless terminals.

Figure 13 is a block diagram of a mobile wireless terminal in accordance with an aspect of the invention in which a WWAN network management operator module is communicatively coupled to at least one other mobile wireless terminal via a WLAN and communicatively coupled to the WWAN.

Figure 14 illustrates a method in accordance with an aspect of the invention in which WWAN communications for a group of wireless terminals are cooperatively processed.

Figure 15 is a plot of a plurality of CI carriers and a superposition of the carriers.

Figure 16A is a plot of the relative frequency-versus-amplitude profile of a plurality of CI carriers that are combined to produce a time-domain pulse train, such as a DS-CDMA chip sequence.

Figure 16B is a time-domain representation of a modulated pulse train produced by providing time offsets to a plurality of modulated pulses, or equivalently, from a superposition of the CI carriers represented in Figure 2A.

Figure 17A illustrates a plurality of CI pulse waveforms modulated with code and/or information symbols .beta..sub.n and positioned orthogonally in time.

Figure 17B illustrates a CI pulse train of orthogonally time-offset pulses.

Figure 18A illustrates CI signal generation.

Figure 18B illustrates a CI transmitter.

Figures 19 and 20 each illustrates a system and method of generating CI signals.

Figure 21 illustrates basic components of CI signal generation software residing on a computer-readable medium.

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Figure 22A is a time-domain plot of a plurality of pulses generated from a superposition of equally spaced carriers, and shows a set of carrier phases corresponding to each of the pulses.

Figure 22B represents basic components and characteristics of a CI waveform.

Figure 23A is a functional flow chart of a CI receiver.

Figure 23B illustrates a CI receiver method and apparatus including a phase-space decoder.

Figure 24A shows an embodiment of a CI receiver.

Figure 24B shows an alternative embodiment of a CI receiver.

Figure 25A illustrates an aspect of a CI reception method and apparatus.

Figure 25B illustrates a CI receiver method and system of the present invention.

Figure 26A illustrates a CI receiver apparatus and method of the invention.

Figure 26B is a flow diagram for a receiver that receives a CI signal and samples the signal in multiple phase spaces.

Figure 26C illustrates basic components of a computer program on a computer-readable medium adapted to control a receiver and optimize performance.

Figure 27A illustrates a CI receiver configured as a multi-element receiver. Such receiver configurations may be employed in multiple-input, multiple-output (MIMO) communications.

Figure 27B illustrates three pulse-waveform blocks wherein each block includes four pulse waveforms of duration T.sub.s.

Figure 28A illustrates a CI transmitter.

Figure 28B illustrates a CI reception method and apparatus.

Figure 28C shows a CI receiver adapted to project a received signal onto at least one orthonormal basis, such as an orthonormal basis corresponding to at least one transmitted signal.

Figure 29A illustrates a block waveform including a set of orthogonal CI pulse waveforms.

Figure 29B illustrates a method for generating sub-carrier weights from a set of data symbols and a CI code matrix.

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Figure 30A illustrates a transmitter apparatus and method configured to generate multiple transmission waveforms.

Figure 30B shows a receiver apparatus and method adapted to process a wide range of single-carrier and/or multi-carrier transmissions.

Figure 31A illustrates a communication method.

Figure 31B shows CI processing of received single-carrier and/or multi-carrier signals.

Figure 32 illustrates a sub-space/sub-carrier processor receiver.

Figure 33A illustrates basic components of CI signal generation software residing on a computer-readable medium.

Figure 33B illustrates basic components of CI receiver software residing on a computer-readable medium.

DETAILED DESCRIPTION

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the exemplary embodiments are not intended to limit the invention to the particular forms disclosed. Instead, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

Figure 1A illustrates how some embodiments of the invention may be employed in a cellular network. Each wireless terminal (WT) of a plurality of WTs 101-103 is in radio contact with at least one wireless wide area network (WWAN) terminal, which may also be referred to as a WWAN node, such as cellular base station 119. The cellular base station 119 may include one or more antennas (e.g., an antenna array). WWAN signals transmitted between the base station 119 and the WTs 101-103 propagate through a WWAN channel 99, which is typically characterized by AWGN, multipath effects, and may include external interference.

The WTs 101-103 represent a wireless local area network (WLAN) group 110 (or local group) if they are currently connected or are capable of being connected via a WLAN 109. Accordingly, the WTs may be adapted to connect to at least one WWAN

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and to at least one WLAN. The WLAN group 110 may consist of two or more WTs in close enough proximity to each other to maintain WLAN communications. A given WWAN may include one or more WLAN groups, such as WLAN group 110.

In an exemplary embodiment of the present invention, the WTs 101-103 may be configured to transmit data $d_t(n)$ over a WWAN channel to the base station 119. The WTs 101-103 may also be configured to receive data $d_r(n)$ on a WWAN channel from the base station 119. The received data $d_r(n)$ is shared by the WTs 101-103 via the WLAN 109. Similarly, the transmitted data $d_t(n)$ may be distributed to the WTs 101-103 via the WLAN 109. The WLAN 109 typically comprises the wireless-communication resource between the WTs 101-103 and the associated physical-layer interface hardware. The WLAN 109 is differentiated from a WWAN by its relatively shorter range. For example, a Bluetooth or UWB system functioning within an IEEE 802.11 network would be referred to as a WLAN, whereas the 802.11 network would be referred to as a WWAN. A WLAN may operate in a different frequency band than the WWAN. Alternatively, other orthogonalizing techniques may be employed for separating WLAN and WWAN signals from each other. WLANs and WWANs, as defined herein, may employ any type of free-space transmissions, including, but not limited to, ultra-low frequency, RF, microwave, infrared, optical, and acoustic transmissions. WLANs and WWANs may employ any type of transmission modality, including, but not limited to, wideband, UWB, spread-spectrum, multi-band, narrowband, or dynamic-spectrum communications.

The WLAN 109 may also comprise the WLAN network-control functionality commonly associated with a WLAN, and the WWAN-access control functionality required to distribute necessary WWAN-access parameters (e.g., node addresses, multiple-access codes, channel assignments, authentication codes, etc.) between active WTs 101-103. The distribution of WWAN-access parameters between multiple WTs 101-103 enables each WT 101-103 to be responsive to transmissions intended for a particular WT in the local group and/or it enables a plurality of WTs 101-103 to function as a single WT when transmitting signals into the WWAN channel 99.

Particular embodiments of the invention provide for adapting either or both the transmitted data $d_t(n)$ and the received data $d_r(n)$ in order to perform beamforming. Specifically, the group of WTs 110 may be adapted to perform antenna-array processing

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by linking the individual WTs together via WLAN links 109 and employing appropriate antenna-array processing on the transmitted and/or the received data, $d_t(n)$ and $d_r(n)$, respectively.

Ad-hoc wireless networks (e.g., multi-hop and peer-to-peer networks) may employ intermediate relay nodes to convey transmissions from a source to a destination. Relays reduce the transmission power requirements for sending information over a given distance. This indirectly increases the spatial-reuse factor, thus enhancing system-wide bandwidth efficiency. For this reason, ad-hoc wireless networking works particularly well with unlicensed spectrum, which is characterized by restrictive power limitations and high path loss compared to cellular bands. Similarly, for certain embodiments of the invention, it may be preferable to employ high-loss (e.g., high-frequency) channels for the WLAN connections 109.

The capacity of wireless ad-hoc networks is constrained by interference caused by the neighboring nodes, such as shown in P. Gupta and P.R. Kumar, "The Capacity of Wireless Networks," IEEE Trans. Info. Theory, vol. IT-46, no. 2, Mar. 2000, pp. 388-404 and in A. Agarwal and P. R. Kumar, ``Improved capacity bounds for wireless networks." Wireless Communications and Mobile Computing, vol. 4, pp. 251-261, 2004, both of which are incorporated by reference herein. Using directional antennas (such as antenna arrays) reduces the interference area caused by each node, which increases the capacity of the network. However, the use of directional antennas and antenna arrays on the WTs 101-103 is often not feasible, especially when there are size constraints, power restrictions, cost constraints, and/or mobility needs. Thus, some embodiments of the present invention may provide for enabling WTs to form groups that cooperate in network-access functions. This provides each member of a given WLAN group with greater network access, as well as other benefits.

Antenna-array processing is generally categorized as multiple-input, single-output (MISO), single-input, multiple-output (SIMO) or multiple input, multiple output (MIMO). Array processing often employs beam forming in at least one predetermined signal space or signal sub-space. For example, phased-array processing involves coherent beam-forming of at least one transmitted signal frequency. Sub-space processing often employs some form of baseband interference cancellation or multi-user detection. Other

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variations of phased-array and sub-space processing also exist and may be implemented in embodiments of the present invention.

Sub-space processing is commonly employed via space-time processing (e.g., Rake receivers are employed in a frequency-selective channel) and/or space-frequency processing (e.g., frequency-domain processing is employed to provide for multiple flat-fading channels). Similarly, sub-space processing may employ other diversity parameters and combinations thereof, including (but not limited to) polarization processing and code-space processing.

MIMO systems have been shown to significantly increase the bandwidth efficiency while retaining the same transmit power budget and bit-error-rate (BER) performance relative to a single input, single output (SISO) system. Similarly, for a given throughput requirement, MIMO systems require less transmission power than SISO systems. MIMO technology is useful for enabling exceptionally high bandwidth efficiency. However, many spatial-multiplexing techniques require rich scattering. Increased path loss and poor scattering are major problems for MIMO systems operating above 2.4GHz. For these reasons, lower (e.g., cellular) frequencies are often preferred for MIMO applications. However, some MIMO benefits can also be achieved at higher frequencies.

Figure 1B illustrates an embodiment of the present invention in which transmitted and/or received data between the WLAN group 110 and the WWAN terminal 119 occupies parallel, redundant channels c_n. This approach is distinct from typical cooperative-diversity implementations in which WWAN data transmissions are conveyed over a plurality of orthogonal channels. Rather, each of the WTs 101-103 transmits and/or receives on a common channel c_n. This enables many well-known types of array processing to be performed.

The WLAN group 110 may function as either or both a transmitting array and a receiving array. The signal received at an antenna array is a noisy superposition of the n transmitted signals:

$$y(n) = \sqrt{\frac{E_s}{M_t}} Hs(n) + v(n)$$

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where $\{s(n)\}_{n=0}^{N-1}$ is a sequence of transmitted vectors, E_s corresponds to the transmit energy assuming that $E_{sn}||s_n|| = 1$ for $n = 1,\ldots,M_t$, $v(n)$ represents AWGN with zero mean and variance, and H is an $M_r \times M_t$ matrix channel (where M_r is the number of receiver elements and M_t is the number of transmitter elements), which is assumed constant over N symbol periods. The nominal rank of a rational matrix H is the order of the largest minor of H that is not identically zero, such as shown in T. Kailath, Linear Systems, Prentice-Hall, Inc., 1980, (especially Sec. 6.5), which is incorporated by reference.

Channel characterization involves finding a set of channel realizations (e.g., functions) that indicate channel quality with respect to some performance metric (e.g., error probability or asymptotic criteria). In the MIMO channel, several variables contribute to the channel quality (and thus, to the optimization of channel quality), including the choice of space-time codes, receiver-terminal selection, and receiver algorithm(s) employed.

In one embodiment of the invention, a subset of WTs in a WLAN group may be selected such as to provide optimal WWAN transmission and/or reception within at least one predetermined constraint, such as an optimal or maximum number of active WWAN transceivers within the WLAN group. Such predetermined constraints may be established to optimize some combination of WWAN link performance and resource use within the WLAN group. In one embodiment, WTs experiencing the best WWAN channel conditions may be selected. Techniques employing antenna selection, such as may be used for diversity processing with antenna arrays, may be used in embodiments of the present invention. In one aspect of the invention, resource conservation may focus on WT battery power, MIMO processing complexity, and/or WLAN bandwidth.

Certain embodiments of the invention may distinguish between circuit power (e.g., power used to perform signal processing) versus transmission power. Other embodiments of the invention may provide consideration for the total battery power (e.g., processing power plus transmission power) budget, such as to provide power (e.g., battery usage) load balancing between WTs. Thus, embodiments of the invention may optimize a balance of signaling parameters, including (but not limited to) transmission power, channel-coding (and decoding) complexity, modulation, signal processing and the

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complexity associated with cooperative array processing parameters (e.g., number of active array elements, number of channels, number of WTs employed to perform signal processing, number of WTs in a WLAN group, type of array-processing operations, etc.).

Any combination of various channel-characterization functions may be employed as a measure of link performance. Example functions including, but not limited to, the following may be employed. Possible functions include the average signal strength:

$$P(\mathrm{H}) = \frac{1}{N}\sum_{n=0}^{N-1}\left\|H^{(n)}\right\|_F^2$$

the average mutual information:

$$\bar{I}(\mathrm{H}) = \frac{1}{N}\sum_{n=0}^{N-1}\log\det\left(I_{M_r} + \frac{E_s}{N_o M_t}H^{(n)}H^{(n)\mathrm{H}}\right)$$

and the normalized average mutual information:

$$\bar{I}(\mathrm{H}) = \frac{1}{N}\sum_{n=0}^{N-1}\log\det\left(I_{M_r} + \frac{E_s}{N_o}\frac{1}{\alpha}H^{(n)}H^{(n)\mathrm{H}}\right)$$

where $\alpha = \frac{1}{NM_tM_r}\sum_{n=0}^{N-1}\left\|H^{(n)}\right\|_F^2$ is an estimate of the path loss.

Theoretical capacity in a MIMO channel is typically expressed as:

$$C = \log_d \det\left[I_{M_r} + \rho/M_t HH^*\right]$$

where ρ is the average SNR.

A preferred embodiment of the invention may employ error-correcting codes to add structured redundancy to the information bits. This can be done to provide diversity, such as temporal diversity, spatial diversity, and/or frequency diversity. Embodiments of the invention may employ spreading codes, which are well known in the art. In addition to collaborative MIMO operations, the WTs may engage in collaborative decoding. In particular, a WLAN group may be provided with functionality that directs the WTs to coordinate WWAN information exchange and decoding via the WLAN.

In yet another embodiment of the invention, a WWAN terminal may be adapted to receive channel information (and/or even received data) from WTs, perform array-processing (e.g., MIMO) computations, and then upload the resulting array-processing

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weights to the WTs. The WTs may simply apply the weights to their transmitted and/or received WWAN signals, and perform any other related operations, such as combining.

Figure 1C illustrates a WLAN group 110 comprising a plurality of WTs 101-103 adapted to communicate with at least one WWAN node 119. A WWAN channel 99 expresses distortions, interference, and noise that affect WWAN transmissions between the WTs 101-103 and the WWAN node 119. Channel estimation characterizes propagation characteristics (e.g., multipath, shadowing, path loss, noise, and interference) in the WWAN channel.

In one embodiment of the invention, a given WWAN transmission is separated into spectral components (such as denoted by f_1, f_2, and f_3) by the WLAN group 110. For example, each of the WTs 101-103 may be adapted to receive predetermined spectral components f_1, f_2, and f_3 of a given transmission intended for a particular WT. Alternatively, each of the WTs 101-103 may be adapted to transmit one or more associated predetermined spectral components to the WWAN node 119.

The selection of spectral components f_1, f_2, and f_3 and their association with particular WTs 101-103 is typically performed to optimize WWAN system performance relative to the current WWAN channel 99. For example, since the frequency-dependent fading profile in a scattering-rich environment tends to be unique for each spatially separated WT 101-103 channel, the spectral components f_1, f_2, and f_3 are preferably selected to minimize the effects of deep fades and/or interference. Spectral-component selection may be selected and/or adapted to optimize one or more WWAN link-performance metrics, including, but not limited to, SNR, BER, PER, and throughput. Spectral-component selection may be performed to achieve other objectives, such as to distribute processing loads across the WLAN group 110.

The spectral components f_1, f_2, and f_3 may be characterized by overlapping or non-overlapping frequency bands. Spectral components f_1, f_2, and f_3 may each include continuous or discontinuous (e.g., frequency interleaved) frequency-band components. Spectral components f_1, f_2, and f_3 may comprise similar or different bandwidths. Furthermore, the spectral components f_1, f_2, and f_3 may include gaps or notches, such as to notch out interference or deep fades. Accordingly, an aggregate signal derived from combining the spectral components f_1, f_2, and f_3 may include gaps or notches.

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WWAN communication signals may include multicarrier (e.g., OFDM) or single-carrier signals. In the case of single-carrier signals, the WTs 101-103 can be adapted to perform frequency-domain synthesis and/or decomposition, such as described in published patent appl. nos. 20040086027 and 20030147655, which are hereby incorporated by reference in their entireties.

Figure 1D illustrates a similar communication-system embodiment to that shown in Figure 1C, except that the transmissions between the WWAN node 119 and the WTs 101-103 are characterized by different, yet complementary, code spaces c_1, c_2, and c_3. In this case, the term complementary means that the coded transmissions corresponding to the code spaces c_1, c_2, and c_3 can sum to produce at least one predetermined WWAN coded data sequence. This may be a weighted sum due to the given channel conditions. A predetermined WWAN coded data sequence may employ a code that would ordinarily (in view of the prior art) be employed in whole. That is, it would not ordinarily be partitioned into sub-codes to be transmitted by different transmitters or received by different receivers.

In one embodiment of the invention, the code spaces c_1, c_2, and c_3 correspond to direct-sequence codes, such as may be used to provide for spreading and/or multiple access. A superposition of signals transmitted across the code spaces c_1, c_2, and c_3 may provide at least one predetermined WWAN coded data sequence received by at least one WWAN node 119. Similarly, a superposition of signals received by the WTs 101-103 and mapped onto the code spaces c_1, c_2, and c_3 may provide at least one predetermined WWAN coded data sequence that would ordinarily (in view of the prior art) be intended for a single WT. Preferred embodiments of the invention may provide for channel corrections (e.g., pre-distortion and/or receiver-side channel compensation) by either or both the WLAN group 110 and the WWAN node 119. Accordingly, the code spaces c_1, c_2, and c_3 may be adapted to account for channel conditions.

In another embodiment of the invention, the code spaces c_1, c_2, and c_3 may correspond to direct-sequence codes having predetermined spectral characteristics. It is well known that different time-domain data sequences may be characterized by different spectral distributions. Accordingly, embodiments of the invention may provide for selecting complementary codes c_1, c_2, and c_3 having predetermined spectral

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characteristics with respect to WWAN channel conditions affecting the links between the WTs 101-103 and the WWAN node 119. Thus, the codes c_1, c_2, and c_3 may be selected according to the same criteria employed for selecting the spectral components f_1, f_2, and f_3.

Figure 1E illustrates an embodiment of the invention in which a first WLAN group 110 (such as comprising WTs 101-103 connected via WLAN 109) is adapted to communicate with a second WLAN group 120 (such as comprising WTs 111-113 connected via WLAN 118) via WWAN channel 99. Applications of this embodiment may be directed toward peer-to-peer and multi-hop networks. Specifically, antenna-array processing (e.g., MIMO operations) may be performed by both WLAN groups 110 and 120. Each WLAN group (such as WLAN groups 110 and 120) may function as a single node in an ad-hoc network, a peer-to-peer network, or a multi-hop network. For example, any communication addressed to (or routed through) a particular node (such as one of the WTs 101-103) may be advantageously processed by one or more of the WTs 101-103 in the WLAN group 110. In one embodiment, each active WT 101-103 in the WLAN group 110 may be responsive to communications addressed to itself and to at least one other WT 101-103 in the WLAN group 110.

The WLAN 109 may be used to inform individual WTs 101-103 which node address(es) (or multiple-access channel assignments) to be responsive to. Similarly, the WLAN 109 may convey information to WTs 101-103 in order to spoof node addresses and/or multiple-access information and otherwise help WTs 101-103 assume channelization information related to a particular WT identity prior to transmitting signals into the WWAN. Thus, the WLAN 109 can be used to assist in synchronizing WT interactions with the WWAN. The functionality of providing for sharing WWAN-access information between WTs 101-103 may be coordinated and controlled with respect to cooperative-array (e.g., MIMO) processing.

Figure 1F shows an embodiment of the invention wherein a WLAN group 110 includes a plurality of WWAN-active WTs 101-103 and at least one WWAN-inactive WT, such as WTs 104-106. The WWAN-active WTs 101-103 may be configured to directly transmit and/or receive WWAN communication signals 129. WWAN-inactive WTs 104-106 are defined as WLAN-connected terminals that do not directly

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communicate with the WWAN. Rather, the WWAN-inactive WTs 104-106 may be in a sleep or standby mode.

In a preferred embodiment of the invention, signals routed to and from a particular WT 101-103 may be provided with beam-forming weights that allow for phased-array and/or sub-space processing. Calculation of the weights may be facilitated via distributed computing (e.g., as a load-balancing measure) across a plurality of the WTs (101-106). This allows the WLAN group 110 to scale the effective throughput of the WWAN link and coordinate system throughput with local area load balancing. In particular, the efficiency of the WWAN link is proportional to the smaller of the number of array elements at the WWAN terminal (not shown) and the number of WWAN-active transceiver antennas linked by the WLAN 109. When an equal number N of antennas is employed on both sides of the link, up to an N-fold increase in the link throughput is possible. Channel coding can be employed to exchange this increase for improved probability-of-error performance, increased range, and/or lower transmission power.

Although the capacity of a MIMO channel increases with the number of antennas employed at both ends of the link, the complexity of the transmission and reception algorithms increases accordingly. For example, the sphere decoder has a typical complexity of $O(M_T^6)$, where M_T is the number of transmitting antennas, and V-Blast has a typical complexity of $O((M_R M_T)^3)$, where M_R and M_T are respectively the number of receiving and transmitting antennas. However, the computational power increases only linearly with respect to the number of WTs (assuming each WT has identical processing capability). Thus, the aggregate processing power of the WTs may determine the maximum number of active antennas that a WLAN group 110 can support.

One solution to the disparity between required processing power and the number of WT processors in a given WLAN group 110 is to ensure that the total number of WTs exceeds the number of MIMO channels in the group 110. This approach enables at least two significant processing advantages:

1) The processing load may be spread over a larger number of mobile-terminal processors, and
2) A form of antenna-switching diversity can be used to optimize performance and throughput in the MIMO channel.

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Antenna switching is a well-known technique that switches between various antennas and selects ones having the best signal outputs. This can be done to reduce correlation between antennas, thereby improving MIMO performance. Antenna switching is described in G.J. Foschini, M.J. Gans, "On limits of wireless communication in a fading environment when using multiple antennas," *Wireless PersonalCommunications*, vol. 6, no. 3, pp. 311-335, March 1998, which is incorporated by reference. In some embodiments of the invention, WTs having the most favorable WWAN channel characteristics may be selected to improve MIMO performance without any increase in processing complexity.

In some embodiments of the invention, one or more WWAN-inactive WTs 104-106 may be employed for WLAN-based functions, such as (but not limited to) WLAN network control, distributed-computing applications, and WWAN-interface control. For example, WLAN network control may include any of the well-known network-control functions, such as terminal identification, authentication, error correction, routing, synchronization, multiple-access control, resource allocation, load balancing, power control, terminal-state management, hand-offs, etc.

The WLAN 109 may employ distributed computing across a plurality of the WTs. Distributed computing may be employed simply to achieve increased processing power. Alternatively, distributed computing may include other objectives, such as balancing computational processing loads or balancing power consumption across the WTs 101-106 in the WLAN group 110. Computational loads on the WLAN group can potentially include any WWAN-related computations, such as WWAN channel estimation, WWAN channel compensation, diversity combining, WWAN channel coding/decoding, and cooperative array processing (e.g., MIMO weight calculation, interference cancellation, multi-user detection, matrix operations, and other smart antenna array processing operations).

WWAN-interface control may include distributing WWAN data and control information between the WTs 101-106. In one exemplary embodiment of the invention, at least one of the WTs 101-106 comprises a data source that distributes its data to at least one other WT 101-106 for transmission into the WWAN. In a similar embodiment of the invention, received WWAN signals intended for a particular WT 101-106 are received by

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a plurality of WWAN-active WTs 101-103. The received WWAN signals may optionally be processed by one or more WTs 101-106 prior to being routed to the intended WT 101-106. Accordingly, WWAN channel-access information may be routed to a plurality of WWAN-active WTs 101-103 such that they function together as a single WT 101-106.

The determination of which WTs 101-106 are active is typically performed by decision processing within the WLAN group 110 that determines which WTs 101-106 have the highest quality WWAN channel(s). The number of WWAN-active WTs (such as WTs 101-103) may be determined by one or more factors, including WT channel quality, array-processing complexity, available computational resources within the WLAN group 110, load balancing, and information-bandwidth requirements. In an alternative embodiment of the invention, the WWAN assigns cooperative channel-access information to the WTs 101-103 and may optionally determine which WTs 101-106 are active.

Some embodiments of the invention may take into consideration not only the MIMO complexity at the WTs, but also the added complexity associated with distributing the computational loads over WTs in a given WLAN group. Both MIMO and distributed computing overheads can be characterized as a function of the number of WTs in a WLAN group. Furthermore, the information bandwidth of a given WLAN channel limits the rate of information exchange between WTs. Accordingly, local channel conditions within the WLAN may affect throughput and range, and thus limit the number of WTs within the WLAN group. Either the WLAN capacity or the computational capability of each WT may set a practical limit on the number of WTs in a WLAN group and the overall frequency-reuse factor.

Another important factor that can impact the WLAN group size is the channel rate-of-change, which may be due to motion of the WTs and/or other objects in the WWAN environment. In particular, rapidly changing channel conditions may necessitate frequent updates to the MIMO computations, thus increasing the computational load on WLAN group and potentially increasing the required data transfer across the WLAN. Similarly, local channel conditions may dictate the flow of data if distributed computing is employed.

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MIMO systems experience substantial degradation in data transfer rates in mobile channels. Time-varying multipath-fading profiles commonly experienced in a mobile wireless network exhibit deep fades that often exceed 30dB. Commercial viability of some embodiments of the present invention requires the ability to tolerate a rapidly changing channel. A promising approach to this problem is to employ diversity to reduce the channel rate-of-change. In a wideband system, or equivalently, in a system comprised of a number of narrowband subcarriers distributed (e.g., interleaved) over a wide frequency band, deep fades affect only a portion of the total channel bandwidth. Therefore, frequency and/or spatial diversity may be employed to reduce the likelihood of deep fades in a multipath environment. Similarly, alternative forms of diversity may be employed. In a mobile environment, this translates into reducing the channel rate-of-change.

Figure 1G illustrates a cooperative beam-forming embodiment of the invention that functions in the presence of a desired WWAN terminal 119 and an external interference source (or jammer) 118. WTs 101-103 in a WLAN group 110 may coordinate their received aggregate beam pattern(s) to null out a jamming signal 115. Array-processing operations performed on signals received from the WTs 101-103 may take the form of phased-array processing, which minimizes the array's sensitivity to signals arriving from one or more angles. Alternatively, array processing may employ baseband (or intermediate-frequency) interference cancellation. Similarly, beam-forming operations may be employed to cancel emissions transmitted toward one or more terminals (such as jammer 118).

Figure 1H illustrates a cooperative beam-forming embodiment of the invention configured to function in the presence of a plurality of desired WWAN terminals 119 and 127. In one embodiment of the invention, the WWAN terminals 119 and 127 may be common to a particular WWAN, and the configuration illustrated in Figure 1H may include a soft hand-off in which redundant transmissions are transmitted between the WLAN group 110 and the WWAN terminals 119 and 127. In this case, the WLAN group may be distributed geographically over a plurality of WWAN sectors or cells. In one aspect of the invention, the WLAN group 110 may adapt its connectivity with the WWAN to transition to the cell or sector offering the optimal aggregate WWAN channel

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quality. Accordingly, the WLAN group may adapt its selection of WWAN-active WTs in response to a hand off.

In another embodiment of the invention, the WLAN group 110 may employ a first WWAN connection (such as illustrated by a connection between WTs 101 and 102, and WWAN terminal 119) and a second WWAN connection (such as illustrated by a connection between WT 103 and WWAN terminal 127) to transmit and/or receive one or more data streams. The WLAN group 110 may employ a plurality of WWAN user channels in a given WWAN. Similarly, the WLAN group 110 may employ connections to a plurality of different WWANs.

Figure 1I illustrates an embodiment of the invention that provides a plurality of WTs 101-106 in a WLAN group 110 with access to a plurality of WWAN services (i.e., WWANs). For example, WT 101 is provided with a communication link with an IEEE 802.16 access-point terminal 116 in an IEEE 802.16 network, WT 102 maintains access capabilities to a 3G-cellular terminal 119, and WT 103 has connectivity to an IEEE 802.11 access point 117. WLAN connectivity 109 is adapted to enable any of the WTs 101-106 in the WLAN group 110 to access any of the plurality of WWAN (802.16, 3G, and 802.11) services.

The WLAN 109 may include a WWAN-access controller (not shown), which may take the form of WLAN-control software residing on a physical device, such as one or more WTs 101-106. Connectivity of the WTs 101-106 to the available WWAN services may be performed with respect to a combination of technical rules and business rules. For example, WWAN access is typically managed using technical rules, such as network load balancing, power conservation, and minimizing computational processing loads. However, WWAN access can also be influenced by business rules, such as enabling a predetermined cost/service ratio for individual WTs 101-106. For example, the WWAN-access controller (not shown) can anticipate the economic cost of particular WWAN services to the user, as well as user communication needs, when assigning WWAN access to individual WTs 101-106. Each WT 101-106 may provide the WWAN-access controller (not shown) with a cost tolerance, which can be updated relative to the type of communication link desired. For example, high-priority communication needs (such as particular voice communications or bidding on an online auction) may include

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permissions to access more expensive WWAN connections in order to ensure better reliability.

The overall goal of WWAN access may be to achieve optimal connectivity with minimum cost. Accordingly, WWAN-access algorithms may include optimization techniques, including stochastic search algorithms (like multi-objective genetic algorithms). Multi-objective optimization are well known in the art, such as described in E.Zitzler and L.Thiele," Multiobjective evolutionary algorithms: A comparative case study and the strength pareto approach," *IEEE Tran. on Evol. Comput.*, vol. 3, no. 4, Nov 1999, pp. 257-271 and J.D. Schaffer, "Multiple objective optimization with vector evaluated genetic algorithms," *Proceedings of 1st International Conference on Genetic Algorithms*, 1991, pp. 93-100, both of which are incorporated by reference.

A WWAN-access controller (not shown) preferably ensures an uninterrupted session when transitioning from one WWAN to another. In particular, the transition between different WWANs should be invisible to the user. This requires that the WWAN-access controller (not shown) be adapted to store user state information (e.g., save browser pages or buffer multimedia data streams). Furthermore, back-end systems may preferably be employed to manage cooperative WWAN access in order to consolidate different WWAN-access charges into a single bill for the user.

In Figure 1J, a plurality of WTs 101-106 in a WLAN group 110 includes at least one WWAN terminal 106. The WTs 101-105 may contribute beam-forming capabilities to the WWAN terminal 106, such as to increase range, increase spatial reuse, reduce transmission power, and/or achieve any of other various beamforming objectives.

In one embodiment of the invention the WTs 101-105 function as lens for WWAN signals transmitted and received by the WWAN terminal 106. For example, the WTs 101-106 may collect received WWAN signals and then focus retransmitted WWAN signals at the WWAN terminal 106. Similarly, the WTs 101-105 may assist in the transmission of WWAN signals from the WWAN terminal 106 to one or more remote sources. In essence, the WTs 101-105 may function like a radio relay, but with directionality and focusing capabilities. In this embodiment, the WLAN connectivity of WTs 101-105 with the WWAN terminal 106 may not be necessary.

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In another embodiment of the invention, one or more of the WTs 101-106, such as WWAN terminal 106, may be adapted to process the majority (or entirety) of necessary beam-forming computations. In this case, WT 106 is designated as a computer-processing terminal. The computer-processing terminal 106 is adapted to include specific computational resources for processing WWAN signals received by other WTs (such as WTs 101-103), which are then relayed via the WLAN 109 to the computer-processing terminal 106. Similarly, the computer-processing terminal 106 may be adapted to perform signal-processing operations associated with WWAN transmission. Computational operations associated with other WWAN signal-processing operations (e.g., coding, decoding, channel estimation, network-access control, etc.) may be provided by the computer-processing terminal 106.

Figure 2A illustrates a functional embodiment of the invention that may be realized in both method and apparatus embodiments. A plurality *M* of WWAN Interfaces 1101.1-1101.M is provided for coupling WWAN signals to and/or from at least one WWAN. In one functional embodiment, WWAN Interfaces 1101.1-1101.M may include WWAN transceivers adapted to convert received WWAN signals into received baseband signals. A plurality of WWAN baseband processors 1102.1-1102.M are optionally provided for performing baseband processing (such as, but not limited to, channel compensation, A/D conversion, frequency conversion, filtering, and demultiplexing) on the received baseband signals. Alternatively, the function of the WWAN baseband processors 1102.1-1102.M may be performed by the WWAN Interfaces 1101.1-1101.M.

Baseband outputs from the WWAN baseband processors 1102.1-1102.M are coupled into a plurality of array processors, such as MIMO combiners 1103.1-1103.M. In a MIMO channel, the received WWAN signals (and thus, the baseband outputs) are characterized by a plurality of overlapping (i.e., interfering) signals. Although MIMO combiners 1103.1-1103.M are shown, any type of array processor may be employed. The number of array processors may be less than, equal to, or greater than the number *M* of WWAN Interfaces 1101.1-1101.M. Baseband outputs may also be coupled into a WLAN 1105, which is coupled to the plurality of MIMO combiners 1103.1-1103.M. Each MIMO combiner 1103.1-1103.M may be adapted to receive baseband outputs from two

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or more baseband processors 1102.1-1102.M wherein at least one of those baseband outputs is coupled to the MIMO combiner 1103.1-1103.M via the WLAN 1105.

A particular m^{th} MIMO combiner 1103.m need not process data from a corresponding (m^{th}) WWAN Interface 1101.m. Rather, the mth MIMO combiner 1103.m may process baseband signal outputs from a plurality of WWAN Interfaces 1101.p {p = 1,...,M, where $p \neq m$}.

The WLAN 1105 comprises at least one WLAN channel between at least one baseband output (e.g., baseband processor 1102.1-1102.M outputs) and at least one array processor, such as the MIMO combiners 1103.1-1103.M. The WLAN 1105 may include WLAN interfaces (not shown) and associated WLAN-control hardware and/or software (not shown).

The MIMO combiners 1103.1-1103.M may be adapted to separate the overlapping signals and output at least one desired transmission therefrom. Outputs of the MIMO combiners 1103.1-1103.M are optionally processed by secondary data processors 1104.1-1104.M, which may provide coupling into the WLAN 1105. The secondary data processors 1104.1-1104.M may be adapted to perform demodulation, error-correction decoding, data formatting, and/or other related baseband-processing functions.

In some embodiments of the invention, MIMO combiner 1103.1-1103.M outputs may be coupled via the WLAN 1105 to other MIMO combiners 1103.1-1103.M and/or secondary data processors 1104.1-1104.M. For example, embodiments of the invention may employ an iterative cancellation process, such as successive interference cancellation (which is well-known in the art), involving the use of strongest-signal estimates, and then next-strongest-signal estimates to cancel known interference in weaker signals. Alternatively, embodiments may employ parallel cancellation.

Figure 2B illustrates an embodiment of the invention including a plurality M of WTs 1109.1-1109.M, each comprising a corresponding combination of a WWAN Interface 1101.1-1101.M, an optional WWAN baseband processor 1102.1-1102.M, a combiner (such as a MIMO combiner 1103.1-1103.M), and a secondary data processor 1104.1-1104.M. The WTs 1109.1-1109.M are coupled together by a WLAN 1105, which is configured to convey data between the WTs 1109.1-1109.M in order to enable cooperative antenna-array processing.

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A WT, such as any of the WTs 1109.1-1109.M, includes any system or device provided with communicative connectivity means to a WLAN 1105. Two or more WTs 1109.1-1109.M are preferably provided with WWAN interfaces, such as WWAN Interface 1101.1-1101.M. A plurality of WTs 1109.1-1109.M may share at least one WLAN 1105. In one embodiment of the invention, individual WTs 1109.1-1109.M may share the same WWAN service. This enables the WLAN group 110 to perform either or both transmit beam-forming and receive beam-forming (i.e., combining) operations.

In another embodiment of the invention, WTs 1109.1-1109.M may have connections to different WWANs and/or WWAN services. This enables the WLAN group 110 to achieve WWAN-service diversity. One or more WTs 1109.1-1109.M may optionally be capable of accessing multiple WWAN services. For example, many cellular handsets are provided with multi-mode capabilities, which give them the ability to access multiple WWANs. Some of the WTs 1109.1-1109.M may have no WWAN service. For example, one or more WTs 1109.1-1109.M may be out of range, in a WWAN dead spot, in an inactive WWAN state, or configured only to communicate via the WLAN 1105. WTs 1109.1-1109.M include, but are not limited to, cell phones, radio handsets, pagers, PDAs, wireless sensors, RFID devices, vehicle radio communication devices, laptop computers with wireless modems, wireless network access points, wireless routers, wireless switches, radio repeaters, transponders, and devices adapted to include satellite modems.

A WLAN group 110 may be adapted to perform any of various types and combinations of diversity and MIMO beam-forming. Three commonly used linear diversity-combining techniques include switched (or selection) combining, maximal ration combining (MRC), and equal gain combining (EGC). Other combining techniques may be employed. The impact of using diversity may be expressed by a probability distribution $p(\gamma)$ of the SNR γ at the output of a combining network. For switched diversity, wherein the combiner switches to the diversity branches (e.g., WTs) having the strongest signal, $p(\gamma)$ is given by:

$$p(\gamma) = \frac{L}{\Gamma} e^{-\gamma/\Gamma} \left[1 - e^{-\gamma/\Gamma}\right]^{L-1}$$

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where Γ is the average SNR for each diversity branch and L is the number of diversity branches. MRC weights branches (e.g., WT signals received from the WWAN) having better SNR more heavily (i.e., with greater-magnitude weights) than branches having poorer SNR. The $p(\gamma)$ for MRC is given by:

$$p(\gamma) = \frac{\gamma^{l-1} e^{-\gamma/\Gamma}}{\Gamma^{L}(l-1)!}$$

For EGC, $p(\gamma)$ is given by:

$$p(\gamma) = \frac{L}{a\Gamma} e^{-\gamma/a\Gamma}\left[1 - e^{-\gamma/a\Gamma}\right]^{L-1}$$

where $a = \sqrt{L/1.25}$ for $L \geq 2$, and 1 otherwise.

These diversity techniques provide the greatest improvements when the branches are uncorrelated.

Adaptive arrays (or smart antennas) may include antenna systems that automatically adjust to achieve some predetermined performance criterion, such as maximizing the signal to interference (S/I) ratio, SINR, or link margin. Adaptive antenna techniques include switched beam, beam steering, and optimum combining (e.g., a linear spatial filtering approach that employs adaptation to closely match an output signal with a reference signal). A filtering process typically suppresses any artifacts that are not part of the desired incoming signal, including noise and interference.

In an optimum combining system, signals from each WT are down converted to baseband and converted to digital signals in an ADC. Noise associated with the front end of the down converter and other sources is naturally added to the signal. The resulting signal $x_m(k)$ is multiplied by a complex weighting function $w_m(k)$ and summed with similar signals from other WT antenna elements. The resulting sum signal $\Sigma\, w_m(k)x_m(k)$ is compared with a previously derived (and updated) reference signal (e.g., a training sequence). An error signal $e(k)$ is generated and used to adjust the weight values in order to minimize $e(k)$. The objective is to derive the weighting function $w_m(k)$ that enables the best match between an estimated received signal and the actual transmitted signal. Alternatively, an adaptive WT array may be configured as an analog array wherein amplitude and phase adjustments (i.e., weighting functions) are performed at RF or IF.

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In a MIMO communication system, signals transmitted from M_T transmit sources interfere with each other at a receiver comprising the WTs 1109.1-1109.M. Thus, interference cancellation (such as matrix inversion, channel transfer function inversion, and adaptive filtering) may be employed by one or more MIMO combiners 1103.1-1103.M to separate the signals. The received signal is expressed by:

$$y = Hx + n$$

where the received signal, y, is a vector with M_R terms $\{y_i, i = 1,...,N_R\}$ corresponding to signals received by M_R (where M_R may have a value of 2 to M) receiver elements (i.e., WTs); x represents the transmitted signal, which is a vector having M_T terms $\{x_i, i = 1,...,M_T\}$ corresponding to signals transmitted by M_T transmitter elements; H is an $M_R \times M_T$ channel-response matrix that characterizes the complex gains (i.e., transfer function, or spatial gain distribution) from the M_T transmission elements to the M_R receive elements; and n represents AWGN having zero mean and zero variance.

In the case where the channel is characterized by flat fading, such as when a narrowband signal is employed (e.g., a sub-carrier of a multi-carrier signal), the elements in matrix H are scalars. The channel-response matrix H may be diagonalized by performing an eigenvalue decomposition of the $M_T \times M_T$ correlation matrix R, where $R = H^H H$. Eigenvalue decomposition is expressed by:

$$R = EDE^H$$

where E is an $M_T \times M_T$ unitary matrix with columns corresponding to the eigenvectors e_i of R, and D is an $M_T \times M_T$ diagonal matrix wherein the diagonal elements are eigenvalues λ_i of R. The diagonal elements of D indicate the channel gain for each of the independent MIMO channels. Alternatively, other eigenvalue-decomposition approaches, such as singular value decomposition, may be employed.

The process for diagonalizing the MIMO channel response is initiated by multiplying a data vector d with the unitary matrix E to produce the transmitted vector x: $x = Es$. This requires the transmitter to have some information corresponding to the channel-response matrix H, or related information thereof. The received vector y is then multiplied with $E^H H^H$ to provide an estimate of data vector s, which is expressed by:

$$\hat{s} = E^H H^H y = E^H H^H HEs + E^H H^H n = Ds + \hat{n}$$

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where $\hat{n}$ is AWGN having a mean vector of 0 and a covariance matrix of $\Lambda_n=\sigma^2 D$.

The data vector s is transformed by an effective channel response represented by the diagonal matrix D. Thus, there are N_s non-interfering subchannels wherein each subchannel i has a power gain of λ_i^2 and a noise power of $\sigma^2\lambda_i$.

In the case where MIMO processing is performed on a multicarrier signal, or some other wideband signal that is spectrally decomposed into narrowband components, eigenmode decomposition may be performed for each frequency bin f_n.

If multicarrier spreading codes are employed (e.g., orthogonal DFT, or CI, codes), the channel-response matrix H can cause inter-symbol interference between spread data symbols, even in a SISO arrangement. Accordingly, the eigenmode decomposition technique described previously is applicable to multicarrier spreading and despreading. In one embodiment of the invention, eigenmode decomposition may be applied across two or more dimensions (e.g., both spatial and frequency dimensions). In another embodiment of the invention, eigenmode decomposition may be applied across a single dimension (e.g., spatial or frequency dimensions). For example, multicarrier spreading codes (for example, orthogonal codes for data multiplexing in a given multiple-access channel) may be generated and processed via eigenmode decomposition.

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

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In conventional water filling, power allocation is performed such that the total transmission power P_T is some predetermined constant:

$$P_T = \sum_{j \in K} \sum_{k \in L} P_j(k)$$

where $L = \{1,...,N_s\}$ signifies the available subspaces and $K = \{1,...,N_f\}$ represents the available sub-carrier frequencies f_n. The received SNR (expressed by $\psi_j(k)$) for each transmission channel is expressed by:

$$\psi_j(k) = \frac{P_j(k)\lambda_j(k)}{\sigma^2}, \text{ for } j = \{1,..., N_s\} \text{ and } k = \{1,...,N_f\}$$

The aggregate spectral efficiency for the $N_s N_f$ transmission channels is expressed by:

$$C = \sum_{j=1}^{N_s} \sum_{k=1}^{N_f} \log_2\left(1 + \psi_j(k)\right)$$

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

An embodiment of the invention may employ reliability assessment for determining required processing and virtual-array size (i.e., the number of active WTs functioning as WWAN receiver elements). Received bits or symbols that have low reliability need more processing. Bits or symbols with high reliability may be processed with fewer elements (WTs) or provided with lower processing requirements. More information typically needs to be combined for data streams having less reliability and less information may need to be combined for data streams having more reliability. Also, nodes (WTs) with good channel quality may share more information via the WLAN than

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nodes having poor channel quality. Optimization algorithms, such as water-filling algorithms may be employed in the reliability domain.

Figure 3A illustrates an embodiment of the invention in which a WLAN controller for a WLAN group of WTs first identifies received data streams that have the least reliability (e.g., reliability that is below a predetermined threshold) 301. Then the WLAN controller increases allocated processing (e.g., increases the number of receiver nodes, increases the number of processing nodes, employs a processing approach having higher computational complexity, etc.) 302 to those data streams. Data symbols may be combined from the smallest number of nodes such that the reliability of the sum is maximized, or at least exceeds a predetermined threshold reliability. The processes 301 and 302 may be repeated 303 until a predetermined result is achieved or until there is no more data left for processing.

Figure 3B illustrates an embodiment of the invention in which a WLAN controller identifies received data streams that have the most reliability, or data streams having reliability that exceeds a predetermined reliability threshold 311. The WLAN controller may decrease allocated processing (e.g., decrease the number of receiver nodes, decrease the number of processing nodes, employ a processing approach having lower computational complexity, etc.) 312 to those data streams. The processes 301 and 302 may be repeated 303 until a predetermined result is achieved or until there is no more data left for processing. Embodiments of the invention may provide for encoding information across channels having a wide range of reliability.

Embodiments of the invention may be configured to perform blind signal separation (BSS), such as independent component analysis. For example, A. Jourjine, S. Rickard, and O. Yilmaz, "Blind Separation of Disjoint Orthogonal Signals: Demixing N Sources from 2 Mixtures," in *Proceedings of the 2000 IEEE International Conference on Acoustics, Speech, and Signal Processing*, Istanbul, Turkey, June 2000, vol. 5, pp. 2985–88, which is included herein by reference, describes a blind source separation technique that allows the separation of an arbitrary number of sources from just two mixtures, provided the time-frequency representations of the sources do not overlap. The key observation in the technique is that for mixtures of such sources, each time-frequency point depends on at most one source and its associated mixing parameters.

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In multi-user wireless communication systems that employ multiple transmit and receive antennas, the transmission of user information through a dispersive channel produces an instantaneous mixture between user transmissions. BSS may be used in such instances to separate received transmissions, particularly when training sequences and channel estimation are absent. In an exemplary embodiment of the invention, an OFDM-MIMO protocol may be provided across multiple independent WTs. Multiple transmissions are provided on at least one frequency channel, and frequency-domain techniques of BSS may be employed to recover received signals.

In one embodiment of the invention, at least one data transmission source may be adapted to convey its data across the WLAN to a plurality of WTs for transmission into the WWAN. In another embodiment of the invention, a plurality of WTs are adapted to receive data transmissions from a WWAN and couple said received data transmissions into a WLAN (with or without baseband processing) wherein centralized or distributed signal-processing means are provided for separating the data transmissions. Said signal-processing means includes any MIMO-processing techniques, including multi-user detection, space-time processing, space-frequency processing, phased-array processing, optimal combining, and blind source separation, as well as others.

In one embodiment of the invention, a vector of binary data symbols $b_i(n)$ are encoded with a convolutional encoder to produce a coded signal:

$$s_i(n) = b_i(n) * c(n)$$

where $c(n)$ represents a convolutional code of length L'. A cluster of N coded symbols corresponding to an ith user, data source, or data stream is represented by:

$$s_{n,i} = [s_i(n), \ldots, s_i(n+N-1)]^T$$

The transmit signal is generated by performing an N-point IDFT to $s_{n,i}$ to produce:

$$S_{n,i} = [S_i(n,0), \ldots, S_i(n,N-1)]^T$$

where

$$S_i(n,k) = \sum_{m=0}^{N-1} s_i(n+m) e^{i 2\pi k m / N}$$

The values $S_i(n,k)$ are transmitted via at least one of N_t transmit antennas.

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On the receive side, N_r receive antennas (typically, $N_r \geq N_t$) are employed. The signal received by a jth antenna is expressed by:

$$R_j(n) = \sum_{i=1}^{N_t} S_i(n) * h_{ij} + n_j(n)$$

where $n_j(n)$ represents the zero-mean AWGN introduced by the channel, and h_{ij} is the channel impulse-response of the ith transmit antenna to the jth receive antenna. The received signal can be interpreted as a convolutive mixture of the coded signals, where the channel matrix h represents the mixing system. An N-point DFT is applied to the received signals $R_j(n)$ to produce:

$$r_j = [r_j(n), \ldots, r_j(n + N - 1)]^T$$

where

$$r_j(n) = \sum_{m=0}^{N-1} R_j(n+m) e^{-i 2\pi k m / N}$$

Typically, a sufficient guard interval or cyclic prefix is employed to eliminate inter-symbol interference.

The signals from the N_r receiver antennas are grouped with respect to frequency bin. An observation at a kth frequency bin are expressed by:

$$r_n(k) = \left[r_1(n+k), r_2(n+k), \ldots, r_{N_r}(n+k)\right]^T$$

$$= H(k)s(k) + n(k)$$

Thus, the observations $r_n(k)$ $\{k = 0, \ldots, N\text{-}1\}$ can be interpreted as an instantaneous mixture of the transmitted signals $s(k)$, where $H(k)$ represents the mixing system.

There are many approaches for estimating the transmitted signals $s(k)$ from the received signals $r_n(k)$ that may be employed by the current invention. An exemplary embodiment of the invention employs BSS techniques. One class of BSS produces an output vector having the following form:

$$y(k) = W^H(k) r_n(k)$$

where $W(k)$ is an $N_r \times N_t$ matrix that groups the coefficients of the separating system. The output $y(k)$ can also be expressed by:

$$y(k) = G(k)s(k) + W^H(k)n(k)$$

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where $G(k) = W^H(k)H(k)$ represents the mixing/separating system. The goal of the separation process is to calculate the matrices $W(k)$ so that the $G(k)$ matrices are diagonal and the effects of noise $W^H(k)n(k)$ are minimized. Many different approaches are applicable for achieving these goals.

A BSS algorithm (such as the one described in J. F. Cardoso, A. Souloumiac, "Blind Beamforming for non-Gaussian Signals," *IEEE-Proceedings-F*, vol. 140, no. 6, pp. 362-370, December 1993, which is incorporated by reference herein) may be employed to separate the instantaneous mixture in each frequency bin. Each output at frequency bin k' can be regarded as corresponding to a single source at bin k' multiplied by a particular gain introduce by the algorithm. The outputs $y(k')$ are then used as reference signals in order to recover the sources at frequencies $k' \pm 1$. For example, the separation matrices $W(k)$ are determined by minimizing the mean-square error between the outputs $y(k) = W^H(k)r_n(k)$ and reference signals $y(k')$. For a given frequency bin k:

$$W_o(k) = \arg\min_{W(k)} E\left[\left|y(k) - \alpha y(k')\right|^2\right]$$

where α is a real constant, which is selected with respect to the convolutional code:

$$\alpha = \frac{\sum_{p=0}^{L-1} c^2(p)}{\sum_{p=0}^{L-2} c(p)c(p+1)}$$

This is done to ensure $G(k) = G(k')$. The solution to the optimization problem is given by:

$$W_o(k) = \alpha R_{r_n}^{-1}(k) R_{r_n y}(k,k')$$

where

$$R_{r_n}(k) = E\left[r_n(k)x^H(k)\right] \text{ and}$$

$$R_{r_n y}(k,k') = E\left[r_n(k)y^H(k')\right]$$

Figure 4A illustrates an embodiment of the invention wherein a plurality M of WTs 1109.1-1109.M is coupled to a MIMO processor 1103 via a WLAN 1105. In this particular embodiment, a computer-processing terminal 1119 may include the MIMO processor 1103. The computer processing terminal 1119 may be provided with WLAN-interface functionality, and may optionally include WWAN-interface functionality.

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The computer-processing terminal 1119 may include any of a plurality WLAN-connected devices with signal-processing capability. For example, the computer-processing terminal 1119 may include one of the WTs 1109.1-1109.M. In one aspect of the invention, the computer-processing terminal 1119 comprises a WLAN controller. In another aspect of the invention, the computer processing terminal 1119 comprises a network gateway, router, or access point including a CPU adapted to process signals received from the plurality of WTs 1109.1-1109.M. Applications of embodiments of the invention include (but are not limited to) sensor networks, micro-networks, RFID systems, cellular networks, and satellite networks.

Each WT 1109.1-1109.M may include a baseband processor 1102.1-1102.M adapted to provide WWAN baseband (or IF) signals to the MIMO processor 1103 via the WLAN 1105. The MIMO processor 1103 may be configured to separate interfering WWAN data symbols in the WWAN baseband signals. The separated WWAN data symbols are then coupled back to data processors 1104.1-1104.M in the WTs 1109.1-1109.M.

Figure 4B illustrates a functional embodiment of the invention in which MIMO processing operations (represented by MIMO processors 1103.1-1103.M) may be distributed over two or more WTs 1109.1-1109.M. Baseband processors 1102.1-1102.M provide WWAN baseband signals to a WLAN controller 1106, which may distribute the signals (and signal-processing instructions) to the MIMO processors 1103.1-1103.M. The separated WWAN data symbols are then coupled back to data processors 1104.1-1104.M.

Figure 4C represents a functional embodiment of the invention. At least one WT may provide WWAN access information 1140 to a WLAN controller. The WWAN access information typically includes necessary information (such as at least one WWAN channel assignment, authentication codes, etc.) to access at least one particular WWAN channel. The WWAN access information may optionally include performance information, such as WWAN channel estimates, link-bandwidth demand, link priority, and/or WWAN channel-quality measurements (e.g., SNR, SINR, BER, PER, latency etc.). This information is typically provided to the WLAN controller by one or more WTs.

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The WLAN controller determines which WTs to activate 1141 for a particular WWAN communication link. This may be performed for either or both transmission and reception. The determination of which WTs will be active 1141 in a given WWAN link typically depends on a combination of factors, including (but not limited to) the number *M* of WTs required to achieve predetermined channel characteristics or access parameters, which WTs have the best WWAN channel quality, load balancing, power-consumption balancing, computational overhead, latency, and WLAN-access capabilities. Accordingly, the WLAN controller may send control information via the WLAN to the WTs that includes state information (e.g., operating-mode assignments, such as active, standby, sleep, and awake).

The WLAN controller may convey WWAN information to the active WTs 1142. The WWAN information may be derived from the WWAN access information and provided to the WTs to establish and/or maintain at least one WWAN link. Accordingly, the WWAN information may include WWAN channel assignments. The WWAN information may include beam-forming weights and/or space-time codes. Accordingly, the step of conveying WWAN information to the WTs 1142 may optionally include a preliminary signal-processing step (not shown), such as blind adaptive or deterministic weight calculation. This preliminary signal-processing step (not shown) may be distributed among a plurality of the WTs, or it may be performed in a centralized mode, such as by a single computing terminal. A distributed-computing mode may take various forms. In one mode, each of a plurality of WTs takes its turn functioning as a computing terminal. In another mode, multiple WTs function as computing terminals simultaneously.

Communications in the WWAN link are coordinated between the WTs in order to synchronize the transmitted and/or received WWAN signals 1143. A receiver embodiment of the invention may provide for synchronizing the received WWAN signals, such as to provide for coherent combining. A transmitter embodiment of the invention may provide for synchronizing the transmitted WWAN signals from the WTs such as to enable coherent combining at some predetermined WWAN terminal.

An optional transmitter embodiment of the invention may employ synchronization to deliberately time-offset signals arriving at one or more WWAN

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terminals in order to provide for transmit diversity by the WTs. In such embodiments, one or more of the WT transmissions may be provided with time-varying complex weights (e.g., amplitudes and/or phases), such as described in S. A. Zekavat, C. R. Nassar and S. Shattil, "Combined Directionality and Transmit Diversity via Smart Antenna Spatial Sweeping, " proceedings of *38th Annual Allerton Conference on Communication, Control, and Computing, University of Illinois in Urbana-Champaign,* pp. 203-211, Urbana-Champaign, IL, USA, Oct. 2000, S. A. Zekavat, C. R. Nassar and S. Shattil, "Smart antenna spatial sweeping for combined directionality and transmit diversity," *Journal of Communications and Networks (JCN), Special Issue on Adaptive Antennas for Wireless Communications,* Vol. 2, No. 4, pp. 325-330, Dec. 2000, and S. A. Zekavat, C. R. Nassar and S. Shattil, "Merging multi-carrier CDMA and oscillating-beam smart antenna arrays: Exploiting directionality, transmit diversity and frequency diversity, " *IEEE Transactions on Communications*, Vol. 52, No. 1, pp. 110 – 119, Jan. 2004, which are incorporated by reference herein.

In an alternative embodiment of the invention, providing WWAN access information 1140 may include providing WWAN channel-performance information from the WTs to at least one WWAN terminal. Thus, conveying WWAN information to the WTs 1142 may be performed by at least one WWAN terminal. An optional embodiment of the invention may provide for at least one WWAN terminal determining which WTs in a WLAN group will operate in a given WWAN link and conveying that WWAN information 1142 to the WLAN group. Embodiments of the invention may provide capabilities to WWAN terminals to set up and adapt the formation of WLAN groups and determine which WTs are assigned to which WLAN groups. Such control capabilities may employ GPS positions of WTs to assist in assigning WTs to a WLAN group. Some embodiments of the invention may provide for collaboration between a WWAN and a WLAN group for activating WTs and/or assigning WTs to the WLAN group.

In one embodiment of the invention, step 1142 may include a preliminary signal-processing step (not shown) in which at least one WWAN terminal calculates cooperative-beamforming weights for the WTs based on channel-performance information provided by the WTs. Accordingly, the WWAN information may include cooperative-beamforming weights derived by at least one WWAN terminal and conveyed

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to at least one WT. Synchronization 1143 of the transmitted and/or received WWAN signals by the WTs may optionally be performed by at least one WWAN terminal. Similarly, embodiments of the invention may provide for applying time-varying weights to WWAN-terminal transmissions (such as described previously).

Figure 4D illustrates a functional embodiment of the invention adapted to perform cooperative beamforming. WWAN channel information is provided 1144 for assigning subchannels 1145 and calculating cooperative beamforming (i.e., WT) weights 1146. The beamforming weights are then distributed to the appropriate WTs 1147.

Sub-channel assignments 1145 are typically performed with respect to a predetermined subchannel-quality threshold, such as SNR, SINR, or BER. Subchannels having the required minimum performance may be assigned for transmission and/or reception. Sub-channel assignments 1145 may also provide for bit loading. Alternatively, sub-channel assignments 1145 may be performed without regard to sub-channel quality. In such cases, spreading or channel coding may be performed to mitigate the effects of lost and compromised subchannels.

Weight calculations 1146 may be achieved by either deterministic or blind adaptive techniques. The calculations may be performed by one or more WTs, or alternatively, by at least one WWAN terminal. Cooperative beamforming weights may be provided to achieve at least one form of array processing benefit, including diversity combining, interference cancellation, and spatial reuse.

Figure 5A illustrates a functional embodiment of the invention that may be implemented by hardware and/or software. A plurality of transmitted WWAN signals are received 1150 by a plurality of WTs. Baseband (or IF) WWAN information is derived 1151 from the received WWAN signals. For example, in an OFDM system, a baseband WWAN signal s_k received by a kth WT can be represented by a linear superposition of up to M transmitted data symbols d_i $\{i = 1,...,M\}$ weighted by complex channel weights α_{ik}:

$$s_k = \sum_{i=1}^{M} \alpha_{ik} d_i + \eta_k$$

Baseband WWAN signals (which typically include the complex channel weights α_{ik}), are optionally transmitted 1158 into a WLAN for distribution to one or more other WTs. Accordingly, data (including baseband WWAN signals s_k, complex channel weights α_{ik},

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and/or MIMO weights β_{il}) from the one or more other WTs is received 1152 from the WLAN. MIMO processing 1153 may be performed to produce at least one set of MIMO weights β_{il} and/or estimated transmitted data symbols d_i, which may optionally be transmitted 1159 to at least one other WT via the WLAN. Baseband information recovery 1154 may optionally be performed on the estimated transmitted data symbols d_i. For example, baseband operations may include despreading, demodulation, error correction (e.g., channel decoding), demultiplexing, de-interleaving, data formatting, etc.

Figure 5B illustrates an alternative functional embodiment of the invention that may be implemented by hardware and/or software. In this case, WWAN baseband information that does not include MIMO weights may be received 1155 from at least one other WT via the WLAN. Thus, MIMO processing 1153 includes generating MIMO weights, which may be transmitted 1159 to one or more WTs via the WLAN. The functional embodiment illustrated in Figure 5B is particularly applicable to a WT functioning as a computer-processing terminal in a WLAN group. In the case where the subject WT functions as the only MIMO-processing terminal in a given WLAN group, the functional embodiment may be characterized solely by steps 1155, 1153, 1154, and optional step 1159. Furthermore, the functional embodiments described herein may be adapted to perform other array-processing operations in addition to, or instead of, MIMO.

Figure 6A illustrates functional and apparatus embodiments of the present invention pertaining to one or more WTs, such as WT 1109. In particular, a WWAN interface 1161 may be coupled to a beam-forming system 1162, which is coupled to a WLAN interface 1163. The beam-forming system 1162 may employ data received from the WLAN interface 1163 (and optionally, from data received from the WWAN interface 1161) to perform beam-forming operations. The WLAN interface 1163 is adapted to provide WLAN data communications with at least one other WT (not shown). The beam-forming system 1162 may be adapted to provide either or both WWAN transmission beam-forming and reception beam-forming operations.

Figure 6B illustrates a preferred embodiment of the invention that may be employed as either or both apparatus and functional embodiments. A WWAN interface 1161 includes an RF front-end 1611, a DAC/ADC module 1612, a pulse-shaping filter 1613, a modulator/demodulator module 1614, an equalizer modulator 1615 that

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optionally employs pre-equalization means, a multiplexer/ demultiplexer module 1616, and a baseband-processing module 1617. The WWAN interface may also include a network-control module 1618 that may be responsive to both WWAN control signaling and WLAN-control signals configured to convey WWAN control information to the WWAN interface 1161.

A WLAN interface 1163 includes an RF front-end 1631, a DAC/ADC module 1632, a pulse-shaping filter 1633, a modulator/demodulator module 1634, an equalizer modulator 1635 that optionally employs pre-equalization means, a multiplexer/ demultiplexer module 1636, and a baseband-processing module 1637. A beam-forming module 1162 is adapted to process signals from either or both baseband modules 1617 and 1637. The beam-forming module 1162 may be adapted to process local data symbols generated by a local data source 1160.

As described previously, the beam-forming module 1162 may be adapted to perform beam-forming operations on baseband WWAN signals received from either or both the WWAN interface 1161 and the WLAN interface 1163. Specifically, the beam-forming module 1162 may be adapted to perform beam forming by utilizing baseband WWAN signals, channel weights (or other channel-characterization information), beam-forming weights (such as MIMO weights), and/or baseband data symbols. Baseband data symbols may be received from the local data source 1160, from local data sources on other WTs, and/or from estimated data generated by one or more external beam-forming modules (e.g., beam-forming modules on other WTs). Optionally, the beam-forming module 1162 may be configured to adjust equalization and/or pre-equalization 1615.

In an exemplary embodiment of the invention, the beam-forming module 1162 is configured to process baseband WWAN signals received from the baseband-processing module 1617 and the WLAN interface 1163. Information output from the beam-forming module 1162 is conveyed to at least one of the WLAN interface 1163 and a local data sink 1169. Estimated WWAN data symbols output by the beam-forming module 1162 may optionally be processed by the baseband-processing module 1617 or the local data sink 1169. For example, the baseband-processing module 1617 may be configured to perform various types of signal processing, including error correction (such as Viterbi decoding), constellation mapping, and data formatting on data output by the beam-

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forming module 1162. The resulting processed data may then be coupled to the local data sink 1169 and/or the WLAN interface 1163. Alternatively, the local data sink 1169 may perform the previously described signal-processing types.

Beam forming is performed cooperatively with other WTs to provide predetermined WWAN spatial processing for transmitted and/or received WWAN signals. Thus, a network-function adapter 1165 may be employed to provide WWAN channel-access information to one or more WTs. For example, some embodiments of the invention require multiple WTs to function as a single WT. In this case, each WT is provided with WWAN-access information corresponding to the single WT it is configured to spoof. The network function adapter 1165 may be configured to generate WWAN-access information to be distributed to at least one other WT and/or it may be configured to receive WWAN-access information from the WLAN interface 1163 and convey it to the network-control module 1618 in the WWAN interface 1161.

WWAN-access information typically includes channelization (or some other form of multiple access) information used to transmit and/or receive data from the WWAN. For example, WWAN-access information may take the form of user identification sequences, assigned time slots, frequency band assignments, and/or multiple-access code assignment.

In some embodiments of the invention, a particular WT may be required to function as multiple WTs. In this case, WWAN-access information is conveyed to the network-control module 1618 and data is configured to be appropriately multiplexed and/or demultiplexed relative to a plurality of multiple-access channels.

The network-function adapter 1165 may be used to convey other WWAN control information to WTs, including (but not limited to) power-control commands, timing and synchronization information, key-exchange messages, WWAN routing tables, acknowledgements, requests for retransmission, probing signals, and paging messages. The network-function adapted 1165 may be configured to alter or adapt the WWAN-control information that it receives from either or both the WWAN interface 1161 and the WLAN interface 1163. For example, WWAN power-control commands received by one or more WTs may be adapted by the network-function adapter 1165 prior to being conveyed to network-control modules (such as network-control module 1618) on

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multiple WTs. Power control may be adapted by one or more network-function adapters 1165 for particular WTs depending on their WWAN channel quality and power. Alternatively, the network-function adapter 1165 may adapt the number M of WTs servicing a given link in response to WWAN control information.

In some embodiments of the invention, it may be advantageous to employ a single decision system for network-function adaptation 1165. In one mode of operation, the network-function adapter 1165 of only one of a plurality of WTs assigned to a particular WWAN channel is adapted to convey WWAN control information to the other WTs. In each of the other WTs, the associated network-function adapter 1165 identifies the WWAN control information received from the WLAN and couples it to the network-control module 1618. Thus, the network-function adapter 1165 may instruct the network-control module 1618 to disregard one or more types of WWAN control information received from the WWAN interface 1161. One or more network-function adapters (such as network-function adapter 1165) may synchronize WT responses to WWAN control information.

In another embodiment of the invention, each WT may be responsive to WWAN control information that it receives. In yet another embodiment, each of a plurality of WWAN multiple-access channels is preferably controlled by a separate network-function adapter 1165. These and other adaptations and permutations of network function may be embodied by functional aspects of the network-function adapter 1165.

One embodiment of the invention employs the functionality of a group of WTs corresponding to Figure 1C with respect to the transceiver embodiment shown in Figure 6B. In a transmission configuration, a serial data stream $s(n)$ from the local data source 1160 of a particular WT is channel coded to produce coded data stream $u(n)$, which is grouped in blocks of size N: $\boldsymbol{u}(i) = [u(iN), u(iN+1),\ldots, u(iN+N-1)]^{T}$. In this case, N is chosen to equal the number M of WTs employed as antenna elements. The N-1 coded data symbols $u(n)$ are distributed to the other N-1 WTs via the WLAN interface 1163.

At each WT's Mux/DeMux block 1615, a particular data symbol $u(n)$ is mapped into a frequency bin vector. In one aspect of the invention, each data symbol $u(n)$ is provided with both a unique frequency bin and a unique WT, such as to achieve optimal diversity benefits. This takes the form of a frequency-bin vector having all zeros except

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for one bin corresponding to $u(n)$. This scheme can be used to achieve low transmitted PAPR, as well as other benefits. In other embodiments, alternative WT/frequency-bin combinations may be employed. For example, multiple serial data streams $s(n)$ may be provided to the frequency-bin vector. Redundant symbols may be provided. Alternatively, the data $s(n)$ may be spread across frequencies and/or WTs.

At each Mod/DeMod block 1614, an IFFT is applied to each data block to produce:

$$\tilde{u}(i) = F^H u(i)$$

where F is the $N \times N$ FFT matrix with $F_{nm} = N^{-1/2}\exp(-j2\pi nm/N)$. A cyclic prefix of length N_{CP} may be inserted in $\tilde{u}(i)$ to produce $\tilde{u}_{CP}(i) = \beta T_{CP}\tilde{u}(i)$, which has length $N_T = N+N_{CP}$. The term $\boldsymbol{T}_{CP} = [\boldsymbol{I}_{CP}{}^T \boldsymbol{I}_N{}^T]^T$ represents the cyclic prefix insertion in which the last N_{CP} rows of the $N \times N$ identity matrix $\boldsymbol{I}_N$ (denoted by $\boldsymbol{I}_{CP}$) are concatenated with identity matrix $\boldsymbol{I}_N$. The term β is the power loss factor, $\beta = \sqrt{N/N_T}$.

The block $\tilde{u}_{CP}(i)$ is serialized to yield $\tilde{u}_{CP}(n)$, which is then pulse shaped 1613, carrier modulated 1612, amplified, and transmitted 1611 via multiple antenna elements through a channel. The channel impulse response $h(n)$ includes the effects of pulse shaping, channel effects, receiver filtering, and sampling.

In a receiver configuration of the invention, each of a plurality of WTs is adapted to receive a different transmitted symbol on a different orthogonal carrier frequency. For a WT employing a square-root Nyquist receive filter, the received samples are expressed by:

$$x(n) = \tilde{u}_{CP}(n) * h(n) + v(n)$$

where $v(n)$ is additive white Gaussian noise (AWGN). The received samples are grouped into blocks of size N_T: $x_{CP}(i) = [x(iN_T), x(iN_T+1),\ldots, x(iN_T+N_T-1)]^T$. The first N_{CP} values of $x_{CP}(i)$ corresponding to the cyclic prefix are discarded, which leaves N-length blocks expressed by: $x(i) = [x(iN_T+N_{CP}), x(iN_T+ N_{CP}+1),\ldots, x(iN_T+N_T-1)]^T$. H is defined as an $N \times N$ circulant matrix with $\tilde{H}_{n,m} = h((n-m)_{\bmod N})$. The block input-output relationship is expressed as: $\tilde{x}(i) = \beta\tilde{H}\tilde{u}(i) + \tilde{\eta}(i)$, where $\tilde{\eta}(i) = [v(iN_T+N_{CP}), v(iN_T+ N_{CP}+1),\ldots, v(iN_T+N_T-1)]^T$ is the AWGN block. Applying the FFT to $\tilde{x}(i)$ yields:

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$$x(i) = F\tilde{x}(i) = \beta F\tilde{H}F^H u(i) + \tilde{\eta}(i)$$
$$= \beta D_H u(i) + \eta(i)$$

where

$$D_H = diag\left[H\left(e^{j0}\right), H\left(e^{j(2\pi/N)}\right), \ldots H\left(e^{j(2\pi(N-1)/N)}\right)\right] = F\tilde{H}F^H$$

and $H(e^{j2\pi f})$ is the frequency response of the ISI channel; $H\left(e^{j2\pi f}\right) = \sum_{n=0}^{N_{CP}} h(n)e^{-j2\pi fn}$. An equalizer followed by a decoder uses $x(i)$ to estimate the data symbols encoded on $u(i)$.

Preferred embodiment of the invention may employ Spread-OFDM, which involves multiplying each data block $s(n)$ by a spreading matrix A:

$$u(n) = As(n)$$

In the case where CI spreading codes are employed, $A_{nm} = \exp(-j2\pi nm/N)$. This maps the data symbols to pulse waveforms positioned orthogonally in time. This choice of spreading codes also gives the appearance of reversing the IFFT. However, the resulting set of pulse waveforms is a block, rather than a sequence, wherein each waveform represents a cyclic shift within the block duration T_s, such as described in U.S. Pat. Appl. Pubs. 20030147655 and 20040086027, which are both incorporated by reference.

Figure 7A illustrates a functional embodiment of the invention related to calculating MIMO weights in a cooperative-beamforming network. A plurality of WTs provide received baseband information from a WWAN channel 1701 that includes a training sequence and/or a data sequence having a predetermined constellation of values. WWAN MIMO processing is performed 1702 on the received baseband information to derive a plurality of array-processing weights β_i, which are then distributed 1703 via the WLAN to a predetermined plurality of WTs.

Figure 7B illustrates a functional embodiment of the invention adapted to calculate transmitted data symbols received by a cooperative-beamforming network. A plurality of WTs provide received baseband information from a WWAN channel 1701 that includes a data sequence having a predetermined constellation of values. WWAN MIMO processing may be performed 1704 on the received baseband information to derive a plurality of estimated data symbols d_i, which are then conveyed 1705 via the WLAN to at least one destination WT. The WWAN MIMO processing 1704 may

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optionally include providing for any of a set of signal-processing operations, including filtering, demodulation, demultiplexing, error correction, and data formatting.

Figure 8A illustrates a functional embodiment for a method and apparatus of the invention. Specifically, a data source 1800 is adapted to distribute a plurality of data symbols via a WLAN channel 199 to a plurality N_t of WTs 1806.1-1806.N_t, which are adapted to transmit the data symbols into at least one WWAN channel 99. Although the functional embodiment shown in Figure 8A is illustrated with respect to uplink WWAN functionality, the functional blocks may alternatively be inverted to provide for downlink WWAN functionality.

The data source and the WTs 1806.1-1806.N_t include appropriate WLAN-interface equipment to support distribution of the data symbols to the WTs 1806.1-1806.N_t. For example, the WTs 1806.1-1806.N_t are shown including WLAN-interface modules 1801.1-1801.N_t. The WLAN channel 199 may optionally include additional network devices that are not shown, such as routers, access points, bridges, switches, relays, gateways, and the like. Similarly, the data source 1800 and/or the WTs 1806.1-1806.N_t may include one or more said additional network devices. The data source 1800 may include at least one of the WTs 1806.1-1806.N_t.

A coder 1803.1-1803.N_t in each of the WTs 1806.1-1806.N_t is adapted to receive a baseband data sequence from the associated WLAN-interface module 1801.1-1801.N_t and provide coding, such as channel coding, spreading, and/or multiple-access coding. A coded data sequence output from each coder 1803.1-1803.N_t is mapped into frequency bins of multicarrier generators, such as IDFTs 1804.1-1804N_t. This embodiment may be employed to produce multicarrier signals or to synthesis single-carrier signals from a plurality of spectral components. Alternatively, other types of multicarrier generators may be employed, such as quadrature-mirror filters or DSPs configured to perform other transform operations, including Hadamard transforms. The resulting multicarrier signals are coupled into the WWAN channel 99 by associated WWAN-interface modules 1805.1-1805.N_t.

For each flat-fading subcarrier frequency channel, the WWAN channel may be characterized by channel responses 1890.1-1890-N_t and 1899.1-1899-N_t of a mixing system. The channel responses 1890.1-1890-N_t and 1899.1-1899-N_t represent elements of

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H, an $N_r \times N_t$ channel-response matrix that characterizes the complex gains (i.e., transfer function, or spatial gain distribution) from the N_t transmission elements to the N_r receive elements; and n_i(n) represents an AWGN contribution having zero mean and zero variance.

There are N_r receiver elements comprising WWAN-interface modules 1815.1-1815.N_r and filter banks, such as DFTs 1814.1-1814.N_r, coupled to at least one MIMO combiner 1810. The MIMO combiner 1810 is adapted to perform any number of signal-processing operations, including decoding received data symbols. In one embodiment of the invention, the MIMO combiner 1810 is adapted to perform diversity combining. In another embodiment of the invention, the MIMO combiner 1810 is adapted to perform spatial (e.g., sub-space) processing. Furthermore, many other applications and embodiments of the invention may be achieved using the functional description (or minor variations thereof) depicted in Figure 8A.

Figure 8B illustrates a functional embodiment of the invention that may be incorporated into specific apparatus and method embodiments. In particular, WWAN signals received from a WWAN channel 99 by a plurality N_r of WTs 1836.1-1836.N_r are conveyed via a WLAN channel 199 to a MIMO combiner 1830.

In this case, WWAN data symbols are encoded by one or more coders (such as coders 1821.1-1821.N_t), impressed on a plurality of subcarriers by IDFTs 1822.1-1822.N_t, and coupled into the WWAN channel 99 by a plurality of WWAN-interface modules 1825.1-1825.N_t. Received WWAN signals may be coupled from the WWAN channel 99 by a plurality N_r of WTs 1836.1-1836.N_r. Each WT 1836.1-1836.N_r includes at least one WWAN-interface module (such as WWAN-interface modules 1831.1-1831.N_r), a filter bank (such as DFTs 1834.1-1834.N_r), and a WLAN-interface module (such as 1835.1-1835.N_r).

WWAN signals received by each WT 1836.1-1836.N_r are converted to a baseband data sequence, separated into frequency components (by the DFTs 1834.1-1834.N_r), and then adapted for transmission into the WLAN channel 99. A MIMO combiner 1830 may be configured to receive WLAN transmissions, recover the frequency components, and perform MIMO processing to generate estimates of the transmitted WWAN data symbols. The MIMO combiner 1830 and/or the WTs 1836.1-

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1836.N_r may be adapted to perform decoding. In one embodiment of the invention, the MIMO combiner 1830 may include one or more of the WTs 1836.1-1836.N_r.

Figure 8C illustrates an embodiment of the invention in which WTs 1836.1-1836.N_r are adapted to perform time-domain (e.g., Rake) processing. Specifically, each WT 1836.1-1836.N_r includes a Rake receiver 1854.1-1854.N_r. The embodiment illustrated in Figure 8C is particularly suited to performing MIMO operations on received direct-sequence signals, such as direct sequence CDMA (DS-CDMA) signals.

Particular embodiments of the invention may be directed toward transmitting and/or receiving any of the well-known types of spread signals. Spread signals include spread-spectrum signals in which a transmitted signal is spread over a frequency band much wider than the minimum bandwidth needed to transmit the information being sent. Spread spectrum includes direct-sequence modulation commonly used in CDMA systems (e.g., cdmaOne, cdma2000, 1xRTT, cdma 1xEV-DO, cdma 1xEV-DV, cdma2000 3x, W-CDMA, Broadband CDMA, and GPS), as well as frequency-domain spreading techniques, such as spread-OFDM, multi-carrier CDMA, and multi-tone CDMA.

In a DS-CDMA system, a kth WWAN transmission signal $s^k(t)$ that includes N code bits $\{b^k[n]\}_{n=1}^{N}$ is given by:

$$s^k(t) = \sum_{n=0}^{N-1} b^k[n] g_{T_b}(t - nT_b) g_\tau(t) a^k(t - iT_b) \cos(2\pi f_c t)$$

where $a^k(t) = \sum_{i=0}^{G-1} C_i^k g_{T_c}(t - iT_c)$, $C_i^k \in \{-1,1\}$ is the DS spreading signal, G represents processing gain, T_c is the chip duration, T_b is the bit duration, and $g_{T_c}(t)$, $g_{T_b}(t)$, and $g_\tau(t)$ represent the chip, bit, and transmitted pulse shapes, respectively.

A plurality M of WTs linked together by a WLAN comprises elements of an M-element antenna array capable of receiving $K \le M$ transmission channels. In a frequency-selective channel, the received signal at the array is:

$$r(t) = \sum_{k=1}^{K} \sum_{l=0}^{L^k-1} \sum_{n=0}^{N-1} \alpha_l^k \vec{V}(\vartheta_l^k) b_k[n] g(t - \tau_l^k - nT_b) \cos(2\pi f_c t + \varphi_l^k) + \upsilon(t)$$

where $\vec{V}(\vartheta)$ is an array-response vector, K is the number of received transmission channels, L^k is the number of distinct fading paths corresponding to the kth user, α_l^k is the

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fade amplitude associated with path l and user k, $\varphi_l^k = U[0,2\pi]$ represents the associated fade phase, τ_l^k is the path time-delay (which occurs below a predetermined duration threshold T_{max}), and ϑ_l^k denotes angle of arrival. The array response vector $\vec{V}(\vartheta)$ is expressed by:

$$\vec{V}(\vartheta) = \begin{bmatrix} 1 & e^{-2\pi d_1 \cos\theta/\lambda} & \dots & e^{-2\pi d_{M-1}\cos\theta/\lambda} \end{bmatrix}$$

where d_m is the antenna separation, and λ is the wavelength corresponding to carrier frequency f_c. For a jth user's l^{th} path, the nth bit at the beamformer output is given by:

$$z_l^j[n] = W^H(\vartheta_l^k)\int_{+(n-1)T_b}^{+nT_b} r(t)\cos(2\pi f_c t + \varphi_l^j)a^j(t-\tau_l^j-(n-1)T_b)dt$$

where $W(\vartheta_l^k)$ is the weighting vector of the beamforming system. $z_l^k[n]$ can be expressed by four components:

$$z_l^k[n] = S_i^j[n] + ISI_i^j[n] + IXI_i^j[n] + \upsilon_i^j[n]$$

where S is the desired signal, ISI is inter-symbol interference, IXI is cross interference (i.e., multiple-access interference), and ν is the AWGN contribution. These components can be expressed as follows:

$$S_l^j[n] = \alpha_l^j W^H(\vartheta_l^j)\vec{V}(\vartheta_l^j)b^j[n]G$$

$$ISI_i^j[n] = \sum_{\substack{h=0\\h\neq l}}^{L^k-1}\sum_{n=0}^{N-1}\alpha_l^k W^H(\vartheta_h^j)\vec{V}(\vartheta_l^k)b^j[n]\cos(\varphi_h^j-\varphi_l^j)R_{jj}(\tau_h^j-\tau_l^j-nT_b)$$

$$IXI_i^j[n] = \sum_{\substack{k=1\\k\neq j}}^{K}\sum_{\substack{h=0\\h\neq l}}^{L^k-1}\sum_{n=0}^{N-1}\alpha_l^k W^H(\vartheta_h^k)\vec{V}(\vartheta_l^j)b^j[n]\cos(\varphi_h^k-\varphi_l^j)R_{kj}(\tau_l^j-\tau_h^k-nT_b)$$

$$\upsilon_l^j[n] = \int_{+(n-1)T_b}^{+nT_b} W^H(\vartheta_l^j)n(t)a^j(t-\tau_l^j)\cos(2\pi f_c t+\varphi_l^j)dt$$

where $W^H(\vartheta_l^j)\vec{V}(\vartheta_l^j)$ represents the spatial correlation, φ_l^j and τ_l^j are the random phase and time delay for the jth user's l^{th} path, G is the processing gain, and R_{jj} and R_{kj} are the partial auto-correlation and cross-correlation of the direct sequence code(s):

$$R_{kj}(\tau) = \int_\tau^T a^k(t)a^j(t-\tau)dt$$

Maximal ratio combining produces an output:

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$$z^j[n] = \sum_{l=0}^{L-1} \alpha_l^j z_l^j[n]$$

which can be processed by a decision processor. In this case, the BER is given by:

$$P_e = \int_0^\infty Q(2r_o) f(r_o \mid \bar{r}_o) dr_o$$

where $\bar{r}_o$ is the mean value of the instantaneous SINR, r_o, and $Q(\ )$ represents the complementary error function.

It should be appreciated that the WTs may be adapted to perform either or both time-domain (e.g., Rake) or frequency-domain processing as part of a receiver operation. Signals received by a plurality of WTs may be combined with respect to any combining technique, including EGC, MRC, Minimum Mean Squared Error Combining, other types of optimal combining, Successive Interference Cancellation, and other matrix-reduction/matrix diagonalization techniques. Array-processing operations may include combinations of local and global processing. For example, diversity combining may be performed at each multi-element WT. Then signals from each WT may be combined (e.g., in a central processor) to perform sub-space (e.g., directional) processing. Other combinations of local and global processing may be employed. Similarly, combinations of sub-space processing (i.e., capacity enhancement) and diversity combining (i.e., signal-quality enhancement) may be performed. It should also be appreciated that the WTs may be adapted to perform either or both time-domain and frequency-domain processing for transmission. Thus, appropriate delays or complex weights may be provided to WT transmissions to produce a coherent phase front that converges at a predetermined WWAN destination node.

Figure 9A illustrates an optional transmission embodiment of the present invention. That is, method and apparatus configurations can be inferred from the following descriptions. A data source 1900 is adapted to provide data for processing by an array processor, such as MIMO processor 1902. Optionally, other types of array processors may be provided. A physical (e.g., wired) connection 1902 and/or a wireless connection 1901 couple the data between the data source 1900 and the MIMO processor 1902. The wireless connection 1901 is enabled by a WLAN 1999. The MIMO processor

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1902 is adapted to provide MIMO processing to the data, such as providing complex channel weights, providing spreading weights, and/or providing channel coding.

In one exemplary embodiment of the invention, MIMO processor 1902 provides convolutional or block channel coding to the data, which effectively spreads each data bit over multiple coded data bits. The resulting coded data bits are then grouped in serial blocks by the MIMO processor 1902. Signal-block outputs from the MIMO processor 1902 are provided with serial-to-parallel conversion by the WLAN 1999 (which is denoted by S/P 1914) and distributed to a plurality of WTs 1906.1-1906.M.

Each WT 1906.1-1906.M has a WLAN interface 1907.1-1907.M adapted to receive and demodulate the data received from the MIMO processor 1902. The MIMO processor 1902 is accordingly equipped with a WLAN interface that is not shown. The MIMO processor 1902 is typically comprised of one or more WTs 1906.1-1906.M. In some embodiments of the invention, MIMO processor 1902 may include at least one computer-processing terminal that does have a WWAN interface.

Data received from the MIMO processor 1902 is then modulated 1908.1-1908.M by each WT 1906.1-1906.M for transmission into a WWAN channel by a corresponding WWAN interface 1909.1-1909.M. Modulation 1908.1-1908.M typically includes mapping blocks of data bits to data symbols, which are then mapped to a modulation constellation. Modulation 1908.1-1908.M may also include channel coding and/or data interleaving. In an exemplary embodiment of the invention, modulation 1908.1-1908.M includes the application of complex WWAN channel weights. Such channel weights may optionally be provided by the MIMO processor 1902. In alternative embodiment of the invention, modulators 1908.1-1908.M provide a predetermined delay profile (provided by the MIMO processor 1902) to the data to be transmitted into the WWAN channel.

Figure 9B illustrates a functional flow chart that pertains to transmitter apparatus and method embodiments of the invention. One or more data sources 1920.1-1920.K are coupled via a WLAN 1999 to a plurality M of WTs 1926.1-1926.M. Each WT 1926.1-1926.M includes a WLAN interface 1927.1-1927.M, an array processor (such as a MIMO processor 1926.1-1926.M), and a WWAN interface 1929.1-1929.M.

The data sources 1920.1-1920.K optionally include baseband-processing capabilities, such as channel coding, interleaving, spreading, multiplexing, multiple-

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access processing, etc. The data sources 1920.1-1920.K include WLAN interfaces (not shown). The data sources 1920.1-1920.K may include one or more WTs 1926.1-1926.M.

The WLAN interfaces 1927.1-1927.M include apparatus and means for converting received signals that were formatted for transmission in the WLAN 1999 into baseband data signals. The MIMO processors 1926.1-1926.M are adapted to provide for frequency-domain and/or time-domain MIMO operations on the baseband data signals received from the WLAN interfaces 1927.1-1927.M. Alternatively, the MIMO processors 1926.1-1926.M may be adapted to perform phase operations at WWAN carrier frequencies transmitted by the WWAN interfaces 1929.1-1929.M. The WWAN interfaces 1929.1-1929.M provide any necessary baseband, IF, and RF operations necessary for transmitting data in a WWAN channel.

Figure 10A illustrates software components of a transmission embodiment of the invention residing on a computer-readable memory 1950. An array-processing weighting source-code segment 1951 is adapted to generate a plurality of array-element weights for an antenna array comprised of a plurality of WTs coupled to at least one WWAN. The array-element weights may include at least one of frequency-domain weights (e.g., complex sub-carrier weights) and time-domain weights (e.g., weighted Rake taps). The array-processing weighting source-code segment 1951 is adapted to accept as input at least one of a set of information inputs, including data signals for transmission into the WWAN, training signals (e.g., known transmission symbols) received from the WWAN, data signals (e.g., unknown transmission symbols) received from the WWAN, WWAN channel estimates, and WWAN-control information.

The array-processing weighting source-code segment 1951 is adapted to provide as output at least one of a set of information signals, including WWAN weights and weighted data for transmission into the WWAN (i.e., weighted WWAN data). A WLAN distribution source code segment 1952 is provided for distributing either or both WWAN weights and weighted WWAN data received from source-code segment 1951 to a plurality of WTs via at least one WLAN. The WLAN distribution source code segment 1952 may optionally function to couple at least one of a set of information inputs to the source-code segment 1951, including data signals for transmission into the WWAN (such

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as generated by other WTs), training signals received from the WWAN, data signals received from the WWAN, WWAN channel estimates, and WWAN-control information.

Figure 10B illustrates software components of a receiver embodiment of the invention residing on a computer-readable memory 1960. An array-processing weighting source-code segment 1961 is adapted to generate a plurality of array-element weights for an antenna array comprised of a plurality of WTs coupled to at least one WWAN. The array-element weights may include at least one of frequency-domain weights (e.g., complex sub-carrier weights) and time-domain weights (e.g., weighted Rake taps). The array-processing weighting source-code segment 1961 is adapted to accept as input at least one of a set of information inputs, including training signals (e.g., known transmission symbols) received from the WWAN, data signals (e.g., unknown transmission symbols) received from the WWAN, WWAN channel estimates, and WWAN-control information.

The array-processing weighting source-code segment 1961 is adapted to provide as output at least one of a set of information signals, including WWAN weights, weighted received WWAN data for transmission into the WLAN (i.e., weighted received WWAN data), weighted WWAN data received from a plurality of WTs connected by the WLAN and then combined (i.e., combined weighted WWAN data), and estimates of said combined weighted WWAN data. A WLAN distribution source code segment 1962 is provided for distributing at least one of a set of signals (including the WWAN weights, the weighted received WWAN data, the combined weighted WWAN data, and the estimates said combined weighted WWAN data) to a plurality of WTs via at least one WLAN. The WLAN distribution source code segment 1962 may optionally function to couple at least one of a set of information inputs to the source-code segment 1961, including WWAN data signals received by other WTs, training signals received from the WWAN by other WTs, WWAN channel estimates (either of both locally generated and received from other WTs), WWAN-control information, weights received from at least one other WT, and weighted WWAN data received from at least one other WT.

Since software embodiments of the invention may reside on one or more computer-readable memories, the term computer-readable memory is meant to include more than one memory residing on more than one WT. Thus, embodiments of the

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invention may employ one or more distributed-computing methods. In one embodiment of the invention, the computer-readable memory 1950 and/or 1960 further includes a distributed-computing source-code segment (not shown). It will be appreciated that many different types of distributed computing, which are well known in the art, may be performed. The WLAN distribution source code segment 1952 and/or 1962 may be adapted to provide for synchronizing transmitted and/or received WWAN signals.

Embodiments of the invention described herein disclose array-processing methods (including software implementations) and apparatus embodiments employed in a WWAN and coordinated between a plurality of WTs connected via at least one WWAN. WTs in a WLAN group typically share the same WWAN access. However, some embodiments of the invention provide for WTs with access to different WWANs. Furthermore, one or more WTs may have access to a plurality of WWANs and WWAN services. In some cases, one or more WTs may not be configured to access any WWAN.

In some embodiments of the invention, the computer-readable memory 1950 and/or 1960 further includes a WLAN setup source-code segment (not shown) capable of establishing and/or dynamically reconfiguring at least one WLAN group. For example, WTs may convey location information (e.g., GPS) and/or signal-strength information (e.g., in response to a WLAN probing signal) to the WLAN setup source-code segment (not shown). The WLAN setup source-code segment (not shown) may reside on one or more of the WTs and/or at least one WWAN terminal, such as a cellular base station.

The WLAN setup source-code segment (not shown) may provide one or more WLAN group configuration functions, including determining the number of WWAN-enabled WTs, the total number of WTs in the WLAN group, which WTs are active (and inactive), which WTs are in the WLAN group, and selecting which WT(s) has (have) network-control functionality. The WLAN setup source-code segment (not shown) may be adapted to perform WWAN channel quality analysis functions, including determining WWAN link performance (relative to one or more WTs) from training sequences or pilot signals, performing WWAN-channel estimation, receiving link performance or channel estimates from the WWAN, and performing channel-quality calculations (e.g., SNR, BER, PER, etc.).

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The WLAN setup source-code segment (not shown) may select which WTs are WWAN-enabled based on one or more criteria points, including WWAN link performance, WLAN link performance, required transmission and/or reception needs (e.g., the number of WLAN-group WTs requesting WWAN services, the types of WWAN services required, individual and total throughput, required signal-quality threshold, and WWAN bandwidth available to the WLAN group), computational load, WLAN capacity, power-consumption load, diversity gain, and interference mitigation.

The WLAN distribution source code segments 1952 and 1962 may be adapted to route WWAN channel-access information to the WTs. For example, WWAN channel-access information can include multiple-access information (e.g., multiple-access codes, frequency bands, time slots, spatial (or sub-space) channels, etc.), power control commands, timing and synchronization information, channel coding, modulation, channel pre-coding, and/or spread-spectrum coding.

Figure 11 shows a WWAN comprising a WWAN access point (e.g., a base station) 2120 and a local group 2100 comprising a plurality of wireless terminals (WTs) 2101-2104 communicatively coupled together via a WLAN 2105. A network-management operator 2106 is configured to handle WWAN-control operations within the local group 2100. In an exemplary embodiment, the network-management operator 2106 is coupled to at least one of the WTs 2101-2104 (e.g., WT 2103). One or more of the WTs 2101-2104 may be configured to transmit and/or receive WWAN communication signals, such as WWAN traffic channels 2110 and WWAN control messages 2111. Signals in the WWAN traffic channels 2110 may be processed by one or more of the WTs 2101-2104, which may include at least one local area network controller (e.g., 2103). The WWAN control messages 2111 are processed by the network-management operator 2106.

In an exemplary embodiment of the invention, a target WT (e.g., WT 2104) communicates with one or more WTs in the local group 2100 via the WLAN 2105, and the local group 2100 is configured to communicate with the base station 2120 via the WWAN. More specifically, one or more of the WTs 2101-2104 may be configured to participate in WWAN communications at any particular time. The target WT 2104 may communicate with the network controller (e.g., WT 2103), which is configured to

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communicate with other WTs in the local group 2100. The network controller 2103 typically oversees network control functions in the local area network. Alternatively, the target WT 2104 may function as a local area network controller. A particular WT may determine which WTs to use for transmitting and/or receiving signals in the WWAN based on local area network criteria, as well as WWAN-related criteria. Local area network control and/or WWAN control functionality may be distributed between one or more WTs in the local group.

In Figure 12, a communication system comprises a plurality *M* of WTs 2209.1 – 2209.M communicatively coupled together in a WLAN, which comprises a WLAN controller 2206. A WWAN network-management operator 2210 is communicatively coupled to the WLAN controller 2206. WWAN network-management operator 2210 is configured for cooperatively processing WWAN-control messages for the WTs 2209.1 – 2209.M, each of which comprises at least one WWAN interface 2201.1 – 2201.M, respectively.

According to one aspect of the invention, the WWAN interfaces 2201.1 – 2201.M receive WWAN control messages from the WLAN that were processed by the WWAN network-management operator 2210 and transmit those messages into the WWAN. According to another aspect of the invention, the WWAN interfaces 2201.1 – 2201.M receive WWAN control messages from the WWAN and couple those messages through the WLAN to the WWAN network-management operator 2210. According to yet another aspect of the invention, one or more WTs functions as the WWAN network-management operator 2210. Thus, the WWAN network-management operator 2210 may comprise one or more WWAN interfaces and be configured to transmit WWAN control messages into the WWAN.

For the purpose of the present disclosure, a WWAN comprising a plurality of wireless terminals communicatively coupled together via a WLAN may be defined as one or more of the following system configurations:

- A plurality of WTs in a local group configured to receive from a base station a signal intended for at least one WT.

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- A plurality of WTs in a local group configured to receive from a base station a plurality of signals modulated on interfering (e.g., common) channels and intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a base station a plurality of signals modulated on different non-interfering channels and intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a plurality of base stations a signal modulated on a common channel intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a plurality of base stations a signal redundantly modulated on a plurality of different channels intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a plurality of base stations a plurality of signals modulated on interfering channels and intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a plurality of base stations a plurality of signals modulated on different non-interfering channels and intended for at least one WT.
- A plurality of WTs in a local group configured to transmit to a base station a signal originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a base station a plurality of signals modulated on interfering (e.g., common) channels originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a base station a plurality of signals modulated on different non-interfering channels originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a plurality of base stations a signal modulated on a common channel originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a plurality of base stations a signal redundantly modulated on a plurality of different channels originating from at least one WT.

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- A plurality of WTs in a local group configured to transmit to a plurality of base stations a plurality of signals modulated on interfering channels originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a plurality of base stations a plurality of signals modulated on different non-interfering channels and originating from at least one WT.
- A plurality of WTs in a first local group configured to receive from a second local group a signal intended for at least one WT in the first local group.
- A plurality of WTs in a first local group configured to receive from a second local group a plurality of signals modulated on interfering channels and intended for at least one WT in the first local group.
- A plurality of WTs in a first local group configured to receive from second local group a plurality of signals modulated on different non-interfering channels and intended for at least one WT in the first local group.
- A plurality of WTs in a first local group configured to transmit to a second local group a signal originating from at least one WT in the first local group.
- A plurality of WTs in a first local group configured to transmit to a second local group a plurality of signals modulated on interfering channels and originating from at least one WT in the first local group.
- A plurality of WTs in a first local group configured to transmit to a second local group a plurality of signals modulated on different non-interfering channels and originating from at least one WT in the first local group.
- A base station comprising a plurality of WTs in a base station local group configured to transmit a signal intended for at least one subscriber WT not in the base station local group.
- A base station comprising a plurality of WTs in a base station local group configured to transmit a plurality of signals modulated on interfering (e.g., common) channels and intended for at least one subscriber WT not in the base station local group.
- A base station comprising a plurality of WTs in a base station local group configured to transmit a plurality of signals modulated on different non-interfering channels and intended for at least one subscriber WT not in the base station local group.

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- Multiple base stations comprising at least one base station local group configured to transmit a signal modulated on a common channel intended for at least one WT.
- Multiple base stations comprising at least one base station local group configured to transmit to a plurality of WTs a signal redundantly modulated on a plurality of different channels intended for at least one WT.
- Multiple base stations comprising at least one base station local group configured to transmit to a plurality of WTs a plurality of signals modulated on interfering channels and intended for at least one WT.
- Multiple base stations comprising at least one base station local group configured to transmit to a plurality of WTs a plurality of signals modulated on different non-interfering channels and intended for at least one WT.
- A base station comprising a plurality of WTs in a base station local group configured to receive a signal originating from at least one WT.
- A base station comprising a plurality of WTs in a base station local group configured to receive a plurality of signals originating from at least one WT and modulated on interfering channels.
- A base station comprising a plurality of WTs in a base station local group configured to receive a plurality of signals modulated on different non-interfering channels and originating from at least one WT.
- Multiple base stations comprising at least one base station local group configured to receive a signal modulated on a common channel originating from at least one WT.
- Multiple base stations comprising at least one base station local group configured to receive a signal redundantly modulated on a plurality of different channels originating from at least one WT.
- Multiple base stations comprising at least one base station local group configured to receive a plurality of signals modulated on interfering channels and originating from at least one WT.
- Multiple base stations comprising at least one base station local group configured to receive a plurality of signals modulated on different non-interfering channels and originating from at least one WT.

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A WWAN network-management operator may include a single WT or a plurality of WTs. In one embodiment, the WWAN network-management operator includes a single WT communicatively coupled to the WWAN and configured to perform WWAN-control operations for one or more WTs in the local group. For example, a block diagram of a WT 2300 shown in Figure 13 comprises a WWAN network-management operator module 2302 communicatively coupled to a WWAN interface 2301 and a WLAN interface 2303. In another embodiment, the WWAN network-management operator may comprise WWAN network-management operator modules residing in a plurality of WTs. Thus, the WWAN network-management operator may be configured to transmit and/or receive WWAN-control parameters in the WWAN on behalf of one or more WTs in the local group. A local area network controller may also include a WWAN network-management operator module and may perform WWAN network management for one or more WTs in the group.

Each WT may function as its own network-management operator. For example, a WT functioning as its own network-management operator may be communicatively coupled to the WWAN and configured to transmit and receive WWAN control information directly with the WWAN, whereas traffic-channel processing may be performed in cooperation with one or more other WTs in the local group. In another exemplary configuration, WWAN control information may be coupled from a target WT (e.g., a source or destination WT relative to the subject information, i.e., the WWAN control information) to a relay WT communicatively coupled to the WWAN and configured to transmit and receive the target WT's WWAN control information. While the target WT functions as its own network-management operator, it may employ other WTs in the local group to transmit and receive WWAN control messages. Thus, the relay WT may merely function as a pass through having optional added physical-layer adjustments for the WWAN control information. The physical-layer adjustments may be used to condition the WWAN control messages for the WWAN channel and/or the WLAN channel. Similarly, a WT functioning as a network-management operator for itself and/or at least one other WT may employ one or more WTs in the local group for transmitting and receiving WWAN control messages in the WWAN.

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In another embodiment, a WT may function as a network-management operator for one or more other WTs. For example, a network controller may function as a network-management operator for at least one other WT. In another embodiment, at least one WT that is neither a network controller nor a target WT may function as the network-management operator. For example, a WT having the best WWAN channel (such as may be determined by any of a variety of signal quality criteria that are well known in the art) may be selected as the network-management operator. Various criteria for selecting WTs for network-management operator responsibilities may be implemented, including load balancing.

In another embodiment of the invention, a plurality of WTs in a local group may simultaneously function as a network-management operator. The network-management operator may comprise multiple WTs including a target WT, multiple WTs including a network controller, multiple WTs not including a network controller, or multiple WTs not including a target WT. A plurality of WTs may redundantly process WWAN control messages. Alternatively, each of a plurality of WTs configured to perform WWAN-control operations may be configured to perform a predetermined subset of the WWAN-control operations.

A network-management operator may participate in any combination of various WWAN-control operations, including power control, data-rate control, session control, authentication, key exchange, paging, control-channel monitoring, traffic channel request, channel assignment, error detection, acknowledgement, request for retransmission, identification, reconnects, synchronization, flow control, request for service from a particular sector or access point, hand-off.

Figure 14 is a flow diagram of a communication method configured in accordance with an aspect of the invention. A WLAN is employed for sharing WWAN control information between a group of WTs 2401. WWAN control information is coordinated between the group of WTs and the WWAN 2402, and WWAN control information is cooperatively processed by the group 2403.

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The Open Systems Interconnection Reference Model (OSI Reference Model) may be used to describe the function of a WWAN comprising a local group of a plurality of WTs communicatively coupled together via a WLAN.

In the Application Layer, each WT typically employs its own user applications for accessing network services (e.g., login, data upload, data download, multi-media processing). Thus, each WT handles its own application-layer network access, flow control, and error processing. Each WT controls its own user interface for access to services that support user applications. These applications typically are not subject to cooperative access (e.g., sharing). However, certain network resources (e.g., printers, faxes) may be shared. Some applications, such as computational processing applications, may provide for distributed computing processes between WTs in a network. However, such distributed-computing applications have not been employed in the prior art for receiving and decoding wireless communications.

In the Presentation Layer, each WT may translate data from an application format to a network format and vice-versa. Different data formats from different applications are processed to produce a common data format. Each WT may manage its own protocol conversion, character conversion, data encryption/decryption, and data compression/expansion. Alternatively, a network controller that serves multiple WT may perform one or more presentation-layer functions. For example, data-processing intelligence may be handled by a network controller, and individual WTs may function as dumb terminals. In some multimedia applications, a network controller may function essentially as a media server configured to deliver predetermined data formats to each WT functioning as a media device. Furthermore, there are various degrees of how presentation-layer processing may be shared between WTs and a network controller.

In the Session Layer, each WT may be responsible for identification so only designated parties can participate in a session. Session setup, reconnects, and synchronization processes may be managed by the target WT (e.g., a subscriber, an access point, or a base station), which functions as its own network-management operator for session-layer processing. Alternatively, a network controller may manage session-layer activities for each of one or more WTs in the local group. The network controller

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may store identities for each WT and manage sessions and the flow of information for each WT.

In another embodiment, multiple WTs may participate in session management. Some centralized decision-processing (such as by the target WT or a network controller) may be employed to direct one or more WTs to perform specific session-layer activities. Multiple responsibilities may be divided among the WTs. For example, one WT may conduct synchronization processes and another WT may perform session setup. The WTs assigned to perform particular functions may change with respect to signal quality with the WWAN, load balancing criteria, and/or other considerations.

In the Transport Layer, each WT may convert data streams into packets or predetermined segments. Each WT may also process received packets to reassemble messages. Thus, each WT may perform its own error handling, flow control, acknowledgement, and request for retransmission.

Alternatively, a network controller may manage transport-layer operations for each of one or more WTs in a local group. The network controller may be configured to convert data streams received from the WTs into packets. Similarly, the WT may convert data packets received from the WWAN into data streams that are routed to the appropriate WTs. The network controller may perform common network-management operator functions, including error handling, flow control, acknowledgement, and request for retransmission for each of the WTs.

In yet another embodiment, multiple WTs may be used to convert data streams into packets and/or process received packets to reassemble messages for a particular target WT. Each of a plurality of WTs may process only a portion of the received data stream and perform error handling, flow control, acknowledgement, and request for retransmission for the data it processes. Alternatively, multiple WTs may handle the same data. For example, redundant transport-layer processing may be performed by different WTs having uncorrelated WWAN channels in order to reduce errors, and thus, requests for retransmission. In another embodiment, only one WT may handle transport-layer processing at any given time. For example, a particular WT may be assigned to handle transport-layer processing if it has favorable WWAN-channel conditions. Other criteria,

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such as load balancing, may be used to select and transfer transport-layer processing responsibilities between WTs.

In the Network Layer, WTs may perform their own network-layer processing, such as addressing and routing. A WT, such as a router, a base station, a switch, or a relay may perform network-layer processes, including managing data congestion, adjusting data frames, packet switching, and routing. In addition to managing network-layer control within its local group, a network controller may perform network-layer processes for the WWAN.

The Data Link layer includes a Media Access Control (MAC) sub-layer and the Logical Link Control (LLC) sub-layer. Each WT may perform Data-link processing, such as converting received raw data bits into packets and managing error detection for other WTs. Similarly, each WT may convert data packets into raw data bits for one or more other WTs. In one embodiment, a target WT may perform its own data-link processing. Alternatively, a network controller may perform data-link processing for one or more WTs.

A Physical layer embodiment may provide for performing all physical-layer processes by a target WT. For example, a target WT distributes spread, scrambled baseband data to the other WTs, which then up convert and transmit the target's transmission signal as specified by the target WT. Similarly, each WT may receive and down convert WWAN transmissions and direct the down-converted signal via the WLAN for processing (e.g., descrambling and despreading) by a target WT.

In one embodiment, physical-layer processes may be divided between a target WT and other WTs in a local group. For example, the target WT may convey baseband data and control parameters to other WTs, which then spread and scramble the baseband data with respect to the control parameters. Additional control parameters, such as power control, and data rate control may be specified. Similarly, WTs in a local group may descramble and despread received data for further processing by a target WT. WTs may monitor control channels for signals addressed to any of a plurality of WTs in a local group.

In yet another embodiment, a network controller may perform some or all physical-layer processes corresponding to a target WT. A network controller may

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perform all physical-layer processes for a target WT (and other WTs in the corresponding local group if it performs higher-layer processes for the target WT). Alternatively, some of the higher-layer processes may be performed by the network controller and/or other WTs as part of a distributed computing procedure regardless of how the physical-layer processes are performed.

Several aspects of physical-layer processing include WWAN-control operations. Other WWAN-control operations may fall within any of a plurality of the OSI reference model layers. Embodiments and interpretations of the invention should not be constrained to the limitations of the OSI reference model. The OSI reference model is a generalization that may not be suitable for expressing the implementation of all WWAN-control operations.

In one aspect of the invention, a cellular base station may transmit a probe signal (e.g., a predetermined signal that is ramped in signal power) to a plurality of subscriber WTs. A network-management operator in a local group of WTs may be responsive to the probe signal for indicating a signal power level capable of being received from the base station. Similarly, the signal power level may be used as an indicator for transmit power and/or data rate.

Functions of the network-management operator may be distributed over a plurality of WTs in the local group, and network-management responsibilities may be shared by more than one WT and/or dynamically assigned to particular WTs. For example, a WT that first detects the probe signal may be assigned subsequent network-management responsibilities, such as predicting forward-link SINR and an associated achievable data rate, sending an acknowledgement to the base station, or requesting a particular data rate (e.g., sending a dynamic rate control signal to the base station). In another embodiment of the invention, WWAN signals received by a group of WTs may be combined before being processed by a network-management operator.

In one embodiment of the invention, a network-management operator in a local group performs open loop estimation to adjust reverse link (i.e., local group) transmit power. Alternatively, closed-loop power corrections may involve both the network-management operator and the base station. The network-management operator may send

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an access probe sequence and wait for an acknowledgement from a base station. Initial probe power is typically determined via power control.

A WT in the local group is typically denoted as being in an inactive state relative to the WWAN when it is not assigned a forward traffic channel. However, the network-management operator may assign one or more WWAN traffic channels to WTs that the WWAN considers inactive. In such cases, inactive WTs may help transmit and/or receive WWAN communications intended for active WTs in the local group. Similarly, active WTs may be assigned additional traffic channels by the network-management operator for transmitting and/or receiving WWAN communications intended for other active WTs in the group. Such assignments may be invisible to the WWAN, since so-called inactive WTs are used for connecting active WTs to the WWAN. In other embodiments of the invention, complex assignments, including sharing traffic channels between WTs, may be implemented.

A network-management operator may service one or more WTs in a variable-rate state. For example, a forward traffic channel is transmitted at a variable rate determined by the network-management operator's data rate control value. The network-management operator may determine the maximum data rate using any of a variety of well-known techniques. The network-management operator uses a data rate control channel to instruct the WWAN what data rate to serve to a particular WT in the local group. In response, the base station selects modulation, channel coding, power and/or number of multiple-access slots.

The network-management operator may direct its instructions to the best base station (i.e., the base station having the best channel relative to the local group) in its active set via addressing (e.g., a covering code). Alternatively, the network-management operator may instruct multiple base stations to serve the local group. This may occur when WTs can access more than one WWAN. This may also occur when some WTs are better served by one base station or sector while other WTs in the same local group are better served by a different base station or sector.

A WT enters a fixed-rate state when its network-management operator signals a request for a specific fixed rate from a base station or sector. The WT may transition to a variable rate if it cannot receive packets at the previously requested fixed rate. A

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network-management operator may select a fixed rate if there is an imbalance (e.g., different channel conditions) between the forward and reverse links.

In one aspect of the invention, a network-management operator is configured to perform connection-layer protocols that are typically conducted between a target WT and the base station. For example, the network-management operator may participate in acquisition and initialization state protocols, air link management protocols, connection state protocols, route updates, and/or idle state protocols.

A WT in an inactive state typically awakes from a sleep state periodically to monitor a control channel to receive overhead parameter messages and paging messages. In one aspect of the invention, a network-management operator may wait for an activate command from a default air link management protocol. A network-management operator may monitor a WWAN control channel for multiple WTs in a local group. In an alternative embodiment, WTs in the local group may take turns monitoring the WWAN control channel. In this case, responsibilities of the network-management operator are transferred betweens WTs in the local group. In another embodiment, a plurality of WTs may monitor the WWAN control channel, wherein each WT is configured to monitor the channel for only a subset of WTs in the local group.

In a network determination state, the network-management operator selects a channel on which to acquire a base station for a WT in the local group. After selecting a channel, the network-management operator enters a pilot acquisition state in which the network-management operator tunes to a particular channel and searches for the strongest pilot signal. Upon acquiring a pilot, the network-management operator enters a synchronization state. At this point, the network-management operator may transfer synchronization responsibilities to the target WT. If the network-management operator (or the target WT) is unable to obtain a pilot, it reverts back to the network determination state.

In the synchronization state, the network-management operator or the target WT looks for a sync message on the control channel and sets its clock to the time specified in the sync message. Failure to receive the sync message or similar failures may result in returning to the network determination state.

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The base station undergoes various state transitions in the process of serving the WTs. In an initialization state, the base station activates an initialization state protocol, overhead message protocol, and a control channel MAC protocol. A network-management operator may selectively route certain messages through WTs in a local group comprising the base station while reserving other messages for WWAN transmission only by the base station.

An idle state occurs after the network is acquired, but before an open connection is established. The base station initiates an idle state protocol, overhead messages protocol, route update protocol, control channel MAC protocol, access channel MAC protocol, and forward and reverse channel MAC protocols. In the connected state, base station and the target WT have an open connection until the connection is closed (i.e., goes to the idle state) or network redirection (goes to the initialization state). The base station activates a connected state protocol, overhead messages protocol, route update, control channel MAC protocol, and forward and reverse channel MAC protocols.

A network-management operator may be configured to direct hand offs between WWAN sectors, base stations, and/or networks. In one embodiment, a network-management operator in a local group may measure the SINR on each pilot in an active set (e.g., a set of base stations that actively serve the local group) and request data from the sector having the highest SINR. The network-management operator predicts the SINR for the next packet and request a higher data rate if it can decode it at that SINR. The rate request (which may include data rate, format, and modulation type) is sent by the network-management operator to the appropriate sector using a data rate control channel.

Generally, the network-management operator requests data from only one sector at a time. However, different WTs in a local group serving a particular target WT may request WWAN channels from multiple sectors at a time on identical or different WWAN channels. The network-management operator may coordinate requests for channels from different sectors. Multiple sectors (or base stations) may be configured to serve the same WWAN channel simultaneously. Alternatively, multiple WWAN channels may be used to serve one WT in the group. Although the target WT may have a better connection with a particular base station, the local group as a whole may have a better connection with a different base station. Thus, the network-management operator

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may dictate that the link be established and maintained relative to the group's connection rather than the target WT's connection.

A base-station scheduler may allocate physical channels for WTs. However, a network-management operator in a local group may provide logical channel assignments to the WTs that are invisible to the physical channel operation of the WWAN. Multiple WTs in a local group may utilize a single WT channel, such as for packet switched data communications. Each WT may utilize multiple physical channels, such as when higher data rates are required. The network-management operator may assign logical channels to various physical WWAN channels, and thus, effectively hand off those data channels to other sectors, base stations, or WWAN networks serving those physical WWAN channels.

Data rates requested by WTs may follow a channel fading process, wherein higher data requests occur when channel conditions are favorable and lower rates are requested as the channel degrades. It is well known that when a base station serves a large number of WTs, that diversity of multiple units can mitigate system-wide variations in data rate due to changing channel conditions. Multi-user diversity teaches that the opportunity for serving good channels increases with the number of users, which increases total network throughput.

One embodiment of the invention may provide for a network-management operator that dynamically selects one WT in a local group to communicate with a WWAN at a particular time, even though one or more channels may be served between the base station and the local group. The selection of which WT in the group communicates with the WWAN may change with changing channel conditions between the local group and the base station(s). Thus, the update rate for the dynamic selection may be based on the rate of change of WWAN channel conditions. This embodiment may be adapted for simultaneous communication by multiple WTs and/or the use of multiple base stations and/or WWANs. In another exemplary embodiment, the network-management operator may interleave communications (e.g., packets) across multiple WWAN channels undergoing uncorrelated channel distortions. Similarly, a WWAN specifically configured to interact with a local group may interleave messages across multiple WWAN channels transmitted to the local group. Different WWAN channels

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may be transmitted and received by one base station or a plurality of base stations. This type of interleaving (at either the local group and the base station) may be determined by a network-management operator.

In another embodiment, a network-management operator may be configured to redundantly transmit data symbols over multiple slots or physical channels to reduce transmission power or to allocate more power to data.

A network-management operator may employ an authentication protocol to authenticate traffic between a base station and a MT. For example, a network-management operator may identify a particular WT in a local group to a base station. The base station may then verify that the WT has a legitimate subscription record with a service provider that utilizes the WWAN. Upon verification, the base station allows access to the air interface and the network-management operator (whose responsibilities may be transferred to the WT) signs access channel packets to prove it is the true owner of the session. In one exemplary embodiment of the invention, the WT and/or the network-management operator may use IS-856 Air Interface Authentication.

In one embodiment of the invention, a target WT includes a network-management operator that employs other WTs in its local group to interact with a WWAN. In this case, authentication may be performed only with the target WT. In an alternative embodiment, the network-management operator resides in at least one other WT, such as a network controller. Thus, authentication may be performed with a network-management operator in a single terminal that is configured to perform authentication for more than one WT.

A network-management operator may employ a key exchange protocol (e.g., a Diffie-Hellman algorithm) for exchanging security keys between a WT and a WWAN for authentication and encryption. Typically, there is some predetermined key exchange algorithm used within a particular WWAN. Public values are exchanged and then messages are exchanged between the WT and the WWAN to indicate that the session keys have been correctly calculated. The keys may be used by the WT and the WWAN in an encryption protocol to encrypt traffic.

In one embodiment of the invention, a network-management operator resides on a target WT that accesses the WWAN via multiple WTs in a local group. The network-

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management operator may be configured to encrypt and decrypt WWAN traffic for the target WT without vital security information being made available to WTs other than the target WT. In another embodiment, the network-management operator may reside in a network controller. In this case, the network-management operator may be configured to engage in security protocols for more than one WT in the local group. Network-management operators according to various embodiments of the invention may be configured to participate in security protocols used to provide crypto sync, time stamps, and other elements used in authentication and encryption protocols.

Some aspects provide a multicarrier protocol that controls interference relationships between the carriers. This control enables time domain signal shaping, which provides for low PAPR and adaptability to single-carrier waveforms. Disclosed aspects include Carrier Interferometry (CI).

In CI, subcarrier frequencies are selected to provide a predetermined spectral response. Polyphase codes are applied to each subcarrier to control the time-domain characteristics of the superposition signal, as well as provide for orthogonality between data symbols and/or users. In one aspect, a pulse (i.e., a constructive interference resulting from a zero-phase relationship between the subcarriers) is generated from a superposition of the coded signals. Time-offset replicas of the pulse are used to construct waveforms having a predetermined frequency-domain profile.

An objective may be to enable a communication protocol that provides frequency-diversity benefits of multicarrier modulation to single-carrier systems and provides the low-PAPR benefits of single-carrier modulation to multicarrier communication systems, and the ability to provide the benefits of both systems simultaneously.

Figure 15 illustrates a CI pulse shape characterized by an in-phase alignment (e.g., mode locking) of harmonic subcarriers 1505 at a specific time t_1. A composite signal 1530 results from a superposition (i.e., summation) of the carriers 1505. The composite signal 1530 shows a pulse envelope centered at a predetermined time instant t_1. In the case where there is no amplitude tapering (i.e., a rectangular window) and a plurality N of carriers have a uniform frequency separation f_s, a composite CI signal is:

$$e(t) = \sum_{n=1}^{N} e^{i[(\omega_c + n\omega_s)t + n\Delta\phi]}$$

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which is characterized by an envelope-magnitude function:

$$|e(t)| = \left| \frac{\sin(N(\omega_s t + \Delta\phi)/2)}{\sin((\omega_s t + \Delta\phi)/2)} \right|$$

where ω_c is related to a carrier frequency f_c (or equivalently, an offset frequency $f_o = f_c$) by the relationship $\omega_c = 2\pi f_c$. Similarly, ω_s is related to the separation frequency f_s by the relationship $\omega_s = 2\pi f_s$.

The phase offsets $\Delta\phi$ typically correspond to any of N orthogonal time offsets corresponding to N orthogonal pulse positions. A kth bit or data symbol a_k in a user's transmission s(t) modulated onto a particular CI pulse, or phase space is expressed as:

$$s_k(t) = e(t - kT_b)$$

where T_b is a time offset corresponding to the particular CI pulse. Orthogonal pulses are centered at intervals of $T_b = T_s/N$. A burst of bits or symbols may be transmitted onto a contiguous train of pulses, such as shown in Figure 16B. In this case, a transmission corresponding to a particular user is characterized by the following relationship:

$$s(t) = \sum_{k=1}^{N} a_k e(t - kT_b)$$

The time-shifted pulses are orthogonal to each other even though the pulses overlap in time:

$$\int_0^{T_s} e(t - kT_b) e(t - nT_b) \delta t \qquad (k \neq n)$$

Figure 16A illustrates an amplitude distribution of the CI carriers corresponding to the pulse train shown in Figure 16B. In some applications of the invention, carriers may be provided with complex weights to generate superposition signals corresponding to a predetermined sequence of code chips or data symbols.

Figure 17A illustrates individual CI pulses provided with code chips or data symbols, such as symbols $\beta_0(k)$ to $\beta_{14}(k)$. A pulse train 1795 shown in Figure 17B corresponds to the modulated pulses shown in Figure 17A.

In time-division multiplexing (e.g., in TDMA), the symbols modulated onto the pulses are typically data symbols corresponding to a particular user. In frequency-division multiplexing (e.g., in OFDM), data symbols corresponding to a particular user are modulated onto a pulse train (such as the pulse train shown in Figure 16B)

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constructed from a predetermined set of carrier frequencies allocated to that user. In direct sequence code division multiplexing (e.g., DS-CDMA) or direct sequence spread spectrum, data-bearing code symbols are modulated onto the pulse train. In coded multicarrier spreading (e.g., MC-CDMA or Spread OFDM), data-bearing code symbols are modulated directly onto the carriers.

The function e(t) is also characterized by an in-phase carrier component $\cos(\omega_c t)$ and a quadrature-phase component $\sin(\omega_c t)$. The in-phase and quadrature-phase components can correspond to N orthogonal pulse positions (i.e., phase spaces) and N pseudo-orthogonal pulse positions, respectively.

The CI signals are periodic with period $T_s = 1/f_s$ for an odd number of carriers N and with period $2/f_s$ for an even number of carriers N. In either case, data symbols of duration T_s are typically modulated onto the carriers (or pulses). The main lobe has duration $2/Nf_s$ and each of the N-2 side lobes has a duration $1/Nf_s$.

In Figure 16A, 20 carrier frequencies are allocated to a particular user and provided with complex weights to generate a train of CI pulse waveforms that convey information. Figure 16B shows 20 pulses orthogonally (and equally) positioned in time corresponding to data transmitted by (or to) that user. Each pulse waveform is a superposition of the 20 carriers provided with phases relative to the orthogonal positions in time. Predetermined sets of phase offsets are provided to the carriers to position the pulses orthogonally in time.

The cross correlation between the real parts of the pulse waveforms is illustrated by the following equation:

$$R_{k,j}(\tau) = \frac{1}{2f_s}\frac{\sin(2\pi N f_s \tau / 2)}{\sin(2\pi f_s \tau/2)}\cos\left(\frac{(N-1)}{2}2\pi f_s \tau\right)$$

N equally spaced zeros occur over the time interval $T_s = 1/f_s$ as a result of the sinc-like term in the cross-correlation equation. This corresponds to each pulse waveform being centered at a particular time instant corresponding to a zero crossing (i.e., zero value) of all of the other orthogonal pulse waveforms.

The cross-correlation equation expresses the Nyquist zero inter-symbol interference criteria. The Nyquist zero inter-symbol interference criteria requires a waveform to have zero crossings corresponding to positions of the other waveforms.

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The spacing of the pulse positions (i.e., time instants) corresponds to zeroes in the cross-correlation function. The pulses are centered at equally spaced time instants k/Nf_s, where $k = 0,1,\ldots,N-1$, N is the number of carriers, and $f_s = 1/T_s$ is the frequency separation between the carriers. Thus, the time instants are defined by $0, T_s/N,\ldots, T_s(N-1)/N$.

CI waveforms may be implemented with contiguous or non-contiguous carriers. Contiguous carriers are defined as carriers allocated to one or more users characterized by a frequency separation f_s and symbol duration $T_s = 1/f_s$.

In the OFDM implementation of the invention, each user is provided with a unique set of carrier frequencies to eliminate multiple access interference (MAI). Similar frequency-division multiplexing may be provided to other CI-based transmission protocols to reduce or eliminate MAI. The real part of each user's OFDM transmission is expressed by

$$s(t) = \sum_{k=1}^{N} \sum_{i=1}^{N} a_k \cos\left(2\pi\left(f_c + if_s\right)t + mi2\pi / N\right)g(t)$$

where a_k is a kth data symbol (preferably a channel-coded data symbol) that is then spread over the N carriers allocated to the user. Since each data symbol is spread across all of the carriers, the full frequency diversity benefits of the channel can be achieved. Time interleaving may also be provided.

In one aspect, a received CI-OFDM signal for at least one user is separated into its orthogonal frequency components. Channel compensation (e.g., equalization) and combining are performed to provide estimates of the transmitted symbols. Inter-bit interference may be compensated via any combination of equalization and multi-user detection.

Carrier mixers or a carrier generator, as described herein, includes any type of system, method, or combination thereof adapted to perform at least one of a plurality of functions, including carrier generation, carrier selection, carrier allocation, and modulation. Carrier mixers imply the existence of a carrier generator (e.g., a multicarrier generator). Thus, carrier mixers and carrier generator can be equivalent terms as used herein. A carrier generator may include a carrier-mixer circuit. A carrier mixer may include any type of mixer, modulator, or equivalent device adapted to provide carrier

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selection and/or modulation. Carrier mixers/carrier generators may include local oscillators, harmonic signal generators, digital filters, invertible transform algorithms, quadratic mirror filters, sine wave look-up tables, etc. Carrier mixers may be interpreted as performing frequency-domain processes.

Carrier mixers or carrier generators may employ digital signal processing systems, such as microprocessors, may be employed. Consequently, Fourier transforms, such as DFT-based systems may be employed. For example, an IFFT or IDFT may be employed with one or more weight vectors applied to the frequency bins of the transform. A carrier mixer (or carrier generator) may include a weight-vector selector adapted to select predetermined frequency bins. A weight vector may include zero and non-zero values, such as to provide for carrier selection/allocation. Carrier mixers may include one or more carrier-allocation circuits. A carrier mixer allocates one or more carriers to one or more users. A carrier mixer may provide for modulation of data symbols onto the carriers. A carrier mixer may include a plurality of modulators or a modulator adapted to modulate at least one data symbol onto a plurality of carriers.

In this case, the frequencies of the CI carriers are incrementally spaced by a shift frequency f_s. However, non-uniform spacing of the frequencies may also be used to achieve certain benefits. The carrier frequencies are typically chosen to be orthogonal to each other:

$$\int_0^{T_C} \cos(\omega_i t + \phi_i)\cos(\omega_j t + \phi_j)dt = 0$$

where T_c is the chip duration, ω_i and ω_j are the ith and j^{th} carrier frequencies, and ϕ_i and ϕ_j are arbitrary phases. A signal in the jth frequency band does not cause interference in the ith frequency band.

The term carrier, as used herein with respect to a multicarrier signal or system, is equivalent to the terms subcarrier and tone. Orthogonal carriers may be characterized by constant-frequency carriers with orthogonal frequencies. Alternatively, orthogonal carriers may employ dynamically varying carrier frequencies, such as chirped or hopped carriers. For example, the frequency separation between a set of orthogonal carriers with dynamic frequencies may be constant or limited to integer multiples of an orthogonal frequency spacing f_s.

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An input data source includes any input port adapted to receive data bits and/or data symbols, such as coded data bits and/or symbols. An input data source may include any apparatus and/or algorithm adapted to generate data, such as coded or uncoded data bits and/or symbols. An input data source may include at least one coder and/or coding algorithm. Channel coding may include any combination of well known channel coding techniques, such as trellis, block, convolutional, parity check (e.g., Gallagher coding or any other type of low-density parity check coding), and iterative soft-decision feedback (e.g., turbo) coding.

The phase of each CI signal is set with respect to at least one predetermined receiver time interval (i.e., phase space) in which the carriers constructively combine when received by a CI receiver. A set of incremental phase offsets $e^{in\Delta\phi_k}$ corresponding to at least one pulse position is applied to the CI carriers by one of a plurality N of interval delay (i.e., phase) systems. Each pulse's phase space is a set of carrier phases corresponding to the time instant at which the pulse is centered. Thus, each set of phase offsets maps a data symbol to a pulse centered at a particular instant in time.

Interval delay systems, or equivalently, phase-shift systems, include any type of phase shift module, delay module, temporal mapping module, polyphase code module, polyphase filter, etc., adapted to map data symbols to pulse positions. A pulse position is an instant in time at which a CI pulse is centered. A pulse, as used herein, typically refers to a single-pulse waveform generated from a superposition of selected carriers. Pulse waveforms may include a plurality of pulses, such as a pulse train. Delay systems are systems, algorithms, and/or devices adapted to provide time offsets (i.e., phase shifts) to individual carriers to generate carrier superpositions (pulse waveforms). Delay systems may provide phase offsets and/or time offsets to carriers and/or data symbols.

A delay system is typically configured to receive as input at least one of a data sequence and a set of carriers. The delay system directly maps data on modulated carriers to particular instants in time. The delay system may align carriers to produce pulse waveforms centered at one or more time instants and then modulation may be provided to the pulse waveforms. An interval delay system may include a polyphase coder adapted to provide polyphase codes to data symbols and/or carriers. A delay system may provide polyphase codes to frequency bins of an invertible transform, such as an IDFT or IFFT.

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Although the apparatus diagrams illustrated herein illustrate the generation of CI transmission signals as step-by-step procedures, a preferred embodiment for accomplishing these processes may use digital signal-processing techniques, such as Discreet Fourier Transforms. The order of some of these processes may be switched. For example, modulation of each carrier by the input data may be the final step before combining.

Disclosed aspects may provide for any of various forms of duplexing, such as frequency division duplexing, code division duplexing, and time division duplexing (TDD). TDD allows for a highly efficient and cost-effective architecture, since the same frequency is used for both transmission and reception and the channel characteristics in both directions are virtually identical. In array-processing applications, the beam-forming weights can be determined from a base station antenna array for the reverse link and the same weights can be used on the forward link without requiring multiple antennas at the remote unit. This allows the system to deliver the capacity and interference mitigation benefits of adaptive beam forming for both the uplink and the downlink while keeping the complexity and cost of the remote unit very low. Furthermore, the TDD approach eliminates expensive diplexing filters and permits the use of a single RF chain, further reducing subscriber-unit costs.

Figure 18A is a functional diagram of a CI transmitter. An allocation step 1814 is performed by carrier mixers, which allocate a plurality of carrier frequencies (i.e., tones) to a particular user. A mapping step 1816 is performed by phase-shift/delay systems, which map each data symbol from data source 1812 to a particular pulse position. A pulse-generation step 1820' is performed by a combiner, which receives the allocated carriers as inputs and generates CI pulses at predetermined pulse positions. The resulting data-bearing CI waveform may be an analog or digital signal. If it is an analog signal, the waveform may optionally be sampled 1821.

The plurality of carrier mixers performs the allocation step that provides carrier frequencies used to generate at least one superposition signal for a particular user. The plurality of phase-shift/delay systems provides the mapping 1816 of each data symbol from the data source to a predetermined instant in time (i.e., pulse position). Each set of phase shifts applied to the information-modulated carriers by the phase-shift/delay system

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produces a phase alignment of the carriers (i.e., an interference pulse) at the predetermined instant in time. Thus, the combination of the phase-shift/delay systems and the data source produces a discrete signal of the mapped data symbols. The data symbols are typically provided with polyphase codes and modulated onto the individual CI carriers. Each polyphase code maps its associated data symbol to a particular instant in time.

A combining system, or combiner, as described herein, is any system, device or algorithm adapted to combine a plurality of allocated carriers (for transmission or reception) to produce a time-domain waveform. A combiner may be interpreted as a frequency-domain to time-domain converter. A combiner may be referred to as an interpolation circuit because it generates a time-domain waveform from a plurality of frequency-domain components. A combiner may include an inverse-Fourier transform, such as an IDFT or IFFT circuit or algorithm. Thus, one way to implement carrier generation and combining is to provide an IDFT. Consequently, carrier selection and data-symbol mapping may be performed by a polyphase coder adapted to generate a vector of frequency-bin weights.

The combining system (which may equivalently be an interpolation circuit) is adapted to perform pulse generation, as it combines the phase shifted carriers to produce one or more information-modulated pulses centered at the predetermined instants in time. A plurality of information-modulated pulses may be positioned contiguously in time (such as shown in Figures 16B and 17B) to provide a substantially uniform (low PAPR) signal over a predetermined interval (e.g., symbol period T_s or some multiple thereof). The pulse waveforms are functions that span the symbol duration T_s. In this case, a pulse waveform may be a digital or analog signal. The frequency response of the pulses includes sinusoids provided by the carrier mixers (i.e., allocation circuit).

Figure 18B illustrates a CI transmitter that includes a subcarrier allocation module 1814, a mapping module 1816, and an interpolation module 1820. The subcarrier allocation module 1816 performs the function of carrier mixers. Subcarrier allocation assigns a predetermined number N of carriers to one or more users wherein the carrier frequency spacing f_s and data symbol period T_s are selected to ensure orthogonality between the carriers. Orthogonality may be provided between the allocated carriers and

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unallocated carriers (e.g., carriers assigned to other users). For a number N of carriers, there are N orthogonal phase spaces (i.e., pulse positions). Thus, the number of users in an orthogonal CI system is less than or equal to the number N of carriers.

The carriers corresponding to each user may include contiguous carrier frequencies or uniformly spaced frequencies distributed over a broad frequency band. Each user may be allocated a unique set of carriers, thus providing for orthogonal frequency division multiple access. Alternatively, two or more users may share at least one set of carrier frequencies. Thus, CI may employ other multiple-access schemes, including time division and code division.

The mapping module 1816 is equivalently a multicarrier phase-shift module. The mapping module 1816 maps each data symbol from a data source to a predetermined instant in time. Incremental phase offsets applied to a plurality of carriers are equivalent to a time offset (e.g., delay) applied to a superposition of the carriers. Each set of phase offsets produces a phase alignment of the carriers (i.e., an interference pulse) at a predetermined instant in time, thus, mapping each data symbol to an instant in time.

The carriers are provided by the subcarrier allocation module 1814 (e.g., a plurality of carrier mixers) and modulated with one or more data symbols. Modulation may be performed at the carrier mixers. The combination of the phase-shift/delay systems and the data source produces a discrete signal consisting of the mapped data symbols.

The interpolation module 1820 can be expressed by a combining system. The interpolation module 1820 combines the phase-shifted carriers to produce one or more information-modulated pulses centered at the predetermined instants in time. The subcarrier allocation module 1814 provides the carriers from which the pulses are produced. Thus, the frequency response of the pulses may include only the sinusoids allocated by the subcarrier allocation module 1814 to a particular user. Since each user may be assigned a unique set of carriers, the pulse waveforms produced by the communication system can include non-zero sinusoids allocated to a particular user and zero-valued (i.e., an absence of) sinusoids allocated to other users.

The CI transmitter components illustrated in Figure 18B, as well as other components in the transmitter, may be implemented as digital signal processing

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components. Consequently, the information-modulated pulses generated by a CI transmitter may be a digital signal sample vector.

Since the CI pulses are positioned orthogonally in time if the phase offsets are appropriately selected, signal characteristics (e.g., phase, amplitude, frequency, etc.) of each pulse at the pulse maxima conveys the data symbol value assigned to the corresponding phase space (i.e., instant in time at which the pulse is centered).

Figure 19 illustrates a CI transmitter. A set of carrier mixers 1914 (which typically includes a multicarrier signal generator) is adapted to allocate a set of carriers to a particular user. Thus, the carrier mixers 1914 perform the same function as a Discreet Fourier Transform (DFT) circuit combined with a zero-insertion circuit. For example, carriers corresponding to other users are removed, avoided, or otherwise set to zero.

A phase-shift/delay system 1916 is adapted to map each of a plurality of data symbols from a data source 1912 to a predetermined instant in time. The data source 1912 provides data symbols to any of the transmitter modules 1914, 1916, and/or 1920. Data symbols may be modulated directly onto individual carriers, data-bearing polyphase codes may be generated, or CI pulse waveforms may be modulated with data. The phase-shift/delay system 1916 applies sets of phase offsets to a plurality of carriers, which are provided by the carrier mixers 1914 and optionally modulated with one or more data symbols. Each set of phase offsets produces a phase alignment of the carriers (i.e., an interference pulse) at a predetermined instant in time, and thus, maps each data symbol to an instant in time. The combination of the phase-shift/delay systems 1916 and the data source 1912 produces a discrete signal of the mapped data symbols.

A combining system 1920 combines the modulated, phase-shifted carriers to produce information-modulated pulse waveforms. These pulse waveforms are inverse Fourier transforms of the carriers represented in the frequency domain. Thus, the combining system 1920 performs the same function as an Inverse-DFT circuit. Although not shown, a gain adjustment module or system (e.g., a pulse-shaping filter) may optionally be included in the transmitter.

CI signal generator systems may include a transmission system, such as is known in the art with respect to single carrier and multicarrier communications. For example, a

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transmitter may include analog and/or digital components typically used to process a baseband signal for transmission into a communication channel.

Figure 20 illustrates a specific embodiment of a CI transmitter. A carrier generator/mixer circuit 2014 includes a pulse generator 2001 and a carrier-selection filter 2002. The pulse generator 2001 is adapted to generate pulse having a predetermined pulse-repetition frequency to provide a predetermined multicarrier output. Other pulse-generation parameters, such as pulse shape, may be selected and/or adapted to provide for desirable spectral characteristics.

A subcarrier processing module 2016 may be adapted to provide phase offsets to the selected carriers, provide polyphase coding to the carriers, modulate data (or coded data) symbols onto the carriers, and/or provide for carrier gain adjustments (e.g., pulse shaping, channel compensation, carrier selection, etc.). Accordingly, the subcarrier processing module 816 may include any combination of digital filters, modulators, coders, phase shifters, and channel-compensation circuits.

A combiner 2020 is optionally provided to generate a superposition of the carriers. A transmission module 2022 processes the baseband multicarrier signal and couples the processed signal into a communication channel. Although the combiner 2020 is shown coupled between the subcarrier processing module 816 and the transmission module 2022, in-channel combining may be provided. Accordingly, transmitter components (not shown), such as amplifiers, frequency converters, and guard-interval modules may be provided separately to each subcarrier.

A data source 2012 is coupled to at least one of the modules 2014, 2016, and 2020. The pulse generator 2014 may be modulated with data or otherwise adapted to generate information-modulated pulses. Alternatively, the subcarrier processing module 2016 may be adapted to modulate data onto the pulses or the selected individual carriers. In another embodiment of the invention, the combiner 2020 includes a modulator (not shown) adapted to modulate data symbols from data source 2012 onto the superposition signal.

Some aspects may employ any of a number of techniques for providing channel estimating. For many of these methods, a block of pilot chips, tones, or other known signals may be inserted into the transmitted waveform. Known symbols may be mapped

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to CI phase spaces. Training symbols may be provided to individual subcarriers. In other embodiments, various types of coded training symbols may be transmitted. Blind adaptive estimation and equalization may be employed.

Figure 22A illustrates a plurality of CI pulse waveforms 2201 to 2209 orthogonally positioned in time. A plurality N of equally spaced carriers f_1, f_2,…,f_N are combined to generate the pulses 2201 to 2209. A set of carrier phases 2211, 2212,…, 2219 corresponds to each of the pulses 2201, 2202,…, 2209, respectively. Each set of carrier phases 2211, 2212,…, 2219 is an orthogonal polyphase CI code (or phase space) applied to the carriers to center a given pulse waveform at a corresponding instant in time.

A complex-valued data symbol (not shown) impressed onto a pulse (such as pulse 2201) may be characterized by an in-phase (e.g., real) part modulated onto pulse 2201 and a quadrature-phase (e.g., imaginary) part modulated onto a pulse waveform (not shown) centered equidistantly between pulses 2201 and 2202. Similarly, a first set of N real data symbols may be impressed onto a first set of N 9orthogonal pulses (such as the pulses 2201 to 2209). A second set of real data symbols may be impressed onto a quadrature-phase set of orthogonal pulses (not shown) centered equidistantly between adjacent pairs of the pulses 2201 to 2209.

Complex carrier weights corresponding to each of the carriers f_1, f_2,…,f_N, represent a sum of the phase spaces 2211, 2212,…, 2219 multiplied by their corresponding data symbols. In particular, an nth (n = 1,2,…,N) carrier's complex weight equals the sum of each complex data symbol in the nth row of each phase space 2211, 2212,…, 2219 multiplied by the data symbol value (not shown) associated with that phase space 2211, 2212,…, 2219 (i.e., pulse position 2201, 2202,…, 2209).

Fogure 22B represents a CI waveform of the present invention. A plurality N of subcarriers 2221 to 2229 (e.g., sinusoids, or tones) are characterized by at least one predetermined set of complex subcarrier weights 2210. These weights 2210 align the sinusoids 2221 to 2229 to produce a train or sequence of information-modulated pulses 2201 to 2209 in the time domain. These pulses 2201 to 2209 may be generated by applying the subcarrier weights 2210 to subcarriers (such as subcarriers 2221 to 2229) allocated to at least one user in a network.

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A network may be characterized by various types of communication architectures having two or more users, or nodes, including point-to-point, point-to-multipoint, broadcast, multipoint-to-multipoint, multipoint-to-point, hierarchical, ad-hoc, peer-to-peer, multi-hop, and cellular. The invention is independent of the type of network. Accordingly, other network configurations may be employed. Similarly, the invention is independent of the propagation medium (i.e., communication channel) connecting the nodes.

Alternatively, multiple time-offset pulses are combined wherein each pulse 2201 to 2209 is generated from a superposition of predetermined subcarriers 2221 to 2229 and modulated with a corresponding data symbol. In some cases, time-domain waveforms are provided with frequency-domain processing (e.g., pulse-rate control, rise-time and roll-off control, pulse shaping, pulse-width control, frequency-selective filtering, windowing, and/or frequency masking) to generate pulse waveforms having predetermined spectral characteristics.

Variations of the disclosed pulse-generation techniques and/or multicarrier-generation techniques, as well as other techniques, may be employed in generating CI pulse waveforms. Pulse generators include circuits, systems, software, etc., adapted to generate pulse waveforms. Pulse generators can also include carrier-generation circuits, systems, software, etc. having some carrier-weighting apparatus or algorithm (e.g., CI coder, phase shifter, delay device, mode-locking system, etc.) adapted to produce a plurality of carriers having complex weights that shape a superposition of the carriers into one or more pulse waveforms. Since there are many techniques for generating CI waveforms, the invention is not limited to any specific embodiment for generating CI waveforms disclosed herein. Other techniques for generating CI waveforms will be evident to persons skilled in the art.

CI waveforms are typically impressed onto one or more carriers. CI subcarriers may be impressed onto multiple transmission carrier signals, such as carriers corresponding to different frequency bands. CI waveforms may be conveyed as analog waveforms (such as generated by a D/A converter or a bank of oscillators). CI waveforms may be digital signals (such as a digital output generated by an IDFT or other transform). Digital CI waveforms may be generated from an A/D conversion of at least one analog

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CI waveform. Digital CI waveforms may be generated by appropriately weighting and summing a predetermined set of digital sinusoids that are dynamically generated or stored in memory. Digital CI waveforms may include binary or M-ary (i.e., higher order) signals. Digital CI signals may be expressed as discreet or continuous modulation symbols, including, but not limited to, QAM, PSK, CPM, FSK, AM, FM, PAM, and TOM. The digital signals may be transmitted in any order.

Various interleaving and/or channel-coding techniques may be employed in the transmission of digital signals associated with CI waveforms. In one aspect of the invention, coding (which is not necessarily limited to channel coding) and/or interleaving are applied to data symbols prior to generating the CI waveforms. In another aspect of the invention, coding and/or interleaving are applied to digitized CI signals. In yet another embodiment, modulation symbols may be interleaved.

The offset frequency f_o represents the carrier frequency. In some applications, CI waveforms may be conveyed in their baseband form (i.e., a carrier frequency, or offset frequency f_o, having zero frequency). For example, baseband CI waveforms may be conveyed inside a digital signal processor or equivalent device, between storage devices (physical and/or virtual memory) and signal-processing devices (e.g., DSPs, microprocessors, CPUs), inside transmitter components, inside receiver components, and/or between transmitter and receiver components. CI waveforms may be conveyed in an intermediate-frequency (IF) form. For example, the multicarrier CI signal may be impressed on an IF carrier. Carriers having other frequencies, including optical, infra-red, and microwave, may be employed.

Complex subcarrier weights convey phase space (e.g., CI codes, phase-shift sets, carrier delays, pulse (time-) offset, or any other interpretation of carrier superposition signals resulting from carrier phase alignments at predetermined times) and information (e.g., data symbol) values. Complex subcarrier weights may be generated from a product of a vector or matrix of data symbols with a vector or matrix of phase space (i.e., CI code) values. Complex subcarrier weights may be generated from sums of information-modulated phase spaces. Complex subcarrier weights may be generated from a sum of products of each of a plurality of phase-shift sets corresponding to a particular phase space with data symbols corresponding to that particular phase space. Carrier weights

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may be generated by calculating or measuring subcarrier amplitudes and phases resulting from combining a plurality of information-modulated, time-offset pulse waveforms.

Subcarrier weights may optionally include channel compensation weights, array-processing weights, and/or coding (e.g., channel coding, multiple-access coding, spread-spectrum coding, etc.). The subcarrier weights may optionally provide for data interleaving.

In some aspects of the invention, subcarrier weights may be provided with at least one code (e.g., a complex-valued or real code) adapted to de-orthogonalize (e.g., provide time-domain spreading, and thus, overlapping of) the transmitted pulses. Upon reception, an appropriate derivative of the code (e.g., a complex-conjugate code) can be applied to the appropriate frequency-domain components to re-orthogonalize the pulse waveforms.

Figure 21 illustrates basic components of CI signal generation software residing on a computer-readable medium 2199. CI signal generation software is typically configured to control the function and transmission-signal output of a single carrier or multicarrier transmitter. In some cases, a CI transmission may be characterized as a single-carrier signal in the time domain having a plurality of predetermined frequency-domain (or spectral) components.

A subcarrier allocation source code segment 2191 is adapted to generate a plurality of subcarriers allocated to at least one user or allocate a plurality of input subcarriers (not shown) to a particular user. A subcarrier weighting source code segment 2192 is adapted to provide complex weights (e.g., CI codes) to a plurality of the allocated subcarriers. The weights are configured to map one or more input data symbols into one or more phase spaces.

The computer-readable medium 2199 may include any item of manufacture adapted to store or convey software and/or firmware. The source-code segments 2191 and 2192 may reside on a physical memory storage device, such as any magnetic, electrical, or optical device adapted to store data and/or computer command instructions. The source-code segments 2191 and 2192 may be implemented as gate configurations on a programmable or integrated circuit. Other means for arranging physical devices and/or electromagnetic phenomena may be employed to convey the function of the source-code

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segments 2191 and 2192. Accordingly, the computer-readable medium 2199 may include any combination of FPGAs, ASICs, transient memory, and persistent memory.

Subcarrier allocation may include generating subcarriers, providing for receiving input subcarriers, retrieving subcarriers or superposition waveforms from memory (e.g., a look-up table), or selecting non-zero (or equivalently, zero) valued input bin weights of an invertible transform, such as a DFT. In some applications, subcarrier allocation can include pulse shaping, controlling symbol durations, and/or selecting subcarrier frequency spacing. Some frequencies may be selected or avoided relative to channel conditions, bandwidth requirements, and/or interference.

The subcarrier allocation source code segment 2191 and subcarrier weighting source code segment 2192 may be implemented in one program. Similarly, other processing operations typically performed in a communication system transmitter may be implemented in, or in addition to, the source-code segments 2191 and 2192. It should be appreciated that subcarrier allocation, selection, and assignment can include providing subcarriers for system control and/or monitoring. Subcarrier allocation, as described throughout the specification may include providing for pilot tones, training sequences, and/or other subcarriers allocated to other system-control functions. Subcarrier weighting may include channel coding, source coding, spread-spectrum coding, formatting, multiple-access coding, multiplexing, encryption, array processing, and/or modulation. Systems and methods illustrated herein and described throughout the specification may be implemented as source-code segments residing on one or more computer-readable mediums.

Network control in CI communications may be adapted to enable users to share network resources (e.g., bandwidth). For example, channel resources in the form of phase spaces and/or subcarriers may be allocated to each user relative to their level of service. Bandwidth may be allocated to users relative to any combination of individual throughput requirements, purchased level of service, and availability of bandwidth. Circuit-switched processes may be implemented with respect to subcarrier allocations. Packet-switched processes may be implemented with respect to phase spaces. CI communications provides for the concurrent implementation of circuit switching and packet switching.

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Figure 23A is a functional flow chart of a CI receiver. A receiver process 2301 couples at least one transmitted signal from a communication channel and converts it to an IF or baseband signal. Multicarrier receivers typically include various combinations of signal-processing components, such as amplifiers, filters, down converters, A/D converters, cyclic prefix removers, beam forming circuits, as well as other components. The receiver process 2301 may generate analog or digital signals.

A filtering process 2302 performs a time-domain to frequency-domain conversion of the received signal to produce a plurality of frequency-domain components. Filtering may remove one or more frequency components, or otherwise provide frequency-domain constraints such that the resulting frequency-domain components correspond to components of at least one desired transmit signal. The frequency-domain components may include subcarriers or complex weights corresponding to the magnitude and phase of each subcarrier. Time-domain to frequency-domain processes and frequency-domain to time-domain processes are commonly performed using Fourier transforms or cosine transforms.

An optional frequency domain equalization (FEQ) step 2303 may be provided. The FEQ step 2303 typically involves applying complex channel-compensation weights to the frequency-domain components. An equalizer, as used herein, is a digital hardware/software apparatus adapted to correct for the inter-symbol interference, fading, and/or other distortions of the received digitally-encoded signals so that the initial data can be recovered. Typically, an equalizer compensates for inter-symbol interference via several processes, such as linear equalization or decision feedback equalization. In linear equalization, the incoming signals are multiplied by the inverse of the inter-symbol interference, generally removing inter-symbol interference from the incoming signals. A drawback of linear equalization is that noise inherent in the data transmission is undesirably simultaneously amplified. Decision feedback equalization avoids the noise amplification problems of linear equalization, but runs the risk of error propagation since any decision errors that are made are fed back. Other types of equalization that may be included in the invention include maximum likelihood sequence estimation, iterative equalization, inter-symbol interference cancellation, and/or turbo equalization.

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A combining process 2304 combines the selected frequency-domain components to produce a time-domain signal (e.g., a superposition signal or a sequence of data symbols). Thus, the combining process 2304 is equivalent to other frequency-domain to time-domain conversion processes. Combining 2304 may be followed by an optional time-domain equalization (TEQ) step 2305 and/or an optional multi-user detection (MUD) step 2306. A decision process 2307 is adapted to estimate the received data in order to recover transmitted data symbols. Various types of decision processing 2307 may be employed. An integration step (not shown) is typically provided with combining 2304 and/or decision processing 2307 to combine samples, or otherwise process the received signal, over one or more symbol durations T_s.

A decision system, as used herein, describes any combination of devices and/or algorithms adapted to process an input signal to provide at least one estimate of the input signal's value. Hard and/or soft decisions may be employed. A decision system may provide for various signal-processing techniques (e.g., decoding, feedback, as well as various adaptive routines), such as are typically associated with receivers and reception techniques. A decision system may employ some reference, such as a reference symbol constellation.

Figure 23B illustrates a receiver method and apparatus similar to that shown in Figure 23A with the addition of a CI phase space decoder step 2310. A plurality of CI phase spaces (i.e., time intervals) can be selected by the same transversal filter described with respect to the TEQ 2305. In this case, data symbols impressed onto different phase spaces are separated by applying the appropriate incremental delays (i.e., phase offsets) to the individual carriers prior to combining 2304. If the components are complex values (e.g., output-bin values of a discreet Fourier transform), a complex conjugate of each CI code used to map a data symbol to a particular phase space may be employed to recover the corresponding mapped symbol.

Figure 24A shows an embodiment of a CI receiver that includes a receiving module 2301, a filter bank 2302, a delay system (or phase-shifter bank) 2310, a combiner 2304, and a decision module 2307. Received signals are processed by the receiving module 2301 prior to processing at the filter bank 2302. The filter bank 2302 may include a plurality of filters, such as a plurality of analysis filters. The filter bank 2302 is typically

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a complementary system with respect to a carrier synthesizer (not shown) employed on the transmit side to generate CI signals. Alternatively, the filter bank 2302 may include a transform operation that is complementary (e.g., inverted) relative to an associated transform function in a corresponding CI transmission process. For example, the filter bank 2302 may be adapted to perform a Fourier transform operation (e.g., a DFT implemented with a fast transform algorithm, such as a fast Fourier transform). Alternatively, the filter bank 2302 may be adapted to perform matched filtering. In any of these cases, the function of the filter bank 2302 is to convert an input time-domain signal into a plurality of frequency-domain components.

The delay system 2310 is adapted to provide incremental delays to a plurality of subcarrier waveforms generated by the filter bank 2302. Equivalently, the delay system 2310 may provide incremental phase offsets to frequency-bin values or equivalent complex values corresponding to carrier magnitudes and phases. It is well known that there is a linear relationship between carrier time offsets τ and carrier phase offsets ϕ related to a given carrier frequency f_n: $\phi = 2\pi f_n \tau$. The delay system 2310 typically provides a complementary or inverse set of delays (or equivalently, phase shifts) to the component waveforms. Accordingly, the delay system 2310 is adapted to provide complementary phase offsets (or time offsets) that are complex conjugates of terms corresponding to each predetermined phase space, such as the phase spaces 2211, 2212,…, 2219 shown in Figure 22A.

The combiner 2304 is adapted to combine one or more sets of the delayed (or phase offset) carrier components. Combining may include equalization, such as frequency-domain equalization. Similarly, some form of time-domain equalization and/or multi-user detection may be performed after combining. Consequently, the combiner 2304 may include at least one equalizer (not shown).

The combiner 2304 combines the frequency-domain components to generate a time-domain sequence, such as a reconstructed CI pulse waveform or a sequence of symbol values corresponding to the transmitted data. A CI pulse waveform typically includes a plurality of orthogonally positioned CI pulses (i.e., a pulse train, such as illustrated in Figures 16B and 17B) wherein each pulse conveys (e.g., is modulated with) a data symbol. Thus, the combiner 2304 generates signal values from data symbols that

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were mapped to predetermined instants in time (i.e., phase spaces, or pulse positions centered at equally spaced time instants) by at least one transmitter.

The decision module 2307 processes the signal values to generate estimated data symbols. Methods of formatting information symbols, such as mapping a constellation of data symbols to a constellation of modulation levels, and the reverse operation, are typically understood to be a process within a symbol-estimation step or decision step. Such as in which information symbols are converted to waveform symbols at a transmitter and the reverse conversion is performed at a receiver. A decoder may perform symbol-to-bit mapping. Digital data may be mapped into a signal point sequence with respect to a predetermined code, and an inverse mapping produces an estimated data sequence from a received signal point sequence. An inverse-mapping device (not shown), which may be part of the decision module 2307, produces an estimated data sequence from a received signal point sequence. Receivers may employ channel estimation. Channel estimation in multicarrier systems is typically regarded as part of an equalization process.

Figure 24B illustrates a CI receiver. A DFT 2302 functions as a filter bank. A delay system 2310 is implemented as a plurality M of phase-space modules 2310.1 to 2310.M. Each phase-space module 2310.1 to 2310.M, such as phase-space module 2310.1, is adapted to generate a plurality N of phase offsets, such as 2310.11 to 2310.1N corresponding to a particular phase space. Phase-shifted values or time-offset carriers generated by each phase-space module 2310.1 to 2310.M are coupled to a corresponding combiner of a plurality M of combiners 2304.1 to 2304.M. A decision module 2307 is adapted to process combined symbols or waveforms to generate at least one data estimate. A decision module or a delay system may include at least one decoder (not shown) adapted to perform any necessary decoding, such as channel decoding, multiple-access decoding, demultiplexing, de-spreading, decryption, etc.

Figure 25A illustrates a CI reception method and functional components of a CI receiver. A receiver module 2501 is adapted to process transmissions from a communication channel to generate one or more received signals for baseband or IF processing. A projection module 2502 is adapted to project the received signals onto at least one orthonormal basis corresponding to at least one user's transmissions. A

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combining module 2504 is adapted to combine the projections and optionally perform equalization. Combined signals are processed in a decision module 2507 adapted to generate one or more estimated data symbol values.

In particular, the steps of performing time-domain to frequency-domain conversion and filtering the frequency-domain signal may be achieved by projecting the received signal onto the orthonormal basis of the transmitted signals (such as indicated by the projection module 2502). Projecting a received multicarrier signal onto an orthonormal basis of a particular user's transmitted signal produces frequency-domain signal components $r = (r_0, r_1, \ldots, r_{N-1})$ corresponding to that user's assigned carriers. Equivalently, the projection of a received signal onto an orthonormal basis excludes signals (e.g., carriers and/or phase spaces) that do not correspond to that orthonormal basis.

Figure 25B illustrates a CI receiver method and system. A receiver module 2501 is adapted to process and couple one or more transmitted signals from a communication channel to a matched filter 2502. The receiver module 2501 is adapted to perform various types of signal processing (e.g., amplification, filtering, down conversion, A/D conversion, guard-interval removal, beam forming, and/or other types of signal processing) to modify a received signal into an appropriate format for baseband or IF signal processing. The modified signal may include an analog or digital signal.

The matched filter 2502 is typically matched to one or more signal characteristics (e.g., subcarriers, phase spaces, time intervals, codes, etc.) of at least one user or data stream. Different users and/or transmitted data symbols are typically characterized by at least one set of unique diversity parameter values, such as carrier frequencies, phase spaces, time intervals, codes, subspaces, polarizations, or combinations thereof. Other diversity parameters may be used to characterize different users and/or data streams. The matched filter 2502 may include one or more matched-filter elements.

The output(s) of the matched filter 2502 typically characterizes the degree of matching (e.g., correlation) of the filter 2502 with the received signal(s). Measured variations in the degree of matching can indicate the transmitted symbol values. Thus, these measurements may be mapped to a predetermined symbol constellation. The temporal characteristics (e.g., synchronization and duration) of these measurements are

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typically selected in an integrator 2504. The integrator's 2504 function is typically optimized relative to the probability of error (or BER) of the symbol estimates generated by a decision module 2507.

Integration represents combining in the time domain. Consequently, integration may be part of a combining process (not shown). Frequency-domain combining is typically performed in the matched filter 2502. For example, matching of a particular phase space includes carrier selection, and accordingly, a combining of the appropriately phase-shifted carriers. Alternatively, the matched filter 2502 simply matches components of a signal space corresponding to a particular user or data channel. In this case, the integrator 2504 produces values corresponding to the components over a predetermined time interval, and the decision module 2507 combines the component values to generate symbol estimates. Thus, the matched filter 2502 may employ polyphase codes corresponding to CI phase spaces as part of its matching function. Similarly, the decision module 2507 may employ polyphase CI codes as part of a combining process.

The decision module 2507 may be adapted to perform any of various functions related to data-symbol processing. For example, the decision module 2507 may perform any combination of channel decoding, demodulation, spread-spectrum decoding, de-interleaving, demultiplexing, multiple-access decoding, and formatting. Equalization may be performed by one or more receiver modules 2502, 2504, and/or 2507.

Figure 26A illustrates a CI receiver apparatus and method of the invention. A receiver module or system 2501 is adapted to receive and process at least one transmitted signal to provide a digital or analog time-domain signal to a first software module 2502. The first software module 2502 is adapted to project the received signal onto the orthonormal basis of the transmitted signals. This achieves a combined time-domain to frequency-domain transform and tone filtering.

The first software module 2502 includes a plurality N of multipliers 2511.1 to 2511.N adapted to multiply the received signal by reference signals having orthogonal carrier frequencies $f_n = f_o + nf_s$ (n=0,…,N-1) and at least one predetermined phase relationship $n\Delta\Phi_k$,. Software module 2502 also includes a plurality N of integrators 2504.1 to 2501.N adapted to integrate the products over each symbol interval T_s. The outputs of the first module 2502 are frequency-domain signal components $r = (r_0, r_1, \ldots,$

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r_{N-1}) corresponding to a particular user's assigned carriers. The first module 2502 is typically adapted to generate phase offsets $\Delta\Phi$ corresponding to a plurality of phase spaces (i.e., time offsets).

A second software module 2514 takes the form of a combiner, which performs a frequency-domain to time-domain transform. Equalization (not shown) may be performed by either or both first and second modules 2502 and 2514, respectively. Time-domain equalization and/or frequency-domain equalization may be employed. Various combining techniques, such as any appropriate optimal-combining technique may be employed. The combined frequency-domain components produce a time-domain signal, such as shown in FIGS. 1, 2B, and 3B. The time-domain signal may include an analog or digital waveform. Alternatively, a time-domain signal may include a sequence of digital symbol values.

Each set of phase offsets $\Delta\Phi$ corresponds to a particular phase space or time offset. Each received data symbol is characterized by a data-modulated pulse centered at a particular time instant. The inclusion of phase selection in the reference signals used in the multipliers 2511.1 to 2511.N of the first software module 2502 provides for selection of signal values at predetermined instants in time. Thus, the process of combining 2514 the phase-offset signals generated in the first module 2502 is part of a time-instant to symbol-mapping process. Decision processing 2507 provides for estimation of the received data. Decision processing 2507 is a mapping process that maps received signal values corresponding to each pulse (i.e., equally spaced instants in time used to transmit symbol values) into decision variables (i.e., estimated signal values).

Figure 26B illustrates a CI receiver, including a receiver module 2501, a matched filter or projection module 2502, a plurality M of integrators 2504.1 to 2504.M, and a decision device 2507. The projection module 2502 includes a discreet Fourier transform (e.g., FFT 2512). Equivalently, other types of filters may be included, such as to select one or more subcarrier components allocated to a particular user. N frequency-domain components generated by the FFT 2512 are phase shifted by a plurality M of phase-shift systems (e.g., interval delay systems) 2510.1-2510.M. The N signal components corresponding to each phase-shift system 2510.1-2510.M are combined in an associated combiner 2514.1 to 2514.M to generate a time-domain signal.

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A plurality M of time-domain signals is output from the projection module 2502. Each of the M time-domain signals is integrated over each symbol interval T_s by the integrators 2504.1 to 2504.M. Signal values generated by the integrators 2504.1 to 2504.M are processed by the decision module 2507 to generate a sequence of estimated data symbols.

Various embodiments may include variations in system configurations and the order of steps in which methods are provided. For example, the order of frequency-domain combining (illustrated by the combiners 2514.1 to 2514.M) and time-domain combining (illustrated by the integrators 2504.1 to 2504.M) may be switched. Multiple steps and/or multiple components may be consolidated.

Figure 26C illustrates a subcarrier weighting source code segment 2591 and a CI combining source code segment 2592 residing on a computer-readable medium 2599. Source code segment 2591 is adapted to process one or more received channel measurements (such as frequency-domain or time-domain measurements) for generating a plurality of subcarrier weights. These weights are adapted to compensate for one or more channel effects, including, but not limited to, multipath, dispersion, and co-channel interference. The weights may be adapted to provide CI decoding. The weights may be adapted relative to one or more channel and/or data-quality measurements. The weights may be configured relative to data-processing measurements, such as hard-decision, soft-decision, and/or iterative feedback decision processing. The weights are typically applied to a plurality of subcarriers, such as frequency components produced by a filter bank or an FFT. Subcarrier weighting may include filtering, such as providing for acquiring subcarrier frequencies allocated to at least one predetermined user. Consequently, subcarrier weights may include both zero and non-zero values. Subcarrier weighting may include channel decoding, source decoding, spread-spectrum decoding, formatting, multiple-access decoding, demultiplexing, decryption, array processing, and/or modulation.

Source-code segment 2592 is adapted to combine the received and weighted carriers to generate a processed signal output, which is typically a sequence of symbols. At least one type of optimal combining may be provided. Code segment 2592 is adapted to receive as input at least one received signal, such as a sequence of data symbols. The

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received signal may be impressed onto the weights, weighted subcarriers, or waveforms generated from one or more superpositions of the weighted subcarriers. The weights are configured to map one or more input data symbols into one or more phase spaces. In some applications, data-modulated weights may be generated in source-code segment 2591. In this case, source-code segment 2591 is adapted to process the received signal to generate at least one set of information-bearing weights.

Figure 27A illustrates a number M of CI receiver branches. A plurality of input couplers (e.g., antenna elements) 2701.1 to 2701.M couple signals from a communications medium (e.g., a free-space channel, a waveguide, etc.) and process the signals. The input couplers 2701.1 to 2701.M are typically adapted to perform any combination of front-end receiver-side processing, including amplification, filtering, frequency conversion, and/or A/D conversion. Other types of processing may be performed. For example, a plurality of optional guard interval (e.g., cyclic prefix) removal circuits 2702.1 to 2702.M may be incorporated in the input couplers 2701.1 to 2701.M. Similarly, each of a plurality M of serial-to-parallel converters 2703.1 to 2703.M may be included in the input couplers 2701.1 to 2701.M or in each of a plurality M of invertible-transform (e.g., FFT) circuits 2704.1 to 2704.M.

Each of the invertible-transform circuits 2704.1 to 2704.M transforms an input time-domain signal into a plurality N of frequency-domain components. The components are weighted with at least one set of CI combining weights $\alpha_m(n)$, where m = 1,…,M and n = 1,…,N, by a plurality M of component-weighting modules 2705.1 to 2705.M. In the case where MMSE combining is employed, the weights $\alpha_m(n)$ are expressed by:

$$\alpha_m(n) = h_m^*(n) \Big/ \left(N|h_m(n)|^2 + \sigma^2 \right)$$

where $h_m(n)$ is the channel response for the nth frequency channel of the mth spatial subchannel, and σ^2 is the noise power. Other types and combinations of combining may be employed.

A plurality M of combiners, such as IFFTs 2706.1 to 2706.M, combine the weighted frequency-domain components to generate a plurality of time-domain signals. Time-domain outputs of the IFFTs 2706.1 to 2706.M are coupled to beam-forming modules 2707.1 to 2707.M, which are adapted to provide beam-forming weights that cancel co-channel interference in a plurality of combiners 2708.1 to 2708.M. Each

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combiner 2708.1 to 2708.M may include a summing circuit, an adder, an accumulator, an integrator, or any appropriate invertible transform.

The beam-forming modules 2707.1 to 2707.M and the combiners 2708.1 to 2708.M may be adapted to perform any of various types and combinations of adaptive combining. In some applications, maximal ratio combining may be employed. Other combining schemes may be employed. Combining may include interference cancellation, multi-user detection, null steering, spatial interferometry multiplexing, etc. In some cases, space-time processing may be employed. Successive interference cancellation, as well as other multi-level cancellation techniques, can be used. In other cases, space-frequency processing may be provided. Channel decoding weights may be provided by either or both the component-weighting modules 2705.1 to 2705.M and the beam-forming modules 2707.1 to 2707.M. Symbols output by the combiners 2708.1 to 2708.M are converted to a data stream by a parallel-to-serial converter 2709 prior to being demodulated and decoded 2710.

In some disclosed aspects, the subcarriers may be selected for a particular user, such as in an orthogonal frequency division multiple access system. Subcarriers allocated to a particular user may be interleaved in frequency with subcarriers allocated to one or more other users. In another aspect of the invention, a different set of subcarriers is selected for each of a plurality of data symbols or data symbol groups transmitted by and/or to a particular user. A plurality of users may share a common set of subcarriers, yet share the channel via time division multiple access (TDMA), code division multiple access (CDMA), and/or space division multiple access (SDMA). Other multiple-access schemes may be employed. Similarly, different data symbols corresponding to a particular user may share the channel relative to the previously mentioned multiple-access schemes.

In one aspect, a signal generator or transmitter includes a subcarrier allocator, a pulse generator, a modulator, and a sequential pulse positioner. The subcarrier allocator assigns a predetermined set of subcarriers to a particular data symbol, user, or group of users. The pulse generator produces a plurality of pulses wherein the spectrum of each pulse or group of pulses is characterized by the set of subcarriers. The modulator

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modulates the pulses or subcarriers with at least one data symbol. The pulse positioner sequentially positions the modulated pulses.

A transmitter may include a polyphase, poly-amplitude code generator, a subcarrier allocator, a subcarrier weighting module, and a subcarrier combiner. The code generator produces at least one of a set of polyphase, poly-amplitude codes configured to produce a predetermined time-domain signal, such as a direct sequence coded signal. The transmitter may include a modulator adapted to modulate data onto the codes, the subcarriers, or the time-domain signal. The subcarrier weighting module impresses the polyphase, poly-amplitude codes onto a predetermined set of orthogonal subcarriers selected by the subcarrier allocator. The combiner combines the subcarriers to produce the time-domain signal.

A CI decoder may include receiver components illustrated in the figures and described throughout the specification and incorporated references. For example, a CI decoder may include an equalizer (such as a time-domain equalizer and/or a frequency-domain equalizer), a de-mapper, a de-interleaver, a decoder, a de-scrambler, a filter (such as a matched filter), an integrator, and/or a decision module.

CI receivers may be adapted to process either or both single-carrier and multicarrier signals. Frequency-domain analysis and processing of single-carrier signals may be performed relative to pulse characteristics. For example, number of subcarriers, subcarrier spacing, and window durations in receiver processing may be selected relative to physical signal parameters, such as pulse width, pulse shape, and pulse spacing.

In one aspect, a received signal is separated into a plurality of orthogonal subcarrier components by a time-domain to frequency-domain converter. The output of the converter is characterized by orthogonal poly-amplitude (and polyphase) coded data. The converter may be adapted to perform a Fourier transform, such as an FFT or a DFT. A combiner performs frequency-domain equalization and provides CI decoding of the coded data.

Functional aspects are described with respect to signal-waveform illustrations and corresponding descriptions. For example, Figure 27B illustrates a block transmission characterized by symbol duration T_s, and includes four orthogonal sinc-like pulse

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waveforms 341, 342, 343, and 344. Each pulse waveform (such as pulses 341, 342, 343, and 344) may be impressed with a unique data symbol.

A preceding block transmission includes orthogonal pulse waveforms 331, 332, 333, and 334 and a following block transmission includes orthogonal pulse waveforms 351, 352, 353, and 354. Block transmissions are characteristic of multicarrier operation. For example, OFDM employs subcarrier blocks defined by uniform start and end times for each subcarrier, the difference in times typically being equal to the symbol duration T_s, or the symbol duration T_s plus a cyclic prefix. Cyclic prefixes, cyclic "post-fixes", or some other guard interval may be included in the signal plots, such as between the blocks shown in Figure 27B.

Since the pulse waveforms 341, 342, 343, and 344 have the same starting and ending times, the waveform shapes 341, 342, 343, and 344are different from each other. For example, waveform 341 has all of its sidelobes to the right of its main lobe, whereas all of the sidelobes of waveform 344 occur to the left of the main lobe. This tends to increase the interference in systems that perform time-domain equalization and Rake reception. In particular, inter-pulse interference is not limited to nearby pulses because the side-lobe structure is periodic, or cyclic, over the symbol duration T_s. For example, the side-lobe amplitude (and thus, interference) of waveform 341 diminishes across pulse 342 and increases across pulse 344. In this particular example, the pulse waveforms may be generated from four orthogonal subcarrier frequencies, which are not shown.

Figure 28A illustrates a CI transmitter that includes a CI coder 2802, an IDFT (such as IFFT 2804), a polyphase filter 2809, and a transmission system 2807. The CI coder 2802 is adapted to map multiple input data symbols onto a plurality of subcarriers. This is achieved via CI coding. The IFFT 2804 is adapted to receive the plural sub-channel signals and transform them into plural time-domain signals. The polyphase filter 2809 receives the time-domain signals and outputs a plurality of filtered signals. The polyphase filter 2809 may be adapted to provide the filtered signals with a predetermined spectral profile of selected subcarriers. Polyphase filters operate by multiplying selected phases, or samples, of a filter impulse response with samples of one or more input signals.

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Figure 28B illustrates a CI reception method that implies an apparatus for carrying out the method. A receiver step 2851 processes transmissions from a communication channel to generate received signals. Time-domain to frequency-domain conversion and filtering the resulting frequency-domain signal is achieved by projecting the received signal onto an orthonormal basis of the transmitted signals (such as indicated by a projection step 2852). Projecting a received multicarrier signal onto an orthonormal basis of a particular user's transmitted signal produces frequency-domain signal components $r = (r_0, r_1, \ldots, r_{N-1})$ corresponding to that user's assigned subcarriers. Equivalently, the projection of a received signal onto an orthonormal basis excludes signals (e.g., carriers and/or phase spaces) that do not correspond to that orthonormal basis.

Frequency-domain to time-domain conversion is achieved by combining 2854 the received frequency-domain components produced by either band-pass filtering or projection onto a predetermined orthonormal basis. The combined frequency-domain components produce a time-domain signal. The step of recovering symbols is provided in the decision process 2857.

Figure 28C illustrates a CI receiver including a receiver module 2861, a matched filter or projection module 2862, a plurality M of integrators 2864.1 to 2864.M, and a decision device or module 2867. The projection module 2862 includes a DFT, such as an FFT 2872. Equivalently, other types of filters may be included, such as to select one or more subcarrier components allocated to a particular user. N frequency-domain components generated by the FFT 2872 are phase shifted by a plurality M of phase-shift systems (e.g., interval-delay systems) 2870.1 to 2870.M. The N signal components corresponding to each phase-shift system 2870.1 to 2870.M are combined in an associated combiner 2874.1 to 2874.M to generate a time-domain signal.

A plurality M of time-domain signals is output from the projection module 2862. Each of the M time-domain signals is integrated over each symbol interval T_s, by the integrators 2864.1 to 2864.M. Signal values generated by the integrators 2864.1 to 2864.M are processed by the decision module 2867 to generate a sequence of estimated data symbols.

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Various embodiments of the invention may include variations in system configurations and the order of steps in which methods are provided. Multiple steps and/or multiple components may be consolidated.

Figure 29A illustrates a block waveform including a set of N orthogonal CI pulse waveforms 2941 to 2949 having a duration of T_s. CI pulse waveforms (such as pulse 2941 to 2949) may be generated from a superposition of orthogonal subcarriers. Each of the pulse waveforms 2941 to 2949, which represents a CI phase space, is modulated with one of a plurality of data symbols d_1 to d_N, respectively. In one aspect of the invention, each data symbol d_1 to d_N includes a code chip of an orthogonal code, such as Hadamard-Walsh (Walsh) code or a Walsh code multiplied by a long code. Pseudo-orthogonal coding may be employed. Other codes, including Gold codes, Barker codes, Kasami codes, CI codes, and/or DeBot codes, may be modulated onto the pulses 2941 to 2949. The subcarrier weights resulting from the application of these time-domain codes provide orthogonal or pseudo-orthogonal CI codes expressed as frequency-domain codes, which are characterized by low PAPR in multicarrier synthesis.

Figure 29B illustrates a plurality of CI subcarrier weights w_1 to w_N generated from a set of data symbols d_1 to d_N mapped to a number N of orthogonal CI phase spaces. A CI code matrix of dimension NXN containing polyphase code chips is multiplied by a set of data vectors or a data matrix. In particular, each column of the CI code matrix (such as column 2951) is multiplied by a corresponding data symbol (such as symbol d_2). In some cases, the CI code matrix and an NXN data matrix (not shown) may be provided with an element-by-element multiplication. Each row of a product matrix resulting from the product of the data symbols d_1 to d_N with the CI code matrix are summed to produce the subcarrier weights w_1 to w_N. For example, elements in row 2953, after multiplication by the data symbols d_1 to d_N, are summed to generate weight w_2. Since rows and columns of the basic CI code matrix resemble the vectors of complex values used in DFTs, the subcarrier weights w_1 to w_N can be calculated using a fast transform algorithm.

Figure 30A illustrates transmitter apparatus and method embodiments of the present invention. An input data stream is serial-to-parallel converted and processed in a subcarrier-weighting module 3002. The weighting module 3002 provides one or more orthogonal poly-amplitude codes to the subcarriers. The codes may also be characterized

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by polyphase values. The codes are typically indicative of the data and are used as subcarrier weights. In this case, block codes are provided. The weights may be used to synthesize at least one predetermined direct-sequence (e.g., DSSS or DS-CDMA) waveform. The weights are converted to at least one time-domain waveform in a frequency-domain to time-domain converter 3004, such as an inverse Fourier transform.

The time-domain output of the converter 3004 is processed in a transmission system 3006, which may optionally provide a guard interval or cyclic prefix (and/or postfix), perform digital-to-analog conversion, up convert the signal, provide amplification, optionally filter the signal, and provide for coupling the signal into a communication channel. Other transmitter-side signal-processing operations may be provided, including MIMO (e.g., array) processing. This transmitter embodiment may be adapted to generate multicarrier signals configured to appear as a single-carrier signal in the time domain.

Figure 30B shows a receiver apparatus and method of the invention. A receiver system 3001 couples single-carrier and/or multicarrier transmissions from a communication channel, and adapts the received signals for baseband or IF processing. In particular, the receiver system 3001 may perform filtering, amplification, down conversion, analog-to-digital conversion, cyclic-prefix removal, and/or other receiver processing operations that are well known in the art. The receiver system 3001 may be adapted to perform MIMO (e.g., array) processing. A received signal is separated into a plurality of orthogonal subcarrier components by a time-domain to frequency-domain converter 3003, such as a Fourier transform. Frequency-domain equalization and decoding of the orthogonal poly-amplitude codes is performed in a combiner 3005. The combiner 3005 multiplies the frequency bin values output by the converter 3003 with a complex conjugate of at least one of poly-amplitude code. A decision module 3007 is adapted to process the combined signal values using any combination of hard-decision and soft-decision processing.

In one aspect, a received signal for at least one user is separated into orthogonal frequency components. Channel compensation (e.g., equalization) and combining are performed to provide estimates of the transmitted symbols. ISI may be compensated via any combination of equalization and multi-user detection.

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Embodiments may employ any of a number of techniques for providing channel estimating. For many of these methods, a block of pilot chips, tones, or other known signals may be inserted into the transmitted waveform. Known symbols may be mapped to CI phase spaces. Training symbols may be provided to individual subcarriers. In other embodiments, various types of coded training symbols may be transmitted. Blind adaptive estimation and equalization may be employed.

Figure 31A illustrates a communication method of the invention. A plurality of orthogonal polyphase / poly-amplitude codes are generated 3061 in a transmitter. The codes are modulated 3062 with different data symbols. A-frequency-domain to time-domain conversion 3063 of the modulated codes is provided to generate a time-domain output. A cyclic prefix or guard interval is optionally prepended 3064 to the time-domain output, followed by transmission processing 3065 adapted to process the signal for transmission into a communication channel 99.

A receiver process 3071 couples the transmission from the channel 99 and performs receiver system processes typically performed to convert a received signal to a digital or analog baseband or IF signal. An optional cyclic-prefix removal 3072 may be performed as necessary prior to time-domain to frequency-domain conversion 3073. Interfering frequency-domain signals are separated in an interference-cancellation process 3074, which may optionally employ frequency-domain and/or time-domain equalization. Separated signal values are then post processed, which may include decision processing 3075.

Figure 31B illustrates a method of receiving single-carrier or multicarrier signals, including providing for receiver-system processing 3151 of received signals, performing a time-domain to frequency-domain conversion 3153 of the received signals to produce a plurality of orthogonal subcarrier values, providing for frequency-domain-equalization of the subcarrier values, providing for CI decoding 3157 (which includes combining), and providing for decision processing 3159.

Figure 32 illustrates a sub-space/subcarrier processor receiver of the invention. A plurality M of receiver systems 3251 to 3259 is adapted to couple a plurality of interfering single-carrier or multicarrier signals from a communication channel. M receiver branches are provided for frequency-domain analysis of received signals.

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Optional cyclic prefix removal modules 3261 may be provided. A set of M time-domain to frequency-domain converters, such as DFTs 3271 to 3279, separate received signals in each branch into a plurality N of subcarrier values. Each of a plurality of sub-space processors 3281 to 3289 processes the subcarrier values. For example, N sub-space processors 3281 to 3289 can process M signals at a time that were mapped into each of the N subcarrier frequencies.

The output of each sub-space processor 3281 to 3289 is characterized by up to M sub-space values. Each of a plurality of CI decoders 3291 to 3299, such as CI block decoders or CI sliding window decoders, combine subcarrier values corresponding to a particular subspace.

Figure 33A illustrates basic components of CI signal generation software residing on a computer-readable medium 3399. CI signal generation software is typically configured to control the function and transmission-signal output of a single carrier or multicarrier transmitter. In some cases, a CI transmission may be characterized as a single-carrier signal in the time domain having a plurality of predetermined frequency-domain (or spectral) components.

A subcarrier allocation source code segment 3301 is adapted to generate a plurality of subcarriers allocated to at least one user or allocate a plurality of input subcarriers (not shown) to a particular user. A subcarrier weighting source code segment 3302 is adapted to provide complex weights (e.g., CI codes) to a plurality of the allocated subcarriers. The weights are configured to map one or more input data symbols into one or more phase spaces.

The computer-readable medium 3399 may include any item of manufacture adapted to store or convey software and/or firmware. The source-code segments 3301 and 3302 may reside on a physical memory storage device, such as any magnetic, electrical, or optical device adapted to store data and/or computer command instructions. The source-code segments 3301 and 3302 may be implemented as gate configurations on a programmable or integrated circuit. Other means for arranging physical devices and/or electromagnetic phenomena may be employed to convey the function of the source-code segments 3301 and 3302. Accordingly, the computer-readable medium 3399 may include any combination of FPGAs, ASICs, transient memory, and persistent memory.

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Subcarrier allocation may include generating subcarriers, providing for receiving input subcarriers, retrieving subcarriers or superposition waveforms from memory (e.g., a look-up table), or selecting non-zero (or equivalently, zero) valued input bin weights of an invertible transform, such as a DFT. In some applications, subcarrier allocation can include pulse shaping, controlling symbol durations, and/or selecting subcarrier frequency spacing. Some frequencies may be selected or avoided relative to channel conditions, bandwidth requirements, and/or interference.

The subcarrier allocation source code segment 3301 and subcarrier weighting source code segment 3302 may be implemented in one program. Similarly, other processing operations typically performed in a communication system transmitter may be implemented in, or in addition to, the source-code segments 3301 and 3302. It should be appreciated that subcarrier allocation, selection, and assignment can include providing subcarriers for system control and/or monitoring. Subcarrier allocation, as described throughout the specification may include providing for pilot tones, training sequences, and/or other subcarriers allocated to other system-control functions. Subcarrier weighting may include channel coding, source coding, spread-spectrum coding, formatting, multiple-access coding, multiplexing, encryption, modulation, and/or array processing. Systems and methods illustrated herein and described throughout the specification may be implemented as source-code segments residing on one or more computer-readable mediums.

Network control in CI communications may be adapted to enable users to share network resources (e.g., bandwidth). For example, channel resources in the form of phase spaces and/or subcarriers may be allocated to each user relative to their level of service. Bandwidth may be allocated to users relative-to any combination of individual throughput requirements, purchased level of service, and availability of bandwidth.

Figure 33B illustrates a subcarrier weighting source code segment 3391 and a CI combining source code segment 3392 residing on a computer-readable medium 3399. Source code segment 3391 is adapted to process one or more received channel measurements (such as frequency-domain or time-domain measurements) for generating a plurality of subcarrier weights. These weights are adapted to compensate for one or more channel effects, including, but not limited to, multipath, dispersion, and co-channel

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interference. The weights may be adapted to provide CI decoding. The weights may be adapted relative to one or more channel and/or data-quality measurements. The weights may be configured relative to data-processing measurements, such as hard-decision, soft-decision, and/or iterative feedback decision processing. The weights are typically applied to a plurality of subcarriers, such as frequency components produced by a filter bank or an FFT. Subcarrier weighting may include filtering, such as providing for acquiring subcarrier frequencies allocated to at least one predetermined user. Consequently, subcarrier weights may include both zero and non-zero values. Subcarrier weighting may include channel decoding, source decoding, spread-spectrum decoding, formatting, multiple-access decoding, demultiplexing, decryption, array processing, and/or modulation.

Source-code segment 3392 is adapted to combine the received and weighted carriers to generate a processed signal output, which is typically a sequence of symbols. At least one type of optimal combining may be provided. Code segment 3392 is adapted to receive as input at least one received signal, such as a sequence of data symbols. The received signal may be impressed onto the weights, weighted subcarriers, or waveforms generated from one or more superpositions of the weighted subcarriers. The weights are configured to map one or more input data symbols into one or more phase spaces. In some applications, data-modulated weights may be generated in source-code segment 3391. In this case, source-code segment 3391 is adapted to process the received signal to generate at least one set of information-bearing weights.

All publications and patent applications mentioned in this specification are herein incorporated by reference to the same extent as if each individual publication or patent application was specifically and individually incorporated by reference.

Various embodiments of the invention may include variations in system configurations and the order of steps in which methods are provided. In many cases, multiple steps and/or multiple components may be consolidated.

The method and system embodiments described herein merely illustrate the principles of the invention. It should be appreciated that those skilled in the art will be able to devise various arrangements, which, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and

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scope. Furthermore, all examples and conditional language recited herein are intended to be only for pedagogical purposes to aid the reader in understanding the principles of the invention. This disclosure and its associated references are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

It should be appreciated by those skilled in the art that the block diagrams herein represent conceptual views of illustrative circuitry, algorithms, and functional steps embodying the principles of the invention. Similarly, it should be appreciated that any flow charts, flow diagrams, signal diagrams, system diagrams, codes, and the like represent various processes which may be substantially represented in computer-readable medium and so executed by a computer or processor, whether or not such computer or processor is explicitly shown.

The functions of the various elements shown in the drawings, including functional blocks labeled as “processors” or “systems,” may be provided through the use of dedicated hardware as well as hardware capable of executing software in association with appropriate software. When provided by a processor, the functions may be provided by a single dedicated processor, by a shared processor, or by a plurality of individual processors, some of which may be shared. Moreover, explicit use of the term "processor" or "controller" should not be construed to refer exclusively to hardware capable of executing software, and may implicitly include, without limitation, digital signal processor (DSP) hardware, read-only memory (ROM) for storing software, random access memory (RAM), and non-volatile storage. Other hardware, conventional and/or custom, may also be included. Similarly, the function of any component or device described herein may be carried out through the operation of program logic, through dedicated logic, through the interaction of program control and dedicated logic, or even manually, the particular technique being selectable by the implementer as more specifically understood from the context.

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Any element expressed herein as a means for performing a specified function is intended to encompass any way of performing that function including, for example, a combination of circuit elements which performs that function or software in any form, including, therefore, firmware, micro-code or the like, combined with appropriate circuitry for executing that software to perform the function. The invention as defined herein resides in the fact that the functionalities provided by the various recited means are combined and brought together in the manner which the operational descriptions call for. Applicant regards any means which can provide those functionalities as equivalent as those shown herein.

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Patent Application

of

Steve Shattil

for

Transmit Pre-Coding

RELATED APPLICATIONS

This application is a Continuation of U.S. Pat. Appl. No. 14/727,769, filed June 1, 2015, which is a Continuation of U.S. Pat. Appl. No. 14/276,309, filed May 13, 2014, now U.S. Pat. No. 9,048,897, which is a Continuation of U.S. Pat. Appl. No. 12/545,572, filed August 21, 2009, now U.S. Pat. No. 9,042,333, which is a Divisional of U.S. Pat. Appl. No. 11/187,107, filed on July 22, 2005, now U.S. Pat. No. 8,670,390, which claims priority to Provisional Appl. No. 60/598,187, filed August 2, 2004, all of which are incorporated by reference in their entireties.

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BACKGROUND

I. Field

Disclosed aspects relate generally to antenna-array processing and ad-hoc networking, and particularly to providing cooperative signal processing between a plurality of wireless terminal devices, such as to improve network access.

II. Background

Wireless data service is an emerging market with high growth potential. However, market growth requires higher bandwidth and better coverage than cellular technologies can provide. Furthermore, state-of-the-art wireless network technologies are mainly focused on the server side, rather than using mobile wireless terminals to extend the network infrastructure.

A peer-to-peer mode of communication is expected to offer distinct performance benefits over the conventional cellular model, including better spatial-reuse characteristics, lower energy consumption, and extended coverage areas. The key advantage of the peer-to-peer network model is the increase in spatial reuse due to its short-range transmissions. Although peer-to-peer networking shows some promise, there are significant drawbacks that prevent conventional peer-to-peer networks from being a technically and commercially viable solution.

Recent analyses of multi-hop networks compared to cellular networks have indicated that the spatial reuse improvement in the peer-to-peer network model does not translate into greater throughput. Rather, the throughput is lower than that observed in the cellular network model. This observation is explained in three parts:

- *Multi-hop Routes:* Although the spatial reuse is increased, since a flow traverses multiple hops in the peer-to-peer network model, the end-to-end throughput of a flow, while directly proportional to the spatial reuse, is also inversely proportional to the hop-length. Moreover, since the expected hop-length in a dense network is of the order of $O(\sqrt{n})$, a tighter bound on the expected per-flow throughput is $O(1/\sqrt{n})$. While this bound is still higher than that of the dense cellular network model ($O(1/n)$), the following two reasons degrade the performance even more.
- *Base-Station Bottleneck:* The degree of spatial reuse and expected per-flow throughput of the peer-to-peer network model is valid for a network where all flows

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have destinations within the same cell. In this case, the base station is the destination for all flows (e.g., it is the destination of the wireless path). Thus, any increase in spatial reuse cannot be fully realized as the channel around the base-station becomes a bottleneck and has to be shared by all the flows in the network. Note that this is not an artifact of the single-channel model. As long as the resources around the base-station are shared by all the flows in the network (irrespective of the number of channels), the performance of the flows will be limited to that of the cellular network model.

- *Protocol Inefficiencies:* The protocols used in the cellular network model are both simple and centralized, with the base station performing most of the coordination. Cellular protocols operate over a single hop, leading to very minimal performance degradation because of protocol inefficiencies. However, in the peer-to-peer network model, the protocols (such as IEEE 802.11 and DSR) are distributed, and they operate over multiple hops. The multi-hop path results in more variation in latency, losses, and throughput for TCP. These inefficiencies (which arise because of the distributed operation of the medium access and routing layers) and the multi-hop operation at the transport layer translate into a further degraded performance.

Similarly, antenna-array processing has demonstrated impressive improvements in coverage and spatial reuse. Array-processing systems typically employ multiple antennas at base stations to focus transmitted and received radio energy and thereby improve signal quality. In cellular communications, improvements in signal quality lead to system-wide benefits with respect to coverage, service quality and, ultimately, the economics of cellular service. Furthermore, the implementation of antenna arrays at both ends of a communication link can greatly increase the capacity and performance benefits via Multiple Input Multiple Output (MIMO) processing. However, power, cost, and size constraints typically make the implementation of antenna arrays on mobile wireless terminals, such as handsets or PDAs, impractical.

In cooperative diversity, each wireless terminal is assigned an orthogonal signal space relative to the other terminals for transmission and/or reception. In particular, both multiplexing and multiple access in cooperative diversity are orthogonal. In antenna-array processing, either or both multiplexing and multiple access are non-orthogonal.

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Specifically, some form of interference cancellation is required to separate signals in an array-processing system because transmitted and/or received information occupies the same signal space.

Applications and embodiments relate to ad-hoc networking and antenna-array processing. Embodiments may address general and/or specific needs that are not adequately serviced by the prior art, including (but not limited to) improving network access (e.g., enhancing range, coverage, throughput, connectivity, and/or reliability). Applications of certain embodiments may include tactical, emergency response, and consumer wireless communications. Due to the breadth and scope of the present invention, embodiments may be provided for achieving a large number of objectives and applications, which are too numerous to list herein. Therefore, only some of the objects and advantages of specific embodiments are discussed in the Summary and in the Detailed Description.

SUMMARY

Some of the exemplary embodiments of the disclosure are summarized as follows. Embodiments include beam-forming systems configured to enable spatially separated wireless terminals (WTs) to perform beam-forming operations in a wireless wide area network (WWAN). A wireless local area network (WLAN) couples together the WTs, which may be configured to share WWAN data, access, and control information. A beam-forming system may comprise the WTs, which function as elements of an antenna array. WWAN network access functions (such as monitoring control channels and exchanging control messages with the WWAN) may be provided in a centralized or a distributed manner with respect to the WTs.

Embodiments also include systems and methods configured for allocating network resources among the WTs, load balancing, distributed computing, antenna-switching diversity, WWAN diversity, interference mitigation, hand off, power control, authentication, session management, ad-hoc network control, error correction coding, and interference mitigation. Other embodiments and variations thereof are described in the Detailed Description.

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In one embodiment, a computer program comprises a beam-forming weight calculation source code segment adapted to calculate at least one set of beam-forming weights for signaling between at least one group of WTs and at least one WWAN, and a WLAN information-distribution source code segment adapted to distribute at least one of a set of signals between the at least one group of WTs, the set of signals including a plurality of received WWAN signals, a plurality of WWAN transmission data, and the at least one set of beam-forming weights.

In another embodiment. a computer program comprises a beam-forming weight source code segment adapted to calculate at least one set of beam-forming weights for signaling between at least one group of WTs and at least one WWAN, and a MIMO combining source code segment adapted to combine a plurality of weighted received WWAN signals, at least one of the beam-forming weight source code segment and the MIMO combining source code segment including WLAN information-distribution source code adapted to distribute at least one of a set of signals between the at least one group of wireless terminals, the set of signals including a plurality of received WWAN signals, a plurality of WWAN transmission data, at least one channel estimate, and the at least one set of beam-forming weights.

A receiver embodiment of the invention comprises a plurality of WWAN interfaces, wherein each WWAN interface is adapted to receive at least one transmitted WWAN signal; a plurality of baseband processors wherein each baseband processor is coupled to at least one WWAN interface in the plurality of WWAN interfaces, the plurality of baseband processors adapted to generate a plurality of WWAN baseband signals; at least one WLAN coupled to the plurality of baseband processors; and at least one MIMO combiner adapted to receive at least one WWAN baseband signal from the WLAN, the at least one MIMO combiner adapted to perform MIMO combining of a plurality of WWAN baseband signals.

A transmitter embodiment of the invention comprises a plurality of WWAN interfaces wherein each WWAN interface is adapted to transmit at least one WWAN signal; at least one data source adapted to generate at least one data signal for transmission into at least one WWAN; at least one WLAN adapted to couple the at least one data signal to the plurality of WWAN interfaces for generating a plurality of WWAN

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data signals; and at least one MIMO processor adapted to generate a plurality of complex weights for weighting the plurality of WWAN data signals.

A wireless terminal according to one aspect of the invention comprises at least one WWAN interface; at least one WLAN interface; and at least one cooperative beam-forming system coupled between the WWAN interface and the WLAN interface and adapted to perform beamforming with information received from the WLAN interface.

Receivers and cancellation systems described herein may be employed in subscriber-side devices (e.g., cellular handsets, wireless modems, and consumer premises equipment) and/or server-side devices (e.g., cellular base stations, wireless access points, wireless routers, wireless relays, and repeaters). Chipsets for subscriber-side and/or server-side devices may be configured to perform at least some of the receiver and/or cancellation functionality of the embodiments described herein.

Additional embodiments, objects, and advantages are described and inferred from the following detailed descriptions and figures. Although particular embodiments are described herein, many variations and permutations of these embodiments fall within the scope and spirit of the invention. Although some benefits and advantages of the preferred embodiments are mentioned, the scope of the invention is not intended to be limited to particular benefits, uses, or objectives. Rather, embodiments of the invention are intended to be broadly applicable to different wireless technologies, system configurations, networks, and transmission protocols, some of which are illustrated by way of example in the figures and in the following detailed description. The detailed description and drawings are merely illustrative of the invention rather than limiting, the scope of the invention being defined by the appended claims and equivalents thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A illustrates an application of various embodiments of the invention to a cellular network.

Figure 1B illustrates an embodiment of the invention in which transmitted and/or received data between a WLAN group and a WWAN terminal occupies parallel, redundant channels c_n.

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Figure 1C illustrates an embodiment of the invention in which a WLAN group comprising a plurality of Wireless Terminals (WTs) is adapted to communicate with at least one WWAN node.

Figure 1D illustrates an embodiment of the invention in which communications between a WWAN node and a plurality of WTs are characterized by different, yet complementary, code spaces c_1, c_2, and c_3.

Figure 1E illustrates an embodiment of the invention in which a first WLAN group is adapted to communicate with a second WLAN group via at least one WWAN channel or network.

Figure 1F shows an embodiment of the invention wherein a WLAN group includes a plurality of WWAN-active WTs and at least one WWAN-inactive WT.

Figure 1G illustrates a cooperative beam-forming embodiment of the invention that functions in the presence of a desired WWAN terminal and a jamming source.

Figure 1H illustrates a cooperative beam-forming embodiment of the invention that functions in the presence of a plurality of desired WWAN terminals.

Figure 1I illustrates an embodiment of the invention adapted to provide a plurality of WTs in a WLAN group with access to a plurality of WWAN services.

Figure 1J illustrates an embodiment of the invention in which a WLAN group includes at least one WWAN terminal.

Figure 2A illustrates a functional receiver embodiment of the invention that may be realized in both method and apparatus embodiments.

Figure 2B illustrates a functional receiver embodiment of the invention that may be realized in both method and apparatus embodiments.

Figure 3A illustrates an embodiment of the invention in which a WLAN controller for a WLAN group allocates processing resources based on WWAN-link performance.

Figure 3B illustrates an alternative embodiment of the invention in which a WLAN controller for a WLAN group allocates processing resources based on WWAN-link performance.

Figure 4A illustrates a MIMO receiver embodiment of the invention.

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Figure 4B illustrates a functional embodiment of the invention in which MIMO processing operations are distributed over two or more WTs.

Figure 4C illustrates a functional embodiment of the invention for transmission and reception of WWAN signals in a distributed network of WTs.

Figure 4D illustrates a functional embodiment of the invention adapted to perform cooperative beamforming.

Figure 5A illustrates a receiver embodiment of the invention that may be implemented by hardware and/or software.

Figure 5B illustrates an alternative receiver embodiment of the invention.

Figure 6A illustrates functional and apparatus embodiments of the present invention pertaining to one or more WTs coupled to at least one WWAN and at least one WLAN.

Figure 6B illustrates a preferred embodiment of the invention that may be employed as either or both apparatus and functional embodiments of one or more WTs.

Figure 7A illustrates a functional embodiment of the invention related to calculating MIMO weights in a cooperative-beamforming network.

Figure 7B illustrates a functional embodiment of the invention adapted to calculate transmitted data symbols received by a cooperative-beamforming network.

Figure 8A illustrates a preferred transmitter embodiment of the invention.

Figure 8B illustrates a preferred receiver embodiment of the invention.

Figure 8C illustrates an embodiment of the invention in which a plurality of WTs is adapted to perform time-domain processing.

Figure 9A illustrates an optional transmission embodiment of the present invention.

Figure 9B illustrates a functional flow chart that pertains to transmitter apparatus and method embodiments of the invention.

Figure 10A illustrates software components of a transmission embodiment of the invention residing on a computer-readable memory.

Figure 10B illustrates software components of a receiver embodiment of the invention residing on a computer-readable memory.

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Figure 11 shows a WWAN comprising a WWAN access point (e.g., a base station) and a local group comprising a plurality of wireless terminals communicatively coupled together via a WLAN. A network-management operator is configured to handle WWAN-control operations within the local group.

Figure 12 is a block diagram of a communication system comprising a WLAN for communicatively coupling a plurality of mobile wireless terminals to a WLAN controller, and a network-management operator for cooperatively processing WWAN-control messages for the mobile wireless terminals.

Figure 13 is a block diagram of a mobile wireless terminal in accordance with an aspect of the invention in which a WWAN network management operator module is communicatively coupled to at least one other mobile wireless terminal via a WLAN and communicatively coupled to the WWAN.

Figure 14 illustrates a method in accordance with an aspect of the invention in which WWAN communications for a group of wireless terminals are cooperatively processed.

Figure 15 is a plot of a plurality of CI carriers and a superposition of the carriers.

Figure 16A is a plot of the relative frequency-versus-amplitude profile of a plurality of CI carriers that are combined to produce a time-domain pulse train, such as a DS-CDMA chip sequence.

Figure 16B is a time-domain representation of a modulated pulse train produced by providing time offsets to a plurality of modulated pulses, or equivalently, from a superposition of the CI carriers represented in Figure 2A.

Figure 17A illustrates a plurality of CI pulse waveforms modulated with code and/or information symbols .beta..sub.n and positioned orthogonally in time.

Figure 17B illustrates a CI pulse train of orthogonally time-offset pulses.

Figure 18A illustrates CI signal generation.

Figure 18B illustrates a CI transmitter.

Figures 19 and 20 each illustrates a system and method of generating CI signals.

Figure 21 illustrates basic components of CI signal generation software residing on a computer-readable medium.

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Figure 22A is a time-domain plot of a plurality of pulses generated from a superposition of equally spaced carriers, and shows a set of carrier phases corresponding to each of the pulses.

Figure 22B represents basic components and characteristics of a CI waveform.

Figure 23A is a functional flow chart of a CI receiver.

Figure 23B illustrates a CI receiver method and apparatus including a phase-space decoder.

Figure 24A shows an embodiment of a CI receiver.

Figure 24B shows an alternative embodiment of a CI receiver.

Figure 25A illustrates an aspect of a CI reception method and apparatus.

Figure 25B illustrates a CI receiver method and system of the present invention.

Figure 26A illustrates a CI receiver apparatus and method of the invention.

Figure 26B is a flow diagram for a receiver that receives a CI signal and samples the signal in multiple phase spaces.

Figure 26C illustrates basic components of a computer program on a computer-readable medium adapted to control a receiver and optimize performance.

Figure 27A illustrates a CI receiver configured as a multi-element receiver. Such receiver configurations may be employed in multiple-input, multiple-output (MIMO) communications.

Figure 27B illustrates three pulse-waveform blocks wherein each block includes four pulse waveforms of duration T.sub.s.

Figure 28A illustrates a CI transmitter.

Figure 28B illustrates a CI reception method and apparatus.

Figure 28C shows a CI receiver adapted to project a received signal onto at least one orthonormal basis, such as an orthonormal basis corresponding to at least one transmitted signal.

Figure 29A illustrates a block waveform including a set of orthogonal CI pulse waveforms.

Figure 29B illustrates a method for generating sub-carrier weights from a set of data symbols and a CI code matrix.

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Figure 30A illustrates a transmitter apparatus and method configured to generate multiple transmission waveforms.

Figure 30B shows a receiver apparatus and method adapted to process a wide range of single-carrier and/or multi-carrier transmissions.

Figure 31A illustrates a communication method.

Figure 31B shows CI processing of received single-carrier and/or multi-carrier signals.

Figure 32 illustrates a sub-space/sub-carrier processor receiver.

Figure 33A illustrates basic components of CI signal generation software residing on a computer-readable medium.

Figure 33B illustrates basic components of CI receiver software residing on a computer-readable medium.

DETAILED DESCRIPTION

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the exemplary embodiments are not intended to limit the invention to the particular forms disclosed. Instead, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

Figure 1A illustrates how some embodiments of the invention may be employed in a cellular network. Each wireless terminal (WT) of a plurality of WTs 101-103 is in radio contact with at least one wireless wide area network (WWAN) terminal, which may also be referred to as a WWAN node, such as cellular base station 119. The cellular base station 119 may include one or more antennas (e.g., an antenna array). WWAN signals transmitted between the base station 119 and the WTs 101-103 propagate through a WWAN channel 99, which is typically characterized by AWGN, multipath effects, and may include external interference.

The WTs 101-103 represent a wireless local area network (WLAN) group 110 (or local group) if they are currently connected or are capable of being connected via a WLAN 109. Accordingly, the WTs may be adapted to connect to at least one WWAN

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and to at least one WLAN. The WLAN group 110 may consist of two or more WTs in close enough proximity to each other to maintain WLAN communications. A given WWAN may include one or more WLAN groups, such as WLAN group 110.

In an exemplary embodiment of the present invention, the WTs 101-103 may be configured to transmit data $d_t(n)$ over a WWAN channel to the base station 119. The WTs 101-103 may also be configured to receive data $d_r(n)$ on a WWAN channel from the base station 119. The received data $d_r(n)$ is shared by the WTs 101-103 via the WLAN 109. Similarly, the transmitted data $d_t(n)$ may be distributed to the WTs 101-103 via the WLAN 109. The WLAN 109 typically comprises the wireless-communication resource between the WTs 101-103 and the associated physical-layer interface hardware. The WLAN 109 is differentiated from a WWAN by its relatively shorter range. For example, a Bluetooth or UWB system functioning within an IEEE 802.11 network would be referred to as a WLAN, whereas the 802.11 network would be referred to as a WWAN. A WLAN may operate in a different frequency band than the WWAN. Alternatively, other orthogonalizing techniques may be employed for separating WLAN and WWAN signals from each other. WLANs and WWANs, as defined herein, may employ any type of free-space transmissions, including, but not limited to, ultra-low frequency, RF, microwave, infrared, optical, and acoustic transmissions. WLANs and WWANs may employ any type of transmission modality, including, but not limited to, wideband, UWB, spread-spectrum, multi-band, narrowband, or dynamic-spectrum communications.

The WLAN 109 may also comprise the WLAN network-control functionality commonly associated with a WLAN, and the WWAN-access control functionality required to distribute necessary WWAN-access parameters (e.g., node addresses, multiple-access codes, channel assignments, authentication codes, etc.) between active WTs 101-103. The distribution of WWAN-access parameters between multiple WTs 101-103 enables each WT 101-103 to be responsive to transmissions intended for a particular WT in the local group and/or it enables a plurality of WTs 101-103 to function as a single WT when transmitting signals into the WWAN channel 99.

Particular embodiments of the invention provide for adapting either or both the transmitted data $d_t(n)$ and the received data $d_r(n)$ in order to perform beamforming. Specifically, the group of WTs 110 may be adapted to perform antenna-array processing

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by linking the individual WTs together via WLAN links 109 and employing appropriate antenna-array processing on the transmitted and/or the received data, $d_t(n)$ and $d_r(n)$, respectively.

Ad-hoc wireless networks (e.g., multi-hop and peer-to-peer networks) may employ intermediate relay nodes to convey transmissions from a source to a destination. Relays reduce the transmission power requirements for sending information over a given distance. This indirectly increases the spatial-reuse factor, thus enhancing system-wide bandwidth efficiency. For this reason, ad-hoc wireless networking works particularly well with unlicensed spectrum, which is characterized by restrictive power limitations and high path loss compared to cellular bands. Similarly, for certain embodiments of the invention, it may be preferable to employ high-loss (e.g., high-frequency) channels for the WLAN connections 109.

The capacity of wireless ad-hoc networks is constrained by interference caused by the neighboring nodes, such as shown in P. Gupta and P.R. Kumar, "The Capacity of Wireless Networks," IEEE Trans. Info. Theory, vol. IT-46, no. 2, Mar. 2000, pp. 388-404 and in A. Agarwal and P. R. Kumar, ``Improved capacity bounds for wireless networks." Wireless Communications and Mobile Computing, vol. 4, pp. 251-261, 2004, both of which are incorporated by reference herein. Using directional antennas (such as antenna arrays) reduces the interference area caused by each node, which increases the capacity of the network. However, the use of directional antennas and antenna arrays on the WTs 101-103 is often not feasible, especially when there are size constraints, power restrictions, cost constraints, and/or mobility needs. Thus, some embodiments of the present invention may provide for enabling WTs to form groups that cooperate in network-access functions. This provides each member of a given WLAN group with greater network access, as well as other benefits.

Antenna-array processing is generally categorized as multiple-input, single-output (MISO), single-input, multiple-output (SIMO) or multiple input, multiple output (MIMO). Array processing often employs beam forming in at least one predetermined signal space or signal sub-space. For example, phased-array processing involves coherent beam-forming of at least one transmitted signal frequency. Sub-space processing often employs some form of baseband interference cancellation or multi-user detection. Other

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variations of phased-array and sub-space processing also exist and may be implemented in embodiments of the present invention.

Sub-space processing is commonly employed via space-time processing (e.g., Rake receivers are employed in a frequency-selective channel) and/or space-frequency processing (e.g., frequency-domain processing is employed to provide for multiple flat-fading channels). Similarly, sub-space processing may employ other diversity parameters and combinations thereof, including (but not limited to) polarization processing and code-space processing.

MIMO systems have been shown to significantly increase the bandwidth efficiency while retaining the same transmit power budget and bit-error-rate (BER) performance relative to a single input, single output (SISO) system. Similarly, for a given throughput requirement, MIMO systems require less transmission power than SISO systems. MIMO technology is useful for enabling exceptionally high bandwidth efficiency. However, many spatial-multiplexing techniques require rich scattering. Increased path loss and poor scattering are major problems for MIMO systems operating above 2.4GHz. For these reasons, lower (e.g., cellular) frequencies are often preferred for MIMO applications. However, some MIMO benefits can also be achieved at higher frequencies.

Figure 1B illustrates an embodiment of the present invention in which transmitted and/or received data between the WLAN group 110 and the WWAN terminal 119 occupies parallel, redundant channels c_n. This approach is distinct from typical cooperative-diversity implementations in which WWAN data transmissions are conveyed over a plurality of orthogonal channels. Rather, each of the WTs 101-103 transmits and/or receives on a common channel c_n. This enables many well-known types of array processing to be performed.

The WLAN group 110 may function as either or both a transmitting array and a receiving array. The signal received at an antenna array is a noisy superposition of the n transmitted signals:

$$y(n) = \sqrt{\frac{E_s}{M_t}} Hs(n) + v(n)$$

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where $\{s(n)\}_{n=0}^{N-1}$ is a sequence of transmitted vectors, E_s corresponds to the transmit energy assuming that $E_{sn}||s_n|| = 1$ for $n = 1,\ldots,M_t$, $v(n)$ represents AWGN with zero mean and variance, and H is an $M_r \times M_t$ matrix channel (where M_r is the number of receiver elements and M_t is the number of transmitter elements), which is assumed constant over N symbol periods. The nominal rank of a rational matrix H is the order of the largest minor of H that is not identically zero, such as shown in T. Kailath, Linear Systems, Prentice-Hall, Inc., 1980, (especially Sec. 6.5), which is incorporated by reference.

Channel characterization involves finding a set of channel realizations (e.g., functions) that indicate channel quality with respect to some performance metric (e.g., error probability or asymptotic criteria). In the MIMO channel, several variables contribute to the channel quality (and thus, to the optimization of channel quality), including the choice of space-time codes, receiver-terminal selection, and receiver algorithm(s) employed.

In one embodiment of the invention, a subset of WTs in a WLAN group may be selected such as to provide optimal WWAN transmission and/or reception within at least one predetermined constraint, such as an optimal or maximum number of active WWAN transceivers within the WLAN group. Such predetermined constraints may be established to optimize some combination of WWAN link performance and resource use within the WLAN group. In one embodiment, WTs experiencing the best WWAN channel conditions may be selected. Techniques employing antenna selection, such as may be used for diversity processing with antenna arrays, may be used in embodiments of the present invention. In one aspect of the invention, resource conservation may focus on WT battery power, MIMO processing complexity, and/or WLAN bandwidth.

Certain embodiments of the invention may distinguish between circuit power (e.g., power used to perform signal processing) versus transmission power. Other embodiments of the invention may provide consideration for the total battery power (e.g., processing power plus transmission power) budget, such as to provide power (e.g., battery usage) load balancing between WTs. Thus, embodiments of the invention may optimize a balance of signaling parameters, including (but not limited to) transmission power, channel-coding (and decoding) complexity, modulation, signal processing and the

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complexity associated with cooperative array processing parameters (e.g., number of active array elements, number of channels, number of WTs employed to perform signal processing, number of WTs in a WLAN group, type of array-processing operations, etc.).

Any combination of various channel-characterization functions may be employed as a measure of link performance. Example functions including, but not limited to, the following may be employed. Possible functions include the average signal strength:

$$P(\mathrm{H}) = \frac{1}{N}\sum_{n=0}^{N-1}\left\|H^{(n)}\right\|_F^2$$

the average mutual information:

$$\bar{I}(\mathrm{H}) = \frac{1}{N}\sum_{n=0}^{N-1}\log\det\left(I_{M_r} + \frac{E_s}{N_o M_t}H^{(n)}H^{(n)\mathrm{H}}\right)$$

and the normalized average mutual information:

$$\bar{I}(\mathrm{H}) = \frac{1}{N}\sum_{n=0}^{N-1}\log\det\left(I_{M_r} + \frac{E_s}{N_o}\frac{1}{\alpha}H^{(n)}H^{(n)\mathrm{H}}\right)$$

where $\alpha = \frac{1}{NM_tM_r}\sum_{n=0}^{N-1}\left\|H^{(n)}\right\|_F^2$ is an estimate of the path loss.

Theoretical capacity in a MIMO channel is typically expressed as:

$$C = \log_d \det\left[I_{M_r} + \rho/M_t HH^*\right]$$

where ρ is the average SNR.

A preferred embodiment of the invention may employ error-correcting codes to add structured redundancy to the information bits. This can be done to provide diversity, such as temporal diversity, spatial diversity, and/or frequency diversity. Embodiments of the invention may employ spreading codes, which are well known in the art. In addition to collaborative MIMO operations, the WTs may engage in collaborative decoding. In particular, a WLAN group may be provided with functionality that directs the WTs to coordinate WWAN information exchange and decoding via the WLAN.

In yet another embodiment of the invention, a WWAN terminal may be adapted to receive channel information (and/or even received data) from WTs, perform array-processing (e.g., MIMO) computations, and then upload the resulting array-processing

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weights to the WTs. The WTs may simply apply the weights to their transmitted and/or received WWAN signals, and perform any other related operations, such as combining.

Figure 1C illustrates a WLAN group 110 comprising a plurality of WTs 101-103 adapted to communicate with at least one WWAN node 119. A WWAN channel 99 expresses distortions, interference, and noise that affect WWAN transmissions between the WTs 101-103 and the WWAN node 119. Channel estimation characterizes propagation characteristics (e.g., multipath, shadowing, path loss, noise, and interference) in the WWAN channel.

In one embodiment of the invention, a given WWAN transmission is separated into spectral components (such as denoted by f_1, f_2, and f_3) by the WLAN group 110. For example, each of the WTs 101-103 may be adapted to receive predetermined spectral components f_1, f_2, and f_3 of a given transmission intended for a particular WT. Alternatively, each of the WTs 101-103 may be adapted to transmit one or more associated predetermined spectral components to the WWAN node 119.

The selection of spectral components f_1, f_2, and f_3 and their association with particular WTs 101-103 is typically performed to optimize WWAN system performance relative to the current WWAN channel 99. For example, since the frequency-dependent fading profile in a scattering-rich environment tends to be unique for each spatially separated WT 101-103 channel, the spectral components f_1, f_2, and f_3 are preferably selected to minimize the effects of deep fades and/or interference. Spectral-component selection may be selected and/or adapted to optimize one or more WWAN link-performance metrics, including, but not limited to, SNR, BER, PER, and throughput. Spectral-component selection may be performed to achieve other objectives, such as to distribute processing loads across the WLAN group 110.

The spectral components f_1, f_2, and f_3 may be characterized by overlapping or non-overlapping frequency bands. Spectral components f_1, f_2, and f_3 may each include continuous or discontinuous (e.g., frequency interleaved) frequency-band components. Spectral components f_1, f_2, and f_3 may comprise similar or different bandwidths. Furthermore, the spectral components f_1, f_2, and f_3 may include gaps or notches, such as to notch out interference or deep fades. Accordingly, an aggregate signal derived from combining the spectral components f_1, f_2, and f_3 may include gaps or notches.

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WWAN communication signals may include multicarrier (e.g., OFDM) or single-carrier signals. In the case of single-carrier signals, the WTs 101-103 can be adapted to perform frequency-domain synthesis and/or decomposition, such as described in published patent appl. nos. 20040086027 and 20030147655, which are hereby incorporated by reference in their entireties.

Figure 1D illustrates a similar communication-system embodiment to that shown in Figure 1C, except that the transmissions between the WWAN node 119 and the WTs 101-103 are characterized by different, yet complementary, code spaces c_1, c_2, and c_3. In this case, the term complementary means that the coded transmissions corresponding to the code spaces c_1, c_2, and c_3 can sum to produce at least one predetermined WWAN coded data sequence. This may be a weighted sum due to the given channel conditions. A predetermined WWAN coded data sequence may employ a code that would ordinarily (in view of the prior art) be employed in whole. That is, it would not ordinarily be partitioned into sub-codes to be transmitted by different transmitters or received by different receivers.

In one embodiment of the invention, the code spaces c_1, c_2, and c_3 correspond to direct-sequence codes, such as may be used to provide for spreading and/or multiple access. A superposition of signals transmitted across the code spaces c_1, c_2, and c_3 may provide at least one predetermined WWAN coded data sequence received by at least one WWAN node 119. Similarly, a superposition of signals received by the WTs 101-103 and mapped onto the code spaces c_1, c_2, and c_3 may provide at least one predetermined WWAN coded data sequence that would ordinarily (in view of the prior art) be intended for a single WT. Preferred embodiments of the invention may provide for channel corrections (e.g., pre-distortion and/or receiver-side channel compensation) by either or both the WLAN group 110 and the WWAN node 119. Accordingly, the code spaces c_1, c_2, and c_3 may be adapted to account for channel conditions.

In another embodiment of the invention, the code spaces c_1, c_2, and c_3 may correspond to direct-sequence codes having predetermined spectral characteristics. It is well known that different time-domain data sequences may be characterized by different spectral distributions. Accordingly, embodiments of the invention may provide for selecting complementary codes c_1, c_2, and c_3 having predetermined spectral

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characteristics with respect to WWAN channel conditions affecting the links between the WTs 101-103 and the WWAN node 119. Thus, the codes c_1, c_2, and c_3 may be selected according to the same criteria employed for selecting the spectral components f_1, f_2, and f_3.

Figure 1E illustrates an embodiment of the invention in which a first WLAN group 110 (such as comprising WTs 101-103 connected via WLAN 109) is adapted to communicate with a second WLAN group 120 (such as comprising WTs 111-113 connected via WLAN 118) via WWAN channel 99. Applications of this embodiment may be directed toward peer-to-peer and multi-hop networks. Specifically, antenna-array processing (e.g., MIMO operations) may be performed by both WLAN groups 110 and 120. Each WLAN group (such as WLAN groups 110 and 120) may function as a single node in an ad-hoc network, a peer-to-peer network, or a multi-hop network. For example, any communication addressed to (or routed through) a particular node (such as one of the WTs 101-103) may be advantageously processed by one or more of the WTs 101-103 in the WLAN group 110. In one embodiment, each active WT 101-103 in the WLAN group 110 may be responsive to communications addressed to itself and to at least one other WT 101-103 in the WLAN group 110.

The WLAN 109 may be used to inform individual WTs 101-103 which node address(es) (or multiple-access channel assignments) to be responsive to. Similarly, the WLAN 109 may convey information to WTs 101-103 in order to spoof node addresses and/or multiple-access information and otherwise help WTs 101-103 assume channelization information related to a particular WT identity prior to transmitting signals into the WWAN. Thus, the WLAN 109 can be used to assist in synchronizing WT interactions with the WWAN. The functionality of providing for sharing WWAN-access information between WTs 101-103 may be coordinated and controlled with respect to cooperative-array (e.g., MIMO) processing.

Figure 1F shows an embodiment of the invention wherein a WLAN group 110 includes a plurality of WWAN-active WTs 101-103 and at least one WWAN-inactive WT, such as WTs 104-106. The WWAN-active WTs 101-103 may be configured to directly transmit and/or receive WWAN communication signals 129. WWAN-inactive WTs 104-106 are defined as WLAN-connected terminals that do not directly

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communicate with the WWAN. Rather, the WWAN-inactive WTs 104-106 may be in a sleep or standby mode.

In a preferred embodiment of the invention, signals routed to and from a particular WT 101-103 may be provided with beam-forming weights that allow for phased-array and/or sub-space processing. Calculation of the weights may be facilitated via distributed computing (e.g., as a load-balancing measure) across a plurality of the WTs (101-106). This allows the WLAN group 110 to scale the effective throughput of the WWAN link and coordinate system throughput with local area load balancing. In particular, the efficiency of the WWAN link is proportional to the smaller of the number of array elements at the WWAN terminal (not shown) and the number of WWAN-active transceiver antennas linked by the WLAN 109. When an equal number N of antennas is employed on both sides of the link, up to an N-fold increase in the link throughput is possible. Channel coding can be employed to exchange this increase for improved probability-of-error performance, increased range, and/or lower transmission power.

Although the capacity of a MIMO channel increases with the number of antennas employed at both ends of the link, the complexity of the transmission and reception algorithms increases accordingly. For example, the sphere decoder has a typical complexity of $O(M_T^6)$, where M_T is the number of transmitting antennas, and V-Blast has a typical complexity of $O((M_R M_T)^3)$, where M_R and M_T are respectively the number of receiving and transmitting antennas. However, the computational power increases only linearly with respect to the number of WTs (assuming each WT has identical processing capability). Thus, the aggregate processing power of the WTs may determine the maximum number of active antennas that a WLAN group 110 can support.

One solution to the disparity between required processing power and the number of WT processors in a given WLAN group 110 is to ensure that the total number of WTs exceeds the number of MIMO channels in the group 110. This approach enables at least two significant processing advantages:

1) The processing load may be spread over a larger number of mobile-terminal processors, and
2) A form of antenna-switching diversity can be used to optimize performance and throughput in the MIMO channel.

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Antenna switching is a well-known technique that switches between various antennas and selects ones having the best signal outputs. This can be done to reduce correlation between antennas, thereby improving MIMO performance. Antenna switching is described in G.J. Foschini, M.J. Gans, "On limits of wireless communication in a fading environment when using multiple antennas," *Wireless PersonalCommunications*, vol. 6, no. 3, pp. 311-335, March 1998, which is incorporated by reference. In some embodiments of the invention, WTs having the most favorable WWAN channel characteristics may be selected to improve MIMO performance without any increase in processing complexity.

In some embodiments of the invention, one or more WWAN-inactive WTs 104-106 may be employed for WLAN-based functions, such as (but not limited to) WLAN network control, distributed-computing applications, and WWAN-interface control. For example, WLAN network control may include any of the well-known network-control functions, such as terminal identification, authentication, error correction, routing, synchronization, multiple-access control, resource allocation, load balancing, power control, terminal-state management, hand-offs, etc.

The WLAN 109 may employ distributed computing across a plurality of the WTs. Distributed computing may be employed simply to achieve increased processing power. Alternatively, distributed computing may include other objectives, such as balancing computational processing loads or balancing power consumption across the WTs 101-106 in the WLAN group 110. Computational loads on the WLAN group can potentially include any WWAN-related computations, such as WWAN channel estimation, WWAN channel compensation, diversity combining, WWAN channel coding/decoding, and cooperative array processing (e.g., MIMO weight calculation, interference cancellation, multi-user detection, matrix operations, and other smart antenna array processing operations).

WWAN-interface control may include distributing WWAN data and control information between the WTs 101-106. In one exemplary embodiment of the invention, at least one of the WTs 101-106 comprises a data source that distributes its data to at least one other WT 101-106 for transmission into the WWAN. In a similar embodiment of the invention, received WWAN signals intended for a particular WT 101-106 are received by

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a plurality of WWAN-active WTs 101-103. The received WWAN signals may optionally be processed by one or more WTs 101-106 prior to being routed to the intended WT 101-106. Accordingly, WWAN channel-access information may be routed to a plurality of WWAN-active WTs 101-103 such that they function together as a single WT 101-106.

The determination of which WTs 101-106 are active is typically performed by decision processing within the WLAN group 110 that determines which WTs 101-106 have the highest quality WWAN channel(s). The number of WWAN-active WTs (such as WTs 101-103) may be determined by one or more factors, including WT channel quality, array-processing complexity, available computational resources within the WLAN group 110, load balancing, and information-bandwidth requirements. In an alternative embodiment of the invention, the WWAN assigns cooperative channel-access information to the WTs 101-103 and may optionally determine which WTs 101-106 are active.

Some embodiments of the invention may take into consideration not only the MIMO complexity at the WTs, but also the added complexity associated with distributing the computational loads over WTs in a given WLAN group. Both MIMO and distributed computing overheads can be characterized as a function of the number of WTs in a WLAN group. Furthermore, the information bandwidth of a given WLAN channel limits the rate of information exchange between WTs. Accordingly, local channel conditions within the WLAN may affect throughput and range, and thus limit the number of WTs within the WLAN group. Either the WLAN capacity or the computational capability of each WT may set a practical limit on the number of WTs in a WLAN group and the overall frequency-reuse factor.

Another important factor that can impact the WLAN group size is the channel rate-of-change, which may be due to motion of the WTs and/or other objects in the WWAN environment. In particular, rapidly changing channel conditions may necessitate frequent updates to the MIMO computations, thus increasing the computational load on WLAN group and potentially increasing the required data transfer across the WLAN. Similarly, local channel conditions may dictate the flow of data if distributed computing is employed.

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MIMO systems experience substantial degradation in data transfer rates in mobile channels. Time-varying multipath-fading profiles commonly experienced in a mobile wireless network exhibit deep fades that often exceed 30dB. Commercial viability of some embodiments of the present invention requires the ability to tolerate a rapidly changing channel. A promising approach to this problem is to employ diversity to reduce the channel rate-of-change. In a wideband system, or equivalently, in a system comprised of a number of narrowband subcarriers distributed (e.g., interleaved) over a wide frequency band, deep fades affect only a portion of the total channel bandwidth. Therefore, frequency and/or spatial diversity may be employed to reduce the likelihood of deep fades in a multipath environment. Similarly, alternative forms of diversity may be employed. In a mobile environment, this translates into reducing the channel rate-of-change.

Figure 1G illustrates a cooperative beam-forming embodiment of the invention that functions in the presence of a desired WWAN terminal 119 and an external interference source (or jammer) 118. WTs 101-103 in a WLAN group 110 may coordinate their received aggregate beam pattern(s) to null out a jamming signal 115. Array-processing operations performed on signals received from the WTs 101-103 may take the form of phased-array processing, which minimizes the array's sensitivity to signals arriving from one or more angles. Alternatively, array processing may employ baseband (or intermediate-frequency) interference cancellation. Similarly, beam-forming operations may be employed to cancel emissions transmitted toward one or more terminals (such as jammer 118).

Figure 1H illustrates a cooperative beam-forming embodiment of the invention configured to function in the presence of a plurality of desired WWAN terminals 119 and 127. In one embodiment of the invention, the WWAN terminals 119 and 127 may be common to a particular WWAN, and the configuration illustrated in Figure 1H may include a soft hand-off in which redundant transmissions are transmitted between the WLAN group 110 and the WWAN terminals 119 and 127. In this case, the WLAN group may be distributed geographically over a plurality of WWAN sectors or cells. In one aspect of the invention, the WLAN group 110 may adapt its connectivity with the WWAN to transition to the cell or sector offering the optimal aggregate WWAN channel

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quality. Accordingly, the WLAN group may adapt its selection of WWAN-active WTs in response to a hand off.

In another embodiment of the invention, the WLAN group 110 may employ a first WWAN connection (such as illustrated by a connection between WTs 101 and 102, and WWAN terminal 119) and a second WWAN connection (such as illustrated by a connection between WT 103 and WWAN terminal 127) to transmit and/or receive one or more data streams. The WLAN group 110 may employ a plurality of WWAN user channels in a given WWAN. Similarly, the WLAN group 110 may employ connections to a plurality of different WWANs.

Figure 1I illustrates an embodiment of the invention that provides a plurality of WTs 101-106 in a WLAN group 110 with access to a plurality of WWAN services (i.e., WWANs). For example, WT 101 is provided with a communication link with an IEEE 802.16 access-point terminal 116 in an IEEE 802.16 network, WT 102 maintains access capabilities to a 3G-cellular terminal 119, and WT 103 has connectivity to an IEEE 802.11 access point 117. WLAN connectivity 109 is adapted to enable any of the WTs 101-106 in the WLAN group 110 to access any of the plurality of WWAN (802.16, 3G, and 802.11) services.

The WLAN 109 may include a WWAN-access controller (not shown), which may take the form of WLAN-control software residing on a physical device, such as one or more WTs 101-106. Connectivity of the WTs 101-106 to the available WWAN services may be performed with respect to a combination of technical rules and business rules. For example, WWAN access is typically managed using technical rules, such as network load balancing, power conservation, and minimizing computational processing loads. However, WWAN access can also be influenced by business rules, such as enabling a predetermined cost/service ratio for individual WTs 101-106. For example, the WWAN-access controller (not shown) can anticipate the economic cost of particular WWAN services to the user, as well as user communication needs, when assigning WWAN access to individual WTs 101-106. Each WT 101-106 may provide the WWAN-access controller (not shown) with a cost tolerance, which can be updated relative to the type of communication link desired. For example, high-priority communication needs (such as particular voice communications or bidding on an online auction) may include

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permissions to access more expensive WWAN connections in order to ensure better reliability.

The overall goal of WWAN access may be to achieve optimal connectivity with minimum cost. Accordingly, WWAN-access algorithms may include optimization techniques, including stochastic search algorithms (like multi-objective genetic algorithms). Multi-objective optimization are well known in the art, such as described in E.Zitzler and L.Thiele," Multiobjective evolutionary algorithms: A comparative case study and the strength pareto approach," *IEEE Tran. on Evol. Comput.*, vol. 3, no. 4, Nov 1999, pp. 257-271 and J.D. Schaffer, "Multiple objective optimization with vector evaluated genetic algorithms," *Proceedings of 1st International Conference on Genetic Algorithms*, 1991, pp. 93-100, both of which are incorporated by reference.

A WWAN-access controller (not shown) preferably ensures an uninterrupted session when transitioning from one WWAN to another. In particular, the transition between different WWANs should be invisible to the user. This requires that the WWAN-access controller (not shown) be adapted to store user state information (e.g., save browser pages or buffer multimedia data streams). Furthermore, back-end systems may preferably be employed to manage cooperative WWAN access in order to consolidate different WWAN-access charges into a single bill for the user.

In Figure 1J, a plurality of WTs 101-106 in a WLAN group 110 includes at least one WWAN terminal 106. The WTs 101-105 may contribute beam-forming capabilities to the WWAN terminal 106, such as to increase range, increase spatial reuse, reduce transmission power, and/or achieve any of other various beamforming objectives.

In one embodiment of the invention the WTs 101-105 function as lens for WWAN signals transmitted and received by the WWAN terminal 106. For example, the WTs 101-106 may collect received WWAN signals and then focus retransmitted WWAN signals at the WWAN terminal 106. Similarly, the WTs 101-105 may assist in the transmission of WWAN signals from the WWAN terminal 106 to one or more remote sources. In essence, the WTs 101-105 may function like a radio relay, but with directionality and focusing capabilities. In this embodiment, the WLAN connectivity of WTs 101-105 with the WWAN terminal 106 may not be necessary.

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In another embodiment of the invention, one or more of the WTs 101-106, such as WWAN terminal 106, may be adapted to process the majority (or entirety) of necessary beam-forming computations. In this case, WT 106 is designated as a computer-processing terminal. The computer-processing terminal 106 is adapted to include specific computational resources for processing WWAN signals received by other WTs (such as WTs 101-103), which are then relayed via the WLAN 109 to the computer-processing terminal 106. Similarly, the computer-processing terminal 106 may be adapted to perform signal-processing operations associated with WWAN transmission. Computational operations associated with other WWAN signal-processing operations (e.g., coding, decoding, channel estimation, network-access control, etc.) may be provided by the computer-processing terminal 106.

Figure 2A illustrates a functional embodiment of the invention that may be realized in both method and apparatus embodiments. A plurality *M* of WWAN Interfaces 1101.1-1101.M is provided for coupling WWAN signals to and/or from at least one WWAN. In one functional embodiment, WWAN Interfaces 1101.1-1101.M may include WWAN transceivers adapted to convert received WWAN signals into received baseband signals. A plurality of WWAN baseband processors 1102.1-1102.M are optionally provided for performing baseband processing (such as, but not limited to, channel compensation, A/D conversion, frequency conversion, filtering, and demultiplexing) on the received baseband signals. Alternatively, the function of the WWAN baseband processors 1102.1-1102.M may be performed by the WWAN Interfaces 1101.1-1101.M.

Baseband outputs from the WWAN baseband processors 1102.1-1102.M are coupled into a plurality of array processors, such as MIMO combiners 1103.1-1103.M. In a MIMO channel, the received WWAN signals (and thus, the baseband outputs) are characterized by a plurality of overlapping (i.e., interfering) signals. Although MIMO combiners 1103.1-1103.M are shown, any type of array processor may be employed. The number of array processors may be less than, equal to, or greater than the number *M* of WWAN Interfaces 1101.1-1101.M. Baseband outputs may also be coupled into a WLAN 1105, which is coupled to the plurality of MIMO combiners 1103.1-1103.M. Each MIMO combiner 1103.1-1103.M may be adapted to receive baseband outputs from two

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or more baseband processors 1102.1-1102.M wherein at least one of those baseband outputs is coupled to the MIMO combiner 1103.1-1103.M via the WLAN 1105.

A particular m^{th} MIMO combiner 1103.m need not process data from a corresponding (m^{th}) WWAN Interface 1101.m. Rather, the mth MIMO combiner 1103.m may process baseband signal outputs from a plurality of WWAN Interfaces 1101.p {p = 1,...,M, where $p \neq m$}.

The WLAN 1105 comprises at least one WLAN channel between at least one baseband output (e.g., baseband processor 1102.1-1102.M outputs) and at least one array processor, such as the MIMO combiners 1103.1-1103.M. The WLAN 1105 may include WLAN interfaces (not shown) and associated WLAN-control hardware and/or software (not shown).

The MIMO combiners 1103.1-1103.M may be adapted to separate the overlapping signals and output at least one desired transmission therefrom. Outputs of the MIMO combiners 1103.1-1103.M are optionally processed by secondary data processors 1104.1-1104.M, which may provide coupling into the WLAN 1105. The secondary data processors 1104.1-1104.M may be adapted to perform demodulation, error-correction decoding, data formatting, and/or other related baseband-processing functions.

In some embodiments of the invention, MIMO combiner 1103.1-1103.M outputs may be coupled via the WLAN 1105 to other MIMO combiners 1103.1-1103.M and/or secondary data processors 1104.1-1104.M. For example, embodiments of the invention may employ an iterative cancellation process, such as successive interference cancellation (which is well-known in the art), involving the use of strongest-signal estimates, and then next-strongest-signal estimates to cancel known interference in weaker signals. Alternatively, embodiments may employ parallel cancellation.

Figure 2B illustrates an embodiment of the invention including a plurality M of WTs 1109.1-1109.M, each comprising a corresponding combination of a WWAN Interface 1101.1-1101.M, an optional WWAN baseband processor 1102.1-1102.M, a combiner (such as a MIMO combiner 1103.1-1103.M), and a secondary data processor 1104.1-1104.M. The WTs 1109.1-1109.M are coupled together by a WLAN 1105, which is configured to convey data between the WTs 1109.1-1109.M in order to enable cooperative antenna-array processing.

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A WT, such as any of the WTs 1109.1-1109.M, includes any system or device provided with communicative connectivity means to a WLAN 1105. Two or more WTs 1109.1-1109.M are preferably provided with WWAN interfaces, such as WWAN Interface 1101.1-1101.M. A plurality of WTs 1109.1-1109.M may share at least one WLAN 1105. In one embodiment of the invention, individual WTs 1109.1-1109.M may share the same WWAN service. This enables the WLAN group 110 to perform either or both transmit beam-forming and receive beam-forming (i.e., combining) operations.

In another embodiment of the invention, WTs 1109.1-1109.M may have connections to different WWANs and/or WWAN services. This enables the WLAN group 110 to achieve WWAN-service diversity. One or more WTs 1109.1-1109.M may optionally be capable of accessing multiple WWAN services. For example, many cellular handsets are provided with multi-mode capabilities, which give them the ability to access multiple WWANs. Some of the WTs 1109.1-1109.M may have no WWAN service. For example, one or more WTs 1109.1-1109.M may be out of range, in a WWAN dead spot, in an inactive WWAN state, or configured only to communicate via the WLAN 1105. WTs 1109.1-1109.M include, but are not limited to, cell phones, radio handsets, pagers, PDAs, wireless sensors, RFID devices, vehicle radio communication devices, laptop computers with wireless modems, wireless network access points, wireless routers, wireless switches, radio repeaters, transponders, and devices adapted to include satellite modems.

A WLAN group 110 may be adapted to perform any of various types and combinations of diversity and MIMO beam-forming. Three commonly used linear diversity-combining techniques include switched (or selection) combining, maximal ration combining (MRC), and equal gain combining (EGC). Other combining techniques may be employed. The impact of using diversity may be expressed by a probability distribution $p(\gamma)$ of the SNR γ at the output of a combining network. For switched diversity, wherein the combiner switches to the diversity branches (e.g., WTs) having the strongest signal, $p(\gamma)$ is given by:

$$p(\gamma) = \frac{L}{\Gamma} e^{-\gamma/\Gamma} \left[1 - e^{-\gamma/\Gamma}\right]^{L-1}$$

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where Γ is the average SNR for each diversity branch and L is the number of diversity branches. MRC weights branches (e.g., WT signals received from the WWAN) having better SNR more heavily (i.e., with greater-magnitude weights) than branches having poorer SNR. The $p(\gamma)$ for MRC is given by:

$$p(\gamma) = \frac{\gamma^{l-1} e^{-\gamma/\Gamma}}{\Gamma^{L}(l-1)!}$$

For EGC, $p(\gamma)$ is given by:

$$p(\gamma) = \frac{L}{a\Gamma} e^{-\gamma/a\Gamma}\left[1 - e^{-\gamma/a\Gamma}\right]^{L-1}$$

where $a = \sqrt{L/1.25}$ for $L \geq 2$, and 1 otherwise.

These diversity techniques provide the greatest improvements when the branches are uncorrelated.

Adaptive arrays (or smart antennas) may include antenna systems that automatically adjust to achieve some predetermined performance criterion, such as maximizing the signal to interference (S/I) ratio, SINR, or link margin. Adaptive antenna techniques include switched beam, beam steering, and optimum combining (e.g., a linear spatial filtering approach that employs adaptation to closely match an output signal with a reference signal). A filtering process typically suppresses any artifacts that are not part of the desired incoming signal, including noise and interference.

In an optimum combining system, signals from each WT are down converted to baseband and converted to digital signals in an ADC. Noise associated with the front end of the down converter and other sources is naturally added to the signal. The resulting signal $x_m(k)$ is multiplied by a complex weighting function $w_m(k)$ and summed with similar signals from other WT antenna elements. The resulting sum signal $\Sigma\, w_m(k)x_m(k)$ is compared with a previously derived (and updated) reference signal (e.g., a training sequence). An error signal $e(k)$ is generated and used to adjust the weight values in order to minimize $e(k)$. The objective is to derive the weighting function $w_m(k)$ that enables the best match between an estimated received signal and the actual transmitted signal. Alternatively, an adaptive WT array may be configured as an analog array wherein amplitude and phase adjustments (i.e., weighting functions) are performed at RF or IF.

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In a MIMO communication system, signals transmitted from M_T transmit sources interfere with each other at a receiver comprising the WTs 1109.1-1109.M. Thus, interference cancellation (such as matrix inversion, channel transfer function inversion, and adaptive filtering) may be employed by one or more MIMO combiners 1103.1-1103.M to separate the signals. The received signal is expressed by:

$$y = Hx + n$$

where the received signal, y, is a vector with M_R terms $\{y_i, i = 1,...,N_R\}$ corresponding to signals received by M_R (where M_R may have a value of 2 to M) receiver elements (i.e., WTs); x represents the transmitted signal, which is a vector having M_T terms $\{x_i, i = 1,...,M_T\}$ corresponding to signals transmitted by M_T transmitter elements; H is an $M_R \times M_T$ channel-response matrix that characterizes the complex gains (i.e., transfer function, or spatial gain distribution) from the M_T transmission elements to the M_R receive elements; and n represents AWGN having zero mean and zero variance.

In the case where the channel is characterized by flat fading, such as when a narrowband signal is employed (e.g., a sub-carrier of a multi-carrier signal), the elements in matrix H are scalars. The channel-response matrix H may be diagonalized by performing an eigenvalue decomposition of the $M_T \times M_T$ correlation matrix R, where $R = H^H H$. Eigenvalue decomposition is expressed by:

$$R = EDE^H$$

where E is an $M_T \times M_T$ unitary matrix with columns corresponding to the eigenvectors e_i of R, and D is an $M_T \times M_T$ diagonal matrix wherein the diagonal elements are eigenvalues λ_i of R. The diagonal elements of D indicate the channel gain for each of the independent MIMO channels. Alternatively, other eigenvalue-decomposition approaches, such as singular value decomposition, may be employed.

The process for diagonalizing the MIMO channel response is initiated by multiplying a data vector d with the unitary matrix E to produce the transmitted vector x: $x = Es$. This requires the transmitter to have some information corresponding to the channel-response matrix H, or related information thereof. The received vector y is then multiplied with $E^H H^H$ to provide an estimate of data vector s, which is expressed by:

$$\hat{s} = E^H H^H y = E^H H^H HEs + E^H H^H n = Ds + \hat{n}$$

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where $\hat{n}$ is AWGN having a mean vector of 0 and a covariance matrix of $\Lambda_n=\sigma^2 D$.

The data vector s is transformed by an effective channel response represented by the diagonal matrix D. Thus, there are N_s non-interfering subchannels wherein each subchannel i has a power gain of λ_i^2 and a noise power of $\sigma^2\lambda_i$.

In the case where MIMO processing is performed on a multicarrier signal, or some other wideband signal that is spectrally decomposed into narrowband components, eigenmode decomposition may be performed for each frequency bin f_n.

If multicarrier spreading codes are employed (e.g., orthogonal DFT, or CI, codes), the channel-response matrix H can cause inter-symbol interference between spread data symbols, even in a SISO arrangement. Accordingly, the eigenmode decomposition technique described previously is applicable to multicarrier spreading and despreading. In one embodiment of the invention, eigenmode decomposition may be applied across two or more dimensions (e.g., both spatial and frequency dimensions). In another embodiment of the invention, eigenmode decomposition may be applied across a single dimension (e.g., spatial or frequency dimensions). For example, multicarrier spreading codes (for example, orthogonal codes for data multiplexing in a given multiple-access channel) may be generated and processed via eigenmode decomposition.

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

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In conventional water filling, power allocation is performed such that the total transmission power P_T is some predetermined constant:

$$P_T = \sum_{j \in K} \sum_{k \in L} P_j(k)$$

where $L = \{1,...,N_s\}$ signifies the available subspaces and $K = \{1,...,N_f\}$ represents the available sub-carrier frequencies f_n. The received SNR (expressed by $\psi_j(k)$) for each transmission channel is expressed by:

$$\psi_j(k) = \frac{P_j(k)\lambda_j(k)}{\sigma^2}, \text{ for } j = \{1,..., N_s\} \text{ and } k = \{1,...,N_f\}$$

The aggregate spectral efficiency for the $N_s N_f$ transmission channels is expressed by:

$$C = \sum_{j=1}^{N_s} \sum_{k=1}^{N_f} \log_2\left(1 + \psi_j(k)\right)$$

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

An embodiment of the invention may employ reliability assessment for determining required processing and virtual-array size (i.e., the number of active WTs functioning as WWAN receiver elements). Received bits or symbols that have low reliability need more processing. Bits or symbols with high reliability may be processed with fewer elements (WTs) or provided with lower processing requirements. More information typically needs to be combined for data streams having less reliability and less information may need to be combined for data streams having more reliability. Also, nodes (WTs) with good channel quality may share more information via the WLAN than

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nodes having poor channel quality. Optimization algorithms, such as water-filling algorithms may be employed in the reliability domain.

Figure 3A illustrates an embodiment of the invention in which a WLAN controller for a WLAN group of WTs first identifies received data streams that have the least reliability (e.g., reliability that is below a predetermined threshold) 301. Then the WLAN controller increases allocated processing (e.g., increases the number of receiver nodes, increases the number of processing nodes, employs a processing approach having higher computational complexity, etc.) 302 to those data streams. Data symbols may be combined from the smallest number of nodes such that the reliability of the sum is maximized, or at least exceeds a predetermined threshold reliability. The processes 301 and 302 may be repeated 303 until a predetermined result is achieved or until there is no more data left for processing.

Figure 3B illustrates an embodiment of the invention in which a WLAN controller identifies received data streams that have the most reliability, or data streams having reliability that exceeds a predetermined reliability threshold 311. The WLAN controller may decrease allocated processing (e.g., decrease the number of receiver nodes, decrease the number of processing nodes, employ a processing approach having lower computational complexity, etc.) 312 to those data streams. The processes 301 and 302 may be repeated 303 until a predetermined result is achieved or until there is no more data left for processing. Embodiments of the invention may provide for encoding information across channels having a wide range of reliability.

Embodiments of the invention may be configured to perform blind signal separation (BSS), such as independent component analysis. For example, A. Jourjine, S. Rickard, and O. Yilmaz, "Blind Separation of Disjoint Orthogonal Signals: Demixing N Sources from 2 Mixtures," in *Proceedings of the 2000 IEEE International Conference on Acoustics, Speech, and Signal Processing*, Istanbul, Turkey, June 2000, vol. 5, pp. 2985–88, which is included herein by reference, describes a blind source separation technique that allows the separation of an arbitrary number of sources from just two mixtures, provided the time-frequency representations of the sources do not overlap. The key observation in the technique is that for mixtures of such sources, each time-frequency point depends on at most one source and its associated mixing parameters.

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In multi-user wireless communication systems that employ multiple transmit and receive antennas, the transmission of user information through a dispersive channel produces an instantaneous mixture between user transmissions. BSS may be used in such instances to separate received transmissions, particularly when training sequences and channel estimation are absent. In an exemplary embodiment of the invention, an OFDM-MIMO protocol may be provided across multiple independent WTs. Multiple transmissions are provided on at least one frequency channel, and frequency-domain techniques of BSS may be employed to recover received signals.

In one embodiment of the invention, at least one data transmission source may be adapted to convey its data across the WLAN to a plurality of WTs for transmission into the WWAN. In another embodiment of the invention, a plurality of WTs are adapted to receive data transmissions from a WWAN and couple said received data transmissions into a WLAN (with or without baseband processing) wherein centralized or distributed signal-processing means are provided for separating the data transmissions. Said signal-processing means includes any MIMO-processing techniques, including multi-user detection, space-time processing, space-frequency processing, phased-array processing, optimal combining, and blind source separation, as well as others.

In one embodiment of the invention, a vector of binary data symbols $b_i(n)$ are encoded with a convolutional encoder to produce a coded signal:

$$s_i(n) = b_i(n) * c(n)$$

where $c(n)$ represents a convolutional code of length L'. A cluster of N coded symbols corresponding to an ith user, data source, or data stream is represented by:

$$s_{n,i} = [s_i(n), \ldots, s_i(n+N-1)]^T$$

The transmit signal is generated by performing an N-point IDFT to $s_{n,i}$ to produce:

$$S_{n,i} = [S_i(n,0), \ldots, S_i(n,N-1)]^T$$

where

$$S_i(n,k) = \sum_{m=0}^{N-1} s_i(n+m) e^{i 2\pi k m / N}$$

The values $S_i(n,k)$ are transmitted via at least one of N_t transmit antennas.

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On the receive side, N_r receive antennas (typically, $N_r \geq N_t$) are employed. The signal received by a jth antenna is expressed by:

$$R_j(n) = \sum_{i=1}^{N_t} S_i(n) * h_{ij} + n_j(n)$$

where $n_j(n)$ represents the zero-mean AWGN introduced by the channel, and h_{ij} is the channel impulse-response of the ith transmit antenna to the jth receive antenna. The received signal can be interpreted as a convolutive mixture of the coded signals, where the channel matrix h represents the mixing system. An N-point DFT is applied to the received signals $R_j(n)$ to produce:

$$r_j = [r_j(n), \ldots, r_j(n + N - 1)]^T$$

where

$$r_j(n) = \sum_{m=0}^{N-1} R_j(n+m) e^{-i 2\pi k m / N}$$

Typically, a sufficient guard interval or cyclic prefix is employed to eliminate inter-symbol interference.

The signals from the N_r receiver antennas are grouped with respect to frequency bin. An observation at a kth frequency bin are expressed by:

$$r_n(k) = \left[r_1(n+k), r_2(n+k), \ldots, r_{N_r}(n+k)\right]^T$$

$$= H(k)s(k) + n(k)$$

Thus, the observations $r_n(k)$ $\{k = 0, \ldots, N\text{-}1\}$ can be interpreted as an instantaneous mixture of the transmitted signals $s(k)$, where $H(k)$ represents the mixing system.

There are many approaches for estimating the transmitted signals $s(k)$ from the received signals $r_n(k)$ that may be employed by the current invention. An exemplary embodiment of the invention employs BSS techniques. One class of BSS produces an output vector having the following form:

$$y(k) = W^H(k) r_n(k)$$

where $W(k)$ is an $N_r \times N_t$ matrix that groups the coefficients of the separating system. The output $y(k)$ can also be expressed by:

$$y(k) = G(k)s(k) + W^H(k)n(k)$$

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where $G(k) = W^H(k)H(k)$ represents the mixing/separating system. The goal of the separation process is to calculate the matrices $W(k)$ so that the $G(k)$ matrices are diagonal and the effects of noise $W^H(k)n(k)$ are minimized. Many different approaches are applicable for achieving these goals.

A BSS algorithm (such as the one described in J. F. Cardoso, A. Souloumiac, "Blind Beamforming for non-Gaussian Signals," *IEEE-Proceedings-F*, vol. 140, no. 6, pp. 362-370, December 1993, which is incorporated by reference herein) may be employed to separate the instantaneous mixture in each frequency bin. Each output at frequency bin k' can be regarded as corresponding to a single source at bin k' multiplied by a particular gain introduce by the algorithm. The outputs $y(k')$ are then used as reference signals in order to recover the sources at frequencies $k' \pm 1$. For example, the separation matrices $W(k)$ are determined by minimizing the mean-square error between the outputs $y(k) = W^H(k)r_n(k)$ and reference signals $y(k')$. For a given frequency bin k:

$$W_o(k) = \arg\min_{W(k)} E\left[\left|y(k) - \alpha y(k')\right|^2\right]$$

where α is a real constant, which is selected with respect to the convolutional code:

$$\alpha = \frac{\sum_{p=0}^{L-1} c^2(p)}{\sum_{p=0}^{L-2} c(p)c(p+1)}$$

This is done to ensure $G(k) = G(k')$. The solution to the optimization problem is given by:

$$W_o(k) = \alpha R_{r_n}^{-1}(k) R_{r_n y}(k,k')$$

where

$$R_{r_n}(k) = E\left[r_n(k)x^H(k)\right] \text{ and}$$

$$R_{r_n y}(k,k') = E\left[r_n(k)y^H(k')\right]$$

Figure 4A illustrates an embodiment of the invention wherein a plurality M of WTs 1109.1-1109.M is coupled to a MIMO processor 1103 via a WLAN 1105. In this particular embodiment, a computer-processing terminal 1119 may include the MIMO processor 1103. The computer processing terminal 1119 may be provided with WLAN-interface functionality, and may optionally include WWAN-interface functionality.

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The computer-processing terminal 1119 may include any of a plurality WLAN-connected devices with signal-processing capability. For example, the computer-processing terminal 1119 may include one of the WTs 1109.1-1109.M. In one aspect of the invention, the computer-processing terminal 1119 comprises a WLAN controller. In another aspect of the invention, the computer processing terminal 1119 comprises a network gateway, router, or access point including a CPU adapted to process signals received from the plurality of WTs 1109.1-1109.M. Applications of embodiments of the invention include (but are not limited to) sensor networks, micro-networks, RFID systems, cellular networks, and satellite networks.

Each WT 1109.1-1109.M may include a baseband processor 1102.1-1102.M adapted to provide WWAN baseband (or IF) signals to the MIMO processor 1103 via the WLAN 1105. The MIMO processor 1103 may be configured to separate interfering WWAN data symbols in the WWAN baseband signals. The separated WWAN data symbols are then coupled back to data processors 1104.1-1104.M in the WTs 1109.1-1109.M.

Figure 4B illustrates a functional embodiment of the invention in which MIMO processing operations (represented by MIMO processors 1103.1-1103.M) may be distributed over two or more WTs 1109.1-1109.M. Baseband processors 1102.1-1102.M provide WWAN baseband signals to a WLAN controller 1106, which may distribute the signals (and signal-processing instructions) to the MIMO processors 1103.1-1103.M. The separated WWAN data symbols are then coupled back to data processors 1104.1-1104.M.

Figure 4C represents a functional embodiment of the invention. At least one WT may provide WWAN access information 1140 to a WLAN controller. The WWAN access information typically includes necessary information (such as at least one WWAN channel assignment, authentication codes, etc.) to access at least one particular WWAN channel. The WWAN access information may optionally include performance information, such as WWAN channel estimates, link-bandwidth demand, link priority, and/or WWAN channel-quality measurements (e.g., SNR, SINR, BER, PER, latency etc.). This information is typically provided to the WLAN controller by one or more WTs.

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The WLAN controller determines which WTs to activate 1141 for a particular WWAN communication link. This may be performed for either or both transmission and reception. The determination of which WTs will be active 1141 in a given WWAN link typically depends on a combination of factors, including (but not limited to) the number *M* of WTs required to achieve predetermined channel characteristics or access parameters, which WTs have the best WWAN channel quality, load balancing, power-consumption balancing, computational overhead, latency, and WLAN-access capabilities. Accordingly, the WLAN controller may send control information via the WLAN to the WTs that includes state information (e.g., operating-mode assignments, such as active, standby, sleep, and awake).

The WLAN controller may convey WWAN information to the active WTs 1142. The WWAN information may be derived from the WWAN access information and provided to the WTs to establish and/or maintain at least one WWAN link. Accordingly, the WWAN information may include WWAN channel assignments. The WWAN information may include beam-forming weights and/or space-time codes. Accordingly, the step of conveying WWAN information to the WTs 1142 may optionally include a preliminary signal-processing step (not shown), such as blind adaptive or deterministic weight calculation. This preliminary signal-processing step (not shown) may be distributed among a plurality of the WTs, or it may be performed in a centralized mode, such as by a single computing terminal. A distributed-computing mode may take various forms. In one mode, each of a plurality of WTs takes its turn functioning as a computing terminal. In another mode, multiple WTs function as computing terminals simultaneously.

Communications in the WWAN link are coordinated between the WTs in order to synchronize the transmitted and/or received WWAN signals 1143. A receiver embodiment of the invention may provide for synchronizing the received WWAN signals, such as to provide for coherent combining. A transmitter embodiment of the invention may provide for synchronizing the transmitted WWAN signals from the WTs such as to enable coherent combining at some predetermined WWAN terminal.

An optional transmitter embodiment of the invention may employ synchronization to deliberately time-offset signals arriving at one or more WWAN

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terminals in order to provide for transmit diversity by the WTs. In such embodiments, one or more of the WT transmissions may be provided with time-varying complex weights (e.g., amplitudes and/or phases), such as described in S. A. Zekavat, C. R. Nassar and S. Shattil, "Combined Directionality and Transmit Diversity via Smart Antenna Spatial Sweeping, " proceedings of *38th Annual Allerton Conference on Communication, Control, and Computing, University of Illinois in Urbana-Champaign,* pp. 203-211, Urbana-Champaign, IL, USA, Oct. 2000, S. A. Zekavat, C. R. Nassar and S. Shattil, "Smart antenna spatial sweeping for combined directionality and transmit diversity," *Journal of Communications and Networks (JCN), Special Issue on Adaptive Antennas for Wireless Communications,* Vol. 2, No. 4, pp. 325-330, Dec. 2000, and S. A. Zekavat, C. R. Nassar and S. Shattil, "Merging multi-carrier CDMA and oscillating-beam smart antenna arrays: Exploiting directionality, transmit diversity and frequency diversity, " *IEEE Transactions on Communications*, Vol. 52, No. 1, pp. 110 – 119, Jan. 2004, which are incorporated by reference herein.

In an alternative embodiment of the invention, providing WWAN access information 1140 may include providing WWAN channel-performance information from the WTs to at least one WWAN terminal. Thus, conveying WWAN information to the WTs 1142 may be performed by at least one WWAN terminal. An optional embodiment of the invention may provide for at least one WWAN terminal determining which WTs in a WLAN group will operate in a given WWAN link and conveying that WWAN information 1142 to the WLAN group. Embodiments of the invention may provide capabilities to WWAN terminals to set up and adapt the formation of WLAN groups and determine which WTs are assigned to which WLAN groups. Such control capabilities may employ GPS positions of WTs to assist in assigning WTs to a WLAN group. Some embodiments of the invention may provide for collaboration between a WWAN and a WLAN group for activating WTs and/or assigning WTs to the WLAN group.

In one embodiment of the invention, step 1142 may include a preliminary signal-processing step (not shown) in which at least one WWAN terminal calculates cooperative-beamforming weights for the WTs based on channel-performance information provided by the WTs. Accordingly, the WWAN information may include cooperative-beamforming weights derived by at least one WWAN terminal and conveyed

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to at least one WT. Synchronization 1143 of the transmitted and/or received WWAN signals by the WTs may optionally be performed by at least one WWAN terminal. Similarly, embodiments of the invention may provide for applying time-varying weights to WWAN-terminal transmissions (such as described previously).

Figure 4D illustrates a functional embodiment of the invention adapted to perform cooperative beamforming. WWAN channel information is provided 1144 for assigning subchannels 1145 and calculating cooperative beamforming (i.e., WT) weights 1146. The beamforming weights are then distributed to the appropriate WTs 1147.

Sub-channel assignments 1145 are typically performed with respect to a predetermined subchannel-quality threshold, such as SNR, SINR, or BER. Subchannels having the required minimum performance may be assigned for transmission and/or reception. Sub-channel assignments 1145 may also provide for bit loading. Alternatively, sub-channel assignments 1145 may be performed without regard to sub-channel quality. In such cases, spreading or channel coding may be performed to mitigate the effects of lost and compromised subchannels.

Weight calculations 1146 may be achieved by either deterministic or blind adaptive techniques. The calculations may be performed by one or more WTs, or alternatively, by at least one WWAN terminal. Cooperative beamforming weights may be provided to achieve at least one form of array processing benefit, including diversity combining, interference cancellation, and spatial reuse.

Figure 5A illustrates a functional embodiment of the invention that may be implemented by hardware and/or software. A plurality of transmitted WWAN signals are received 1150 by a plurality of WTs. Baseband (or IF) WWAN information is derived 1151 from the received WWAN signals. For example, in an OFDM system, a baseband WWAN signal s_k received by a kth WT can be represented by a linear superposition of up to M transmitted data symbols d_i $\{i = 1,...,M\}$ weighted by complex channel weights α_{ik}:

$$s_k = \sum_{i=1}^{M} \alpha_{ik} d_i + \eta_k$$

Baseband WWAN signals (which typically include the complex channel weights α_{ik}), are optionally transmitted 1158 into a WLAN for distribution to one or more other WTs. Accordingly, data (including baseband WWAN signals s_k, complex channel weights α_{ik},

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and/or MIMO weights β_{il}) from the one or more other WTs is received 1152 from the WLAN. MIMO processing 1153 may be performed to produce at least one set of MIMO weights β_{il} and/or estimated transmitted data symbols d_i, which may optionally be transmitted 1159 to at least one other WT via the WLAN. Baseband information recovery 1154 may optionally be performed on the estimated transmitted data symbols d_i. For example, baseband operations may include despreading, demodulation, error correction (e.g., channel decoding), demultiplexing, de-interleaving, data formatting, etc.

Figure 5B illustrates an alternative functional embodiment of the invention that may be implemented by hardware and/or software. In this case, WWAN baseband information that does not include MIMO weights may be received 1155 from at least one other WT via the WLAN. Thus, MIMO processing 1153 includes generating MIMO weights, which may be transmitted 1159 to one or more WTs via the WLAN. The functional embodiment illustrated in Figure 5B is particularly applicable to a WT functioning as a computer-processing terminal in a WLAN group. In the case where the subject WT functions as the only MIMO-processing terminal in a given WLAN group, the functional embodiment may be characterized solely by steps 1155, 1153, 1154, and optional step 1159. Furthermore, the functional embodiments described herein may be adapted to perform other array-processing operations in addition to, or instead of, MIMO.

Figure 6A illustrates functional and apparatus embodiments of the present invention pertaining to one or more WTs, such as WT 1109. In particular, a WWAN interface 1161 may be coupled to a beam-forming system 1162, which is coupled to a WLAN interface 1163. The beam-forming system 1162 may employ data received from the WLAN interface 1163 (and optionally, from data received from the WWAN interface 1161) to perform beam-forming operations. The WLAN interface 1163 is adapted to provide WLAN data communications with at least one other WT (not shown). The beam-forming system 1162 may be adapted to provide either or both WWAN transmission beam-forming and reception beam-forming operations.

Figure 6B illustrates a preferred embodiment of the invention that may be employed as either or both apparatus and functional embodiments. A WWAN interface 1161 includes an RF front-end 1611, a DAC/ADC module 1612, a pulse-shaping filter 1613, a modulator/demodulator module 1614, an equalizer modulator 1615 that

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optionally employs pre-equalization means, a multiplexer/ demultiplexer module 1616, and a baseband-processing module 1617. The WWAN interface may also include a network-control module 1618 that may be responsive to both WWAN control signaling and WLAN-control signals configured to convey WWAN control information to the WWAN interface 1161.

A WLAN interface 1163 includes an RF front-end 1631, a DAC/ADC module 1632, a pulse-shaping filter 1633, a modulator/demodulator module 1634, an equalizer modulator 1635 that optionally employs pre-equalization means, a multiplexer/ demultiplexer module 1636, and a baseband-processing module 1637. A beam-forming module 1162 is adapted to process signals from either or both baseband modules 1617 and 1637. The beam-forming module 1162 may be adapted to process local data symbols generated by a local data source 1160.

As described previously, the beam-forming module 1162 may be adapted to perform beam-forming operations on baseband WWAN signals received from either or both the WWAN interface 1161 and the WLAN interface 1163. Specifically, the beam-forming module 1162 may be adapted to perform beam forming by utilizing baseband WWAN signals, channel weights (or other channel-characterization information), beam-forming weights (such as MIMO weights), and/or baseband data symbols. Baseband data symbols may be received from the local data source 1160, from local data sources on other WTs, and/or from estimated data generated by one or more external beam-forming modules (e.g., beam-forming modules on other WTs). Optionally, the beam-forming module 1162 may be configured to adjust equalization and/or pre-equalization 1615.

In an exemplary embodiment of the invention, the beam-forming module 1162 is configured to process baseband WWAN signals received from the baseband-processing module 1617 and the WLAN interface 1163. Information output from the beam-forming module 1162 is conveyed to at least one of the WLAN interface 1163 and a local data sink 1169. Estimated WWAN data symbols output by the beam-forming module 1162 may optionally be processed by the baseband-processing module 1617 or the local data sink 1169. For example, the baseband-processing module 1617 may be configured to perform various types of signal processing, including error correction (such as Viterbi decoding), constellation mapping, and data formatting on data output by the beam-

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forming module 1162. The resulting processed data may then be coupled to the local data sink 1169 and/or the WLAN interface 1163. Alternatively, the local data sink 1169 may perform the previously described signal-processing types.

Beam forming is performed cooperatively with other WTs to provide predetermined WWAN spatial processing for transmitted and/or received WWAN signals. Thus, a network-function adapter 1165 may be employed to provide WWAN channel-access information to one or more WTs. For example, some embodiments of the invention require multiple WTs to function as a single WT. In this case, each WT is provided with WWAN-access information corresponding to the single WT it is configured to spoof. The network function adapter 1165 may be configured to generate WWAN-access information to be distributed to at least one other WT and/or it may be configured to receive WWAN-access information from the WLAN interface 1163 and convey it to the network-control module 1618 in the WWAN interface 1161.

WWAN-access information typically includes channelization (or some other form of multiple access) information used to transmit and/or receive data from the WWAN. For example, WWAN-access information may take the form of user identification sequences, assigned time slots, frequency band assignments, and/or multiple-access code assignment.

In some embodiments of the invention, a particular WT may be required to function as multiple WTs. In this case, WWAN-access information is conveyed to the network-control module 1618 and data is configured to be appropriately multiplexed and/or demultiplexed relative to a plurality of multiple-access channels.

The network-function adapter 1165 may be used to convey other WWAN control information to WTs, including (but not limited to) power-control commands, timing and synchronization information, key-exchange messages, WWAN routing tables, acknowledgements, requests for retransmission, probing signals, and paging messages. The network-function adapted 1165 may be configured to alter or adapt the WWAN-control information that it receives from either or both the WWAN interface 1161 and the WLAN interface 1163. For example, WWAN power-control commands received by one or more WTs may be adapted by the network-function adapter 1165 prior to being conveyed to network-control modules (such as network-control module 1618) on

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multiple WTs. Power control may be adapted by one or more network-function adapters 1165 for particular WTs depending on their WWAN channel quality and power. Alternatively, the network-function adapter 1165 may adapt the number M of WTs servicing a given link in response to WWAN control information.

In some embodiments of the invention, it may be advantageous to employ a single decision system for network-function adaptation 1165. In one mode of operation, the network-function adapter 1165 of only one of a plurality of WTs assigned to a particular WWAN channel is adapted to convey WWAN control information to the other WTs. In each of the other WTs, the associated network-function adapter 1165 identifies the WWAN control information received from the WLAN and couples it to the network-control module 1618. Thus, the network-function adapter 1165 may instruct the network-control module 1618 to disregard one or more types of WWAN control information received from the WWAN interface 1161. One or more network-function adapters (such as network-function adapter 1165) may synchronize WT responses to WWAN control information.

In another embodiment of the invention, each WT may be responsive to WWAN control information that it receives. In yet another embodiment, each of a plurality of WWAN multiple-access channels is preferably controlled by a separate network-function adapter 1165. These and other adaptations and permutations of network function may be embodied by functional aspects of the network-function adapter 1165.

One embodiment of the invention employs the functionality of a group of WTs corresponding to Figure 1C with respect to the transceiver embodiment shown in Figure 6B. In a transmission configuration, a serial data stream $s(n)$ from the local data source 1160 of a particular WT is channel coded to produce coded data stream $u(n)$, which is grouped in blocks of size N: $\boldsymbol{u}(i) = [u(iN), u(iN+1),\ldots, u(iN+N-1)]^{T}$. In this case, N is chosen to equal the number M of WTs employed as antenna elements. The N-1 coded data symbols $u(n)$ are distributed to the other N-1 WTs via the WLAN interface 1163.

At each WT's Mux/DeMux block 1615, a particular data symbol $u(n)$ is mapped into a frequency bin vector. In one aspect of the invention, each data symbol $u(n)$ is provided with both a unique frequency bin and a unique WT, such as to achieve optimal diversity benefits. This takes the form of a frequency-bin vector having all zeros except

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for one bin corresponding to $u(n)$. This scheme can be used to achieve low transmitted PAPR, as well as other benefits. In other embodiments, alternative WT/frequency-bin combinations may be employed. For example, multiple serial data streams $s(n)$ may be provided to the frequency-bin vector. Redundant symbols may be provided. Alternatively, the data $s(n)$ may be spread across frequencies and/or WTs.

At each Mod/DeMod block 1614, an IFFT is applied to each data block to produce:

$$\tilde{u}(i) = F^H u(i)$$

where F is the $N \times N$ FFT matrix with $F_{nm} = N^{-1/2}\exp(-j2\pi nm/N)$. A cyclic prefix of length N_{CP} may be inserted in $\tilde{u}(i)$ to produce $\tilde{u}_{CP}(i) = \beta T_{CP}\tilde{u}(i)$, which has length $N_T = N+N_{CP}$. The term $\boldsymbol{T}_{CP} = [\boldsymbol{I}_{CP}{}^T \boldsymbol{I}_N{}^T]^T$ represents the cyclic prefix insertion in which the last N_{CP} rows of the $N \times N$ identity matrix $\boldsymbol{I}_N$ (denoted by $\boldsymbol{I}_{CP}$) are concatenated with identity matrix $\boldsymbol{I}_N$. The term β is the power loss factor, $\beta = \sqrt{N/N_T}$.

The block $\tilde{u}_{CP}(i)$ is serialized to yield $\tilde{u}_{CP}(n)$, which is then pulse shaped 1613, carrier modulated 1612, amplified, and transmitted 1611 via multiple antenna elements through a channel. The channel impulse response $h(n)$ includes the effects of pulse shaping, channel effects, receiver filtering, and sampling.

In a receiver configuration of the invention, each of a plurality of WTs is adapted to receive a different transmitted symbol on a different orthogonal carrier frequency. For a WT employing a square-root Nyquist receive filter, the received samples are expressed by:

$$x(n) = \tilde{u}_{CP}(n) * h(n) + v(n)$$

where $v(n)$ is additive white Gaussian noise (AWGN). The received samples are grouped into blocks of size N_T: $x_{CP}(i) = [x(iN_T), x(iN_T+1),\ldots, x(iN_T+N_T-1)]^T$. The first N_{CP} values of $x_{CP}(i)$ corresponding to the cyclic prefix are discarded, which leaves N-length blocks expressed by: $x(i) = [x(iN_T+N_{CP}), x(iN_T+ N_{CP}+1),\ldots, x(iN_T+N_T-1)]^T$. H is defined as an $N \times N$ circulant matrix with $\tilde{H}_{n,m} = h((n-m)_{\bmod N})$. The block input-output relationship is expressed as: $\tilde{x}(i) = \beta\tilde{H}\tilde{u}(i) + \tilde{\eta}(i)$, where $\tilde{\eta}(i) = [v(iN_T+N_{CP}), v(iN_T+ N_{CP}+1),\ldots, v(iN_T+N_T-1)]^T$ is the AWGN block. Applying the FFT to $\tilde{x}(i)$ yields:

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$$x(i) = F\tilde{x}(i) = \beta F\tilde{H}F^H u(i) + \tilde{\eta}(i)$$
$$= \beta D_H u(i) + \eta(i)$$

where

$$D_H = diag\left[H\left(e^{j0}\right), H\left(e^{j(2\pi/N)}\right), \ldots H\left(e^{j(2\pi(N-1)/N)}\right)\right] = F\tilde{H}F^H$$

and $H(e^{j2\pi f})$ is the frequency response of the ISI channel; $H\left(e^{j2\pi f}\right) = \sum_{n=0}^{N_{CP}} h(n)e^{-j2\pi fn}$. An equalizer followed by a decoder uses $x(i)$ to estimate the data symbols encoded on $u(i)$.

Preferred embodiment of the invention may employ Spread-OFDM, which involves multiplying each data block $s(n)$ by a spreading matrix A:

$$u(n) = As(n)$$

In the case where CI spreading codes are employed, $A_{nm} = \exp(-j2\pi nm/N)$. This maps the data symbols to pulse waveforms positioned orthogonally in time. This choice of spreading codes also gives the appearance of reversing the IFFT. However, the resulting set of pulse waveforms is a block, rather than a sequence, wherein each waveform represents a cyclic shift within the block duration T_s, such as described in U.S. Pat. Appl. Pubs. 20030147655 and 20040086027, which are both incorporated by reference.

Figure 7A illustrates a functional embodiment of the invention related to calculating MIMO weights in a cooperative-beamforming network. A plurality of WTs provide received baseband information from a WWAN channel 1701 that includes a training sequence and/or a data sequence having a predetermined constellation of values. WWAN MIMO processing is performed 1702 on the received baseband information to derive a plurality of array-processing weights β_i, which are then distributed 1703 via the WLAN to a predetermined plurality of WTs.

Figure 7B illustrates a functional embodiment of the invention adapted to calculate transmitted data symbols received by a cooperative-beamforming network. A plurality of WTs provide received baseband information from a WWAN channel 1701 that includes a data sequence having a predetermined constellation of values. WWAN MIMO processing may be performed 1704 on the received baseband information to derive a plurality of estimated data symbols d_i, which are then conveyed 1705 via the WLAN to at least one destination WT. The WWAN MIMO processing 1704 may

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optionally include providing for any of a set of signal-processing operations, including filtering, demodulation, demultiplexing, error correction, and data formatting.

Figure 8A illustrates a functional embodiment for a method and apparatus of the invention. Specifically, a data source 1800 is adapted to distribute a plurality of data symbols via a WLAN channel 199 to a plurality N_t of WTs 1806.1-1806.N_t, which are adapted to transmit the data symbols into at least one WWAN channel 99. Although the functional embodiment shown in Figure 8A is illustrated with respect to uplink WWAN functionality, the functional blocks may alternatively be inverted to provide for downlink WWAN functionality.

The data source and the WTs 1806.1-1806.N_t include appropriate WLAN-interface equipment to support distribution of the data symbols to the WTs 1806.1-1806.N_t. For example, the WTs 1806.1-1806.N_t are shown including WLAN-interface modules 1801.1-1801.N_t. The WLAN channel 199 may optionally include additional network devices that are not shown, such as routers, access points, bridges, switches, relays, gateways, and the like. Similarly, the data source 1800 and/or the WTs 1806.1-1806.N_t may include one or more said additional network devices. The data source 1800 may include at least one of the WTs 1806.1-1806.N_t.

A coder 1803.1-1803.N_t in each of the WTs 1806.1-1806.N_t is adapted to receive a baseband data sequence from the associated WLAN-interface module 1801.1-1801.N_t and provide coding, such as channel coding, spreading, and/or multiple-access coding. A coded data sequence output from each coder 1803.1-1803.N_t is mapped into frequency bins of multicarrier generators, such as IDFTs 1804.1-1804N_t. This embodiment may be employed to produce multicarrier signals or to synthesis single-carrier signals from a plurality of spectral components. Alternatively, other types of multicarrier generators may be employed, such as quadrature-mirror filters or DSPs configured to perform other transform operations, including Hadamard transforms. The resulting multicarrier signals are coupled into the WWAN channel 99 by associated WWAN-interface modules 1805.1-1805.N_t.

For each flat-fading subcarrier frequency channel, the WWAN channel may be characterized by channel responses 1890.1-1890-N_t and 1899.1-1899-N_t of a mixing system. The channel responses 1890.1-1890-N_t and 1899.1-1899-N_t represent elements of

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H, an $N_r \times N_t$ channel-response matrix that characterizes the complex gains (i.e., transfer function, or spatial gain distribution) from the N_t transmission elements to the N_r receive elements; and n_i(n) represents an AWGN contribution having zero mean and zero variance.

There are N_r receiver elements comprising WWAN-interface modules 1815.1-1815.N_r and filter banks, such as DFTs 1814.1-1814.N_r, coupled to at least one MIMO combiner 1810. The MIMO combiner 1810 is adapted to perform any number of signal-processing operations, including decoding received data symbols. In one embodiment of the invention, the MIMO combiner 1810 is adapted to perform diversity combining. In another embodiment of the invention, the MIMO combiner 1810 is adapted to perform spatial (e.g., sub-space) processing. Furthermore, many other applications and embodiments of the invention may be achieved using the functional description (or minor variations thereof) depicted in Figure 8A.

Figure 8B illustrates a functional embodiment of the invention that may be incorporated into specific apparatus and method embodiments. In particular, WWAN signals received from a WWAN channel 99 by a plurality N_r of WTs 1836.1-1836.N_r are conveyed via a WLAN channel 199 to a MIMO combiner 1830.

In this case, WWAN data symbols are encoded by one or more coders (such as coders 1821.1-1821.N_t), impressed on a plurality of subcarriers by IDFTs 1822.1-1822.N_t, and coupled into the WWAN channel 99 by a plurality of WWAN-interface modules 1825.1-1825.N_t. Received WWAN signals may be coupled from the WWAN channel 99 by a plurality N_r of WTs 1836.1-1836.N_r. Each WT 1836.1-1836.N_r includes at least one WWAN-interface module (such as WWAN-interface modules 1831.1-1831.N_r), a filter bank (such as DFTs 1834.1-1834.N_r), and a WLAN-interface module (such as 1835.1-1835.N_r).

WWAN signals received by each WT 1836.1-1836.N_r are converted to a baseband data sequence, separated into frequency components (by the DFTs 1834.1-1834.N_r), and then adapted for transmission into the WLAN channel 99. A MIMO combiner 1830 may be configured to receive WLAN transmissions, recover the frequency components, and perform MIMO processing to generate estimates of the transmitted WWAN data symbols. The MIMO combiner 1830 and/or the WTs 1836.1-

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1836.N_r may be adapted to perform decoding. In one embodiment of the invention, the MIMO combiner 1830 may include one or more of the WTs 1836.1-1836.N_r.

Figure 8C illustrates an embodiment of the invention in which WTs 1836.1-1836.N_r are adapted to perform time-domain (e.g., Rake) processing. Specifically, each WT 1836.1-1836.N_r includes a Rake receiver 1854.1-1854.N_r. The embodiment illustrated in Figure 8C is particularly suited to performing MIMO operations on received direct-sequence signals, such as direct sequence CDMA (DS-CDMA) signals.

Particular embodiments of the invention may be directed toward transmitting and/or receiving any of the well-known types of spread signals. Spread signals include spread-spectrum signals in which a transmitted signal is spread over a frequency band much wider than the minimum bandwidth needed to transmit the information being sent. Spread spectrum includes direct-sequence modulation commonly used in CDMA systems (e.g., cdmaOne, cdma2000, 1xRTT, cdma 1xEV-DO, cdma 1xEV-DV, cdma2000 3x, W-CDMA, Broadband CDMA, and GPS), as well as frequency-domain spreading techniques, such as spread-OFDM, multi-carrier CDMA, and multi-tone CDMA.

In a DS-CDMA system, a kth WWAN transmission signal $s^k(t)$ that includes N code bits $\{b^k[n]\}_{n=1}^{N}$ is given by:

$$s^k(t) = \sum_{n=0}^{N-1} b^k[n] g_{T_b}(t - nT_b) g_\tau(t) a^k(t - iT_b) \cos(2\pi f_c t)$$

where $a^k(t) = \sum_{i=0}^{G-1} C_i^k g_{T_c}(t - iT_c)$, $C_i^k \in \{-1,1\}$ is the DS spreading signal, G represents processing gain, T_c is the chip duration, T_b is the bit duration, and $g_{T_c}(t)$, $g_{T_b}(t)$, and $g_\tau(t)$ represent the chip, bit, and transmitted pulse shapes, respectively.

A plurality M of WTs linked together by a WLAN comprises elements of an M-element antenna array capable of receiving $K \le M$ transmission channels. In a frequency-selective channel, the received signal at the array is:

$$r(t) = \sum_{k=1}^{K} \sum_{l=0}^{L^k-1} \sum_{n=0}^{N-1} \alpha_l^k \vec{V}(\vartheta_l^k) b_k[n] g(t - \tau_l^k - nT_b) \cos(2\pi f_c t + \varphi_l^k) + \upsilon(t)$$

where $\vec{V}(\vartheta)$ is an array-response vector, K is the number of received transmission channels, L^k is the number of distinct fading paths corresponding to the kth user, α_l^k is the

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fade amplitude associated with path l and user k, $\varphi_l^k = U[0,2\pi]$ represents the associated fade phase, τ_l^k is the path time-delay (which occurs below a predetermined duration threshold T_{max}), and ϑ_l^k denotes angle of arrival. The array response vector $\vec{V}(\vartheta)$ is expressed by:

$$\vec{V}(\vartheta) = \begin{bmatrix} 1 & e^{-2\pi d_1 \cos\theta/\lambda} & \dots & e^{-2\pi d_{M-1}\cos\theta/\lambda} \end{bmatrix}$$

where d_m is the antenna separation, and λ is the wavelength corresponding to carrier frequency f_c. For a jth user's l^{th} path, the nth bit at the beamformer output is given by:

$$z_l^j[n] = W^H(\vartheta_l^k)\int_{+(n-1)T_b}^{+nT_b} r(t)\cos(2\pi f_c t + \varphi_l^j)a^j(t-\tau_l^j-(n-1)T_b)dt$$

where $W(\vartheta_l^k)$ is the weighting vector of the beamforming system. $z_l^k[n]$ can be expressed by four components:

$$z_l^k[n] = S_i^j[n] + ISI_i^j[n] + IXI_i^j[n] + \upsilon_i^j[n]$$

where S is the desired signal, ISI is inter-symbol interference, IXI is cross interference (i.e., multiple-access interference), and ν is the AWGN contribution. These components can be expressed as follows:

$$S_l^j[n] = \alpha_l^j W^H(\vartheta_l^j)\vec{V}(\vartheta_l^j)b^j[n]G$$

$$ISI_i^j[n] = \sum_{\substack{h=0\\h\neq l}}^{L^k-1}\sum_{n=0}^{N-1}\alpha_l^k W^H(\vartheta_h^j)\vec{V}(\vartheta_l^k)b^j[n]\cos(\varphi_h^j-\varphi_l^j)R_{jj}(\tau_h^j-\tau_l^j-nT_b)$$

$$IXI_i^j[n] = \sum_{\substack{k=1\\k\neq j}}^{K}\sum_{\substack{h=0\\h\neq l}}^{L^k-1}\sum_{n=0}^{N-1}\alpha_l^k W^H(\vartheta_h^k)\vec{V}(\vartheta_l^j)b^j[n]\cos(\varphi_h^k-\varphi_l^j)R_{kj}(\tau_l^j-\tau_h^k-nT_b)$$

$$\upsilon_l^j[n] = \int_{+(n-1)T_b}^{+nT_b} W^H(\vartheta_l^j)n(t)a^j(t-\tau_l^j)\cos(2\pi f_c t+\varphi_l^j)dt$$

where $W^H(\vartheta_l^j)\vec{V}(\vartheta_l^j)$ represents the spatial correlation, φ_l^j and τ_l^j are the random phase and time delay for the jth user's l^{th} path, G is the processing gain, and R_{jj} and R_{kj} are the partial auto-correlation and cross-correlation of the direct sequence code(s):

$$R_{kj}(\tau) = \int_\tau^T a^k(t)a^j(t-\tau)dt$$

Maximal ratio combining produces an output:

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$$z^j[n] = \sum_{l=0}^{L-1} \alpha_l^j z_l^j[n]$$

which can be processed by a decision processor. In this case, the BER is given by:

$$P_e = \int_0^\infty Q(2r_o) f(r_o \mid \bar{r}_o) dr_o$$

where $\bar{r}_o$ is the mean value of the instantaneous SINR, r_o, and $Q(\ )$ represents the complementary error function.

It should be appreciated that the WTs may be adapted to perform either or both time-domain (e.g., Rake) or frequency-domain processing as part of a receiver operation. Signals received by a plurality of WTs may be combined with respect to any combining technique, including EGC, MRC, Minimum Mean Squared Error Combining, other types of optimal combining, Successive Interference Cancellation, and other matrix-reduction/matrix diagonalization techniques. Array-processing operations may include combinations of local and global processing. For example, diversity combining may be performed at each multi-element WT. Then signals from each WT may be combined (e.g., in a central processor) to perform sub-space (e.g., directional) processing. Other combinations of local and global processing may be employed. Similarly, combinations of sub-space processing (i.e., capacity enhancement) and diversity combining (i.e., signal-quality enhancement) may be performed. It should also be appreciated that the WTs may be adapted to perform either or both time-domain and frequency-domain processing for transmission. Thus, appropriate delays or complex weights may be provided to WT transmissions to produce a coherent phase front that converges at a predetermined WWAN destination node.

Figure 9A illustrates an optional transmission embodiment of the present invention. That is, method and apparatus configurations can be inferred from the following descriptions. A data source 1900 is adapted to provide data for processing by an array processor, such as MIMO processor 1902. Optionally, other types of array processors may be provided. A physical (e.g., wired) connection 1902 and/or a wireless connection 1901 couple the data between the data source 1900 and the MIMO processor 1902. The wireless connection 1901 is enabled by a WLAN 1999. The MIMO processor

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1902 is adapted to provide MIMO processing to the data, such as providing complex channel weights, providing spreading weights, and/or providing channel coding.

In one exemplary embodiment of the invention, MIMO processor 1902 provides convolutional or block channel coding to the data, which effectively spreads each data bit over multiple coded data bits. The resulting coded data bits are then grouped in serial blocks by the MIMO processor 1902. Signal-block outputs from the MIMO processor 1902 are provided with serial-to-parallel conversion by the WLAN 1999 (which is denoted by S/P 1914) and distributed to a plurality of WTs 1906.1-1906.M.

Each WT 1906.1-1906.M has a WLAN interface 1907.1-1907.M adapted to receive and demodulate the data received from the MIMO processor 1902. The MIMO processor 1902 is accordingly equipped with a WLAN interface that is not shown. The MIMO processor 1902 is typically comprised of one or more WTs 1906.1-1906.M. In some embodiments of the invention, MIMO processor 1902 may include at least one computer-processing terminal that does have a WWAN interface.

Data received from the MIMO processor 1902 is then modulated 1908.1-1908.M by each WT 1906.1-1906.M for transmission into a WWAN channel by a corresponding WWAN interface 1909.1-1909.M. Modulation 1908.1-1908.M typically includes mapping blocks of data bits to data symbols, which are then mapped to a modulation constellation. Modulation 1908.1-1908.M may also include channel coding and/or data interleaving. In an exemplary embodiment of the invention, modulation 1908.1-1908.M includes the application of complex WWAN channel weights. Such channel weights may optionally be provided by the MIMO processor 1902. In alternative embodiment of the invention, modulators 1908.1-1908.M provide a predetermined delay profile (provided by the MIMO processor 1902) to the data to be transmitted into the WWAN channel.

Figure 9B illustrates a functional flow chart that pertains to transmitter apparatus and method embodiments of the invention. One or more data sources 1920.1-1920.K are coupled via a WLAN 1999 to a plurality M of WTs 1926.1-1926.M. Each WT 1926.1-1926.M includes a WLAN interface 1927.1-1927.M, an array processor (such as a MIMO processor 1926.1-1926.M), and a WWAN interface 1929.1-1929.M.

The data sources 1920.1-1920.K optionally include baseband-processing capabilities, such as channel coding, interleaving, spreading, multiplexing, multiple-

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access processing, etc. The data sources 1920.1-1920.K include WLAN interfaces (not shown). The data sources 1920.1-1920.K may include one or more WTs 1926.1-1926.M.

The WLAN interfaces 1927.1-1927.M include apparatus and means for converting received signals that were formatted for transmission in the WLAN 1999 into baseband data signals. The MIMO processors 1926.1-1926.M are adapted to provide for frequency-domain and/or time-domain MIMO operations on the baseband data signals received from the WLAN interfaces 1927.1-1927.M. Alternatively, the MIMO processors 1926.1-1926.M may be adapted to perform phase operations at WWAN carrier frequencies transmitted by the WWAN interfaces 1929.1-1929.M. The WWAN interfaces 1929.1-1929.M provide any necessary baseband, IF, and RF operations necessary for transmitting data in a WWAN channel.

Figure 10A illustrates software components of a transmission embodiment of the invention residing on a computer-readable memory 1950. An array-processing weighting source-code segment 1951 is adapted to generate a plurality of array-element weights for an antenna array comprised of a plurality of WTs coupled to at least one WWAN. The array-element weights may include at least one of frequency-domain weights (e.g., complex sub-carrier weights) and time-domain weights (e.g., weighted Rake taps). The array-processing weighting source-code segment 1951 is adapted to accept as input at least one of a set of information inputs, including data signals for transmission into the WWAN, training signals (e.g., known transmission symbols) received from the WWAN, data signals (e.g., unknown transmission symbols) received from the WWAN, WWAN channel estimates, and WWAN-control information.

The array-processing weighting source-code segment 1951 is adapted to provide as output at least one of a set of information signals, including WWAN weights and weighted data for transmission into the WWAN (i.e., weighted WWAN data). A WLAN distribution source code segment 1952 is provided for distributing either or both WWAN weights and weighted WWAN data received from source-code segment 1951 to a plurality of WTs via at least one WLAN. The WLAN distribution source code segment 1952 may optionally function to couple at least one of a set of information inputs to the source-code segment 1951, including data signals for transmission into the WWAN (such

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as generated by other WTs), training signals received from the WWAN, data signals received from the WWAN, WWAN channel estimates, and WWAN-control information.

Figure 10B illustrates software components of a receiver embodiment of the invention residing on a computer-readable memory 1960. An array-processing weighting source-code segment 1961 is adapted to generate a plurality of array-element weights for an antenna array comprised of a plurality of WTs coupled to at least one WWAN. The array-element weights may include at least one of frequency-domain weights (e.g., complex sub-carrier weights) and time-domain weights (e.g., weighted Rake taps). The array-processing weighting source-code segment 1961 is adapted to accept as input at least one of a set of information inputs, including training signals (e.g., known transmission symbols) received from the WWAN, data signals (e.g., unknown transmission symbols) received from the WWAN, WWAN channel estimates, and WWAN-control information.

The array-processing weighting source-code segment 1961 is adapted to provide as output at least one of a set of information signals, including WWAN weights, weighted received WWAN data for transmission into the WLAN (i.e., weighted received WWAN data), weighted WWAN data received from a plurality of WTs connected by the WLAN and then combined (i.e., combined weighted WWAN data), and estimates of said combined weighted WWAN data. A WLAN distribution source code segment 1962 is provided for distributing at least one of a set of signals (including the WWAN weights, the weighted received WWAN data, the combined weighted WWAN data, and the estimates said combined weighted WWAN data) to a plurality of WTs via at least one WLAN. The WLAN distribution source code segment 1962 may optionally function to couple at least one of a set of information inputs to the source-code segment 1961, including WWAN data signals received by other WTs, training signals received from the WWAN by other WTs, WWAN channel estimates (either of both locally generated and received from other WTs), WWAN-control information, weights received from at least one other WT, and weighted WWAN data received from at least one other WT.

Since software embodiments of the invention may reside on one or more computer-readable memories, the term computer-readable memory is meant to include more than one memory residing on more than one WT. Thus, embodiments of the

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invention may employ one or more distributed-computing methods. In one embodiment of the invention, the computer-readable memory 1950 and/or 1960 further includes a distributed-computing source-code segment (not shown). It will be appreciated that many different types of distributed computing, which are well known in the art, may be performed. The WLAN distribution source code segment 1952 and/or 1962 may be adapted to provide for synchronizing transmitted and/or received WWAN signals.

Embodiments of the invention described herein disclose array-processing methods (including software implementations) and apparatus embodiments employed in a WWAN and coordinated between a plurality of WTs connected via at least one WWAN. WTs in a WLAN group typically share the same WWAN access. However, some embodiments of the invention provide for WTs with access to different WWANs. Furthermore, one or more WTs may have access to a plurality of WWANs and WWAN services. In some cases, one or more WTs may not be configured to access any WWAN.

In some embodiments of the invention, the computer-readable memory 1950 and/or 1960 further includes a WLAN setup source-code segment (not shown) capable of establishing and/or dynamically reconfiguring at least one WLAN group. For example, WTs may convey location information (e.g., GPS) and/or signal-strength information (e.g., in response to a WLAN probing signal) to the WLAN setup source-code segment (not shown). The WLAN setup source-code segment (not shown) may reside on one or more of the WTs and/or at least one WWAN terminal, such as a cellular base station.

The WLAN setup source-code segment (not shown) may provide one or more WLAN group configuration functions, including determining the number of WWAN-enabled WTs, the total number of WTs in the WLAN group, which WTs are active (and inactive), which WTs are in the WLAN group, and selecting which WT(s) has (have) network-control functionality. The WLAN setup source-code segment (not shown) may be adapted to perform WWAN channel quality analysis functions, including determining WWAN link performance (relative to one or more WTs) from training sequences or pilot signals, performing WWAN-channel estimation, receiving link performance or channel estimates from the WWAN, and performing channel-quality calculations (e.g., SNR, BER, PER, etc.).

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The WLAN setup source-code segment (not shown) may select which WTs are WWAN-enabled based on one or more criteria points, including WWAN link performance, WLAN link performance, required transmission and/or reception needs (e.g., the number of WLAN-group WTs requesting WWAN services, the types of WWAN services required, individual and total throughput, required signal-quality threshold, and WWAN bandwidth available to the WLAN group), computational load, WLAN capacity, power-consumption load, diversity gain, and interference mitigation.

The WLAN distribution source code segments 1952 and 1962 may be adapted to route WWAN channel-access information to the WTs. For example, WWAN channel-access information can include multiple-access information (e.g., multiple-access codes, frequency bands, time slots, spatial (or sub-space) channels, etc.), power control commands, timing and synchronization information, channel coding, modulation, channel pre-coding, and/or spread-spectrum coding.

Figure 11 shows a WWAN comprising a WWAN access point (e.g., a base station) 2120 and a local group 2100 comprising a plurality of wireless terminals (WTs) 2101-2104 communicatively coupled together via a WLAN 2105. A network-management operator 2106 is configured to handle WWAN-control operations within the local group 2100. In an exemplary embodiment, the network-management operator 2106 is coupled to at least one of the WTs 2101-2104 (e.g., WT 2103). One or more of the WTs 2101-2104 may be configured to transmit and/or receive WWAN communication signals, such as WWAN traffic channels 2110 and WWAN control messages 2111. Signals in the WWAN traffic channels 2110 may be processed by one or more of the WTs 2101-2104, which may include at least one local area network controller (e.g., 2103). The WWAN control messages 2111 are processed by the network-management operator 2106.

In an exemplary embodiment of the invention, a target WT (e.g., WT 2104) communicates with one or more WTs in the local group 2100 via the WLAN 2105, and the local group 2100 is configured to communicate with the base station 2120 via the WWAN. More specifically, one or more of the WTs 2101-2104 may be configured to participate in WWAN communications at any particular time. The target WT 2104 may communicate with the network controller (e.g., WT 2103), which is configured to

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communicate with other WTs in the local group 2100. The network controller 2103 typically oversees network control functions in the local area network. Alternatively, the target WT 2104 may function as a local area network controller. A particular WT may determine which WTs to use for transmitting and/or receiving signals in the WWAN based on local area network criteria, as well as WWAN-related criteria. Local area network control and/or WWAN control functionality may be distributed between one or more WTs in the local group.

In Figure 12, a communication system comprises a plurality *M* of WTs 2209.1 – 2209.M communicatively coupled together in a WLAN, which comprises a WLAN controller 2206. A WWAN network-management operator 2210 is communicatively coupled to the WLAN controller 2206. WWAN network-management operator 2210 is configured for cooperatively processing WWAN-control messages for the WTs 2209.1 – 2209.M, each of which comprises at least one WWAN interface 2201.1 – 2201.M, respectively.

According to one aspect of the invention, the WWAN interfaces 2201.1 – 2201.M receive WWAN control messages from the WLAN that were processed by the WWAN network-management operator 2210 and transmit those messages into the WWAN. According to another aspect of the invention, the WWAN interfaces 2201.1 – 2201.M receive WWAN control messages from the WWAN and couple those messages through the WLAN to the WWAN network-management operator 2210. According to yet another aspect of the invention, one or more WTs functions as the WWAN network-management operator 2210. Thus, the WWAN network-management operator 2210 may comprise one or more WWAN interfaces and be configured to transmit WWAN control messages into the WWAN.

For the purpose of the present disclosure, a WWAN comprising a plurality of wireless terminals communicatively coupled together via a WLAN may be defined as one or more of the following system configurations:

- A plurality of WTs in a local group configured to receive from a base station a signal intended for at least one WT.

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- A plurality of WTs in a local group configured to receive from a base station a plurality of signals modulated on interfering (e.g., common) channels and intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a base station a plurality of signals modulated on different non-interfering channels and intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a plurality of base stations a signal modulated on a common channel intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a plurality of base stations a signal redundantly modulated on a plurality of different channels intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a plurality of base stations a plurality of signals modulated on interfering channels and intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a plurality of base stations a plurality of signals modulated on different non-interfering channels and intended for at least one WT.
- A plurality of WTs in a local group configured to transmit to a base station a signal originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a base station a plurality of signals modulated on interfering (e.g., common) channels originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a base station a plurality of signals modulated on different non-interfering channels originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a plurality of base stations a signal modulated on a common channel originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a plurality of base stations a signal redundantly modulated on a plurality of different channels originating from at least one WT.

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- A plurality of WTs in a local group configured to transmit to a plurality of base stations a plurality of signals modulated on interfering channels originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a plurality of base stations a plurality of signals modulated on different non-interfering channels and originating from at least one WT.
- A plurality of WTs in a first local group configured to receive from a second local group a signal intended for at least one WT in the first local group.
- A plurality of WTs in a first local group configured to receive from a second local group a plurality of signals modulated on interfering channels and intended for at least one WT in the first local group.
- A plurality of WTs in a first local group configured to receive from second local group a plurality of signals modulated on different non-interfering channels and intended for at least one WT in the first local group.
- A plurality of WTs in a first local group configured to transmit to a second local group a signal originating from at least one WT in the first local group.
- A plurality of WTs in a first local group configured to transmit to a second local group a plurality of signals modulated on interfering channels and originating from at least one WT in the first local group.
- A plurality of WTs in a first local group configured to transmit to a second local group a plurality of signals modulated on different non-interfering channels and originating from at least one WT in the first local group.
- A base station comprising a plurality of WTs in a base station local group configured to transmit a signal intended for at least one subscriber WT not in the base station local group.
- A base station comprising a plurality of WTs in a base station local group configured to transmit a plurality of signals modulated on interfering (e.g., common) channels and intended for at least one subscriber WT not in the base station local group.
- A base station comprising a plurality of WTs in a base station local group configured to transmit a plurality of signals modulated on different non-interfering channels and intended for at least one subscriber WT not in the base station local group.

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- Multiple base stations comprising at least one base station local group configured to transmit a signal modulated on a common channel intended for at least one WT.
- Multiple base stations comprising at least one base station local group configured to transmit to a plurality of WTs a signal redundantly modulated on a plurality of different channels intended for at least one WT.
- Multiple base stations comprising at least one base station local group configured to transmit to a plurality of WTs a plurality of signals modulated on interfering channels and intended for at least one WT.
- Multiple base stations comprising at least one base station local group configured to transmit to a plurality of WTs a plurality of signals modulated on different non-interfering channels and intended for at least one WT.
- A base station comprising a plurality of WTs in a base station local group configured to receive a signal originating from at least one WT.
- A base station comprising a plurality of WTs in a base station local group configured to receive a plurality of signals originating from at least one WT and modulated on interfering channels.
- A base station comprising a plurality of WTs in a base station local group configured to receive a plurality of signals modulated on different non-interfering channels and originating from at least one WT.
- Multiple base stations comprising at least one base station local group configured to receive a signal modulated on a common channel originating from at least one WT.
- Multiple base stations comprising at least one base station local group configured to receive a signal redundantly modulated on a plurality of different channels originating from at least one WT.
- Multiple base stations comprising at least one base station local group configured to receive a plurality of signals modulated on interfering channels and originating from at least one WT.
- Multiple base stations comprising at least one base station local group configured to receive a plurality of signals modulated on different non-interfering channels and originating from at least one WT.

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A WWAN network-management operator may include a single WT or a plurality of WTs. In one embodiment, the WWAN network-management operator includes a single WT communicatively coupled to the WWAN and configured to perform WWAN-control operations for one or more WTs in the local group. For example, a block diagram of a WT 2300 shown in Figure 13 comprises a WWAN network-management operator module 2302 communicatively coupled to a WWAN interface 2301 and a WLAN interface 2303. In another embodiment, the WWAN network-management operator may comprise WWAN network-management operator modules residing in a plurality of WTs. Thus, the WWAN network-management operator may be configured to transmit and/or receive WWAN-control parameters in the WWAN on behalf of one or more WTs in the local group. A local area network controller may also include a WWAN network-management operator module and may perform WWAN network management for one or more WTs in the group.

Each WT may function as its own network-management operator. For example, a WT functioning as its own network-management operator may be communicatively coupled to the WWAN and configured to transmit and receive WWAN control information directly with the WWAN, whereas traffic-channel processing may be performed in cooperation with one or more other WTs in the local group. In another exemplary configuration, WWAN control information may be coupled from a target WT (e.g., a source or destination WT relative to the subject information, i.e., the WWAN control information) to a relay WT communicatively coupled to the WWAN and configured to transmit and receive the target WT's WWAN control information. While the target WT functions as its own network-management operator, it may employ other WTs in the local group to transmit and receive WWAN control messages. Thus, the relay WT may merely function as a pass through having optional added physical-layer adjustments for the WWAN control information. The physical-layer adjustments may be used to condition the WWAN control messages for the WWAN channel and/or the WLAN channel. Similarly, a WT functioning as a network-management operator for itself and/or at least one other WT may employ one or more WTs in the local group for transmitting and receiving WWAN control messages in the WWAN.

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In another embodiment, a WT may function as a network-management operator for one or more other WTs. For example, a network controller may function as a network-management operator for at least one other WT. In another embodiment, at least one WT that is neither a network controller nor a target WT may function as the network-management operator. For example, a WT having the best WWAN channel (such as may be determined by any of a variety of signal quality criteria that are well known in the art) may be selected as the network-management operator. Various criteria for selecting WTs for network-management operator responsibilities may be implemented, including load balancing.

In another embodiment of the invention, a plurality of WTs in a local group may simultaneously function as a network-management operator. The network-management operator may comprise multiple WTs including a target WT, multiple WTs including a network controller, multiple WTs not including a network controller, or multiple WTs not including a target WT. A plurality of WTs may redundantly process WWAN control messages. Alternatively, each of a plurality of WTs configured to perform WWAN-control operations may be configured to perform a predetermined subset of the WWAN-control operations.

A network-management operator may participate in any combination of various WWAN-control operations, including power control, data-rate control, session control, authentication, key exchange, paging, control-channel monitoring, traffic channel request, channel assignment, error detection, acknowledgement, request for retransmission, identification, reconnects, synchronization, flow control, request for service from a particular sector or access point, hand-off.

Figure 14 is a flow diagram of a communication method configured in accordance with an aspect of the invention. A WLAN is employed for sharing WWAN control information between a group of WTs 2401. WWAN control information is coordinated between the group of WTs and the WWAN 2402, and WWAN control information is cooperatively processed by the group 2403.

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The Open Systems Interconnection Reference Model (OSI Reference Model) may be used to describe the function of a WWAN comprising a local group of a plurality of WTs communicatively coupled together via a WLAN.

In the Application Layer, each WT typically employs its own user applications for accessing network services (e.g., login, data upload, data download, multi-media processing). Thus, each WT handles its own application-layer network access, flow control, and error processing. Each WT controls its own user interface for access to services that support user applications. These applications typically are not subject to cooperative access (e.g., sharing). However, certain network resources (e.g., printers, faxes) may be shared. Some applications, such as computational processing applications, may provide for distributed computing processes between WTs in a network. However, such distributed-computing applications have not been employed in the prior art for receiving and decoding wireless communications.

In the Presentation Layer, each WT may translate data from an application format to a network format and vice-versa. Different data formats from different applications are processed to produce a common data format. Each WT may manage its own protocol conversion, character conversion, data encryption/decryption, and data compression/expansion. Alternatively, a network controller that serves multiple WT may perform one or more presentation-layer functions. For example, data-processing intelligence may be handled by a network controller, and individual WTs may function as dumb terminals. In some multimedia applications, a network controller may function essentially as a media server configured to deliver predetermined data formats to each WT functioning as a media device. Furthermore, there are various degrees of how presentation-layer processing may be shared between WTs and a network controller.

In the Session Layer, each WT may be responsible for identification so only designated parties can participate in a session. Session setup, reconnects, and synchronization processes may be managed by the target WT (e.g., a subscriber, an access point, or a base station), which functions as its own network-management operator for session-layer processing. Alternatively, a network controller may manage session-layer activities for each of one or more WTs in the local group. The network controller

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may store identities for each WT and manage sessions and the flow of information for each WT.

In another embodiment, multiple WTs may participate in session management. Some centralized decision-processing (such as by the target WT or a network controller) may be employed to direct one or more WTs to perform specific session-layer activities. Multiple responsibilities may be divided among the WTs. For example, one WT may conduct synchronization processes and another WT may perform session setup. The WTs assigned to perform particular functions may change with respect to signal quality with the WWAN, load balancing criteria, and/or other considerations.

In the Transport Layer, each WT may convert data streams into packets or predetermined segments. Each WT may also process received packets to reassemble messages. Thus, each WT may perform its own error handling, flow control, acknowledgement, and request for retransmission.

Alternatively, a network controller may manage transport-layer operations for each of one or more WTs in a local group. The network controller may be configured to convert data streams received from the WTs into packets. Similarly, the WT may convert data packets received from the WWAN into data streams that are routed to the appropriate WTs. The network controller may perform common network-management operator functions, including error handling, flow control, acknowledgement, and request for retransmission for each of the WTs.

In yet another embodiment, multiple WTs may be used to convert data streams into packets and/or process received packets to reassemble messages for a particular target WT. Each of a plurality of WTs may process only a portion of the received data stream and perform error handling, flow control, acknowledgement, and request for retransmission for the data it processes. Alternatively, multiple WTs may handle the same data. For example, redundant transport-layer processing may be performed by different WTs having uncorrelated WWAN channels in order to reduce errors, and thus, requests for retransmission. In another embodiment, only one WT may handle transport-layer processing at any given time. For example, a particular WT may be assigned to handle transport-layer processing if it has favorable WWAN-channel conditions. Other criteria,

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such as load balancing, may be used to select and transfer transport-layer processing responsibilities between WTs.

In the Network Layer, WTs may perform their own network-layer processing, such as addressing and routing. A WT, such as a router, a base station, a switch, or a relay may perform network-layer processes, including managing data congestion, adjusting data frames, packet switching, and routing. In addition to managing network-layer control within its local group, a network controller may perform network-layer processes for the WWAN.

The Data Link layer includes a Media Access Control (MAC) sub-layer and the Logical Link Control (LLC) sub-layer. Each WT may perform Data-link processing, such as converting received raw data bits into packets and managing error detection for other WTs. Similarly, each WT may convert data packets into raw data bits for one or more other WTs. In one embodiment, a target WT may perform its own data-link processing. Alternatively, a network controller may perform data-link processing for one or more WTs.

A Physical layer embodiment may provide for performing all physical-layer processes by a target WT. For example, a target WT distributes spread, scrambled baseband data to the other WTs, which then up convert and transmit the target's transmission signal as specified by the target WT. Similarly, each WT may receive and down convert WWAN transmissions and direct the down-converted signal via the WLAN for processing (e.g., descrambling and despreading) by a target WT.

In one embodiment, physical-layer processes may be divided between a target WT and other WTs in a local group. For example, the target WT may convey baseband data and control parameters to other WTs, which then spread and scramble the baseband data with respect to the control parameters. Additional control parameters, such as power control, and data rate control may be specified. Similarly, WTs in a local group may descramble and despread received data for further processing by a target WT. WTs may monitor control channels for signals addressed to any of a plurality of WTs in a local group.

In yet another embodiment, a network controller may perform some or all physical-layer processes corresponding to a target WT. A network controller may

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perform all physical-layer processes for a target WT (and other WTs in the corresponding local group if it performs higher-layer processes for the target WT). Alternatively, some of the higher-layer processes may be performed by the network controller and/or other WTs as part of a distributed computing procedure regardless of how the physical-layer processes are performed.

Several aspects of physical-layer processing include WWAN-control operations. Other WWAN-control operations may fall within any of a plurality of the OSI reference model layers. Embodiments and interpretations of the invention should not be constrained to the limitations of the OSI reference model. The OSI reference model is a generalization that may not be suitable for expressing the implementation of all WWAN-control operations.

In one aspect of the invention, a cellular base station may transmit a probe signal (e.g., a predetermined signal that is ramped in signal power) to a plurality of subscriber WTs. A network-management operator in a local group of WTs may be responsive to the probe signal for indicating a signal power level capable of being received from the base station. Similarly, the signal power level may be used as an indicator for transmit power and/or data rate.

Functions of the network-management operator may be distributed over a plurality of WTs in the local group, and network-management responsibilities may be shared by more than one WT and/or dynamically assigned to particular WTs. For example, a WT that first detects the probe signal may be assigned subsequent network-management responsibilities, such as predicting forward-link SINR and an associated achievable data rate, sending an acknowledgement to the base station, or requesting a particular data rate (e.g., sending a dynamic rate control signal to the base station). In another embodiment of the invention, WWAN signals received by a group of WTs may be combined before being processed by a network-management operator.

In one embodiment of the invention, a network-management operator in a local group performs open loop estimation to adjust reverse link (i.e., local group) transmit power. Alternatively, closed-loop power corrections may involve both the network-management operator and the base station. The network-management operator may send

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an access probe sequence and wait for an acknowledgement from a base station. Initial probe power is typically determined via power control.

A WT in the local group is typically denoted as being in an inactive state relative to the WWAN when it is not assigned a forward traffic channel. However, the network-management operator may assign one or more WWAN traffic channels to WTs that the WWAN considers inactive. In such cases, inactive WTs may help transmit and/or receive WWAN communications intended for active WTs in the local group. Similarly, active WTs may be assigned additional traffic channels by the network-management operator for transmitting and/or receiving WWAN communications intended for other active WTs in the group. Such assignments may be invisible to the WWAN, since so-called inactive WTs are used for connecting active WTs to the WWAN. In other embodiments of the invention, complex assignments, including sharing traffic channels between WTs, may be implemented.

A network-management operator may service one or more WTs in a variable-rate state. For example, a forward traffic channel is transmitted at a variable rate determined by the network-management operator's data rate control value. The network-management operator may determine the maximum data rate using any of a variety of well-known techniques. The network-management operator uses a data rate control channel to instruct the WWAN what data rate to serve to a particular WT in the local group. In response, the base station selects modulation, channel coding, power and/or number of multiple-access slots.

The network-management operator may direct its instructions to the best base station (i.e., the base station having the best channel relative to the local group) in its active set via addressing (e.g., a covering code). Alternatively, the network-management operator may instruct multiple base stations to serve the local group. This may occur when WTs can access more than one WWAN. This may also occur when some WTs are better served by one base station or sector while other WTs in the same local group are better served by a different base station or sector.

A WT enters a fixed-rate state when its network-management operator signals a request for a specific fixed rate from a base station or sector. The WT may transition to a variable rate if it cannot receive packets at the previously requested fixed rate. A

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network-management operator may select a fixed rate if there is an imbalance (e.g., different channel conditions) between the forward and reverse links.

In one aspect of the invention, a network-management operator is configured to perform connection-layer protocols that are typically conducted between a target WT and the base station. For example, the network-management operator may participate in acquisition and initialization state protocols, air link management protocols, connection state protocols, route updates, and/or idle state protocols.

A WT in an inactive state typically awakes from a sleep state periodically to monitor a control channel to receive overhead parameter messages and paging messages. In one aspect of the invention, a network-management operator may wait for an activate command from a default air link management protocol. A network-management operator may monitor a WWAN control channel for multiple WTs in a local group. In an alternative embodiment, WTs in the local group may take turns monitoring the WWAN control channel. In this case, responsibilities of the network-management operator are transferred betweens WTs in the local group. In another embodiment, a plurality of WTs may monitor the WWAN control channel, wherein each WT is configured to monitor the channel for only a subset of WTs in the local group.

In a network determination state, the network-management operator selects a channel on which to acquire a base station for a WT in the local group. After selecting a channel, the network-management operator enters a pilot acquisition state in which the network-management operator tunes to a particular channel and searches for the strongest pilot signal. Upon acquiring a pilot, the network-management operator enters a synchronization state. At this point, the network-management operator may transfer synchronization responsibilities to the target WT. If the network-management operator (or the target WT) is unable to obtain a pilot, it reverts back to the network determination state.

In the synchronization state, the network-management operator or the target WT looks for a sync message on the control channel and sets its clock to the time specified in the sync message. Failure to receive the sync message or similar failures may result in returning to the network determination state.

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The base station undergoes various state transitions in the process of serving the WTs. In an initialization state, the base station activates an initialization state protocol, overhead message protocol, and a control channel MAC protocol. A network-management operator may selectively route certain messages through WTs in a local group comprising the base station while reserving other messages for WWAN transmission only by the base station.

An idle state occurs after the network is acquired, but before an open connection is established. The base station initiates an idle state protocol, overhead messages protocol, route update protocol, control channel MAC protocol, access channel MAC protocol, and forward and reverse channel MAC protocols. In the connected state, base station and the target WT have an open connection until the connection is closed (i.e., goes to the idle state) or network redirection (goes to the initialization state). The base station activates a connected state protocol, overhead messages protocol, route update, control channel MAC protocol, and forward and reverse channel MAC protocols.

A network-management operator may be configured to direct hand offs between WWAN sectors, base stations, and/or networks. In one embodiment, a network-management operator in a local group may measure the SINR on each pilot in an active set (e.g., a set of base stations that actively serve the local group) and request data from the sector having the highest SINR. The network-management operator predicts the SINR for the next packet and request a higher data rate if it can decode it at that SINR. The rate request (which may include data rate, format, and modulation type) is sent by the network-management operator to the appropriate sector using a data rate control channel.

Generally, the network-management operator requests data from only one sector at a time. However, different WTs in a local group serving a particular target WT may request WWAN channels from multiple sectors at a time on identical or different WWAN channels. The network-management operator may coordinate requests for channels from different sectors. Multiple sectors (or base stations) may be configured to serve the same WWAN channel simultaneously. Alternatively, multiple WWAN channels may be used to serve one WT in the group. Although the target WT may have a better connection with a particular base station, the local group as a whole may have a better connection with a different base station. Thus, the network-management operator

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may dictate that the link be established and maintained relative to the group's connection rather than the target WT's connection.

A base-station scheduler may allocate physical channels for WTs. However, a network-management operator in a local group may provide logical channel assignments to the WTs that are invisible to the physical channel operation of the WWAN. Multiple WTs in a local group may utilize a single WT channel, such as for packet switched data communications. Each WT may utilize multiple physical channels, such as when higher data rates are required. The network-management operator may assign logical channels to various physical WWAN channels, and thus, effectively hand off those data channels to other sectors, base stations, or WWAN networks serving those physical WWAN channels.

Data rates requested by WTs may follow a channel fading process, wherein higher data requests occur when channel conditions are favorable and lower rates are requested as the channel degrades. It is well known that when a base station serves a large number of WTs, that diversity of multiple units can mitigate system-wide variations in data rate due to changing channel conditions. Multi-user diversity teaches that the opportunity for serving good channels increases with the number of users, which increases total network throughput.

One embodiment of the invention may provide for a network-management operator that dynamically selects one WT in a local group to communicate with a WWAN at a particular time, even though one or more channels may be served between the base station and the local group. The selection of which WT in the group communicates with the WWAN may change with changing channel conditions between the local group and the base station(s). Thus, the update rate for the dynamic selection may be based on the rate of change of WWAN channel conditions. This embodiment may be adapted for simultaneous communication by multiple WTs and/or the use of multiple base stations and/or WWANs. In another exemplary embodiment, the network-management operator may interleave communications (e.g., packets) across multiple WWAN channels undergoing uncorrelated channel distortions. Similarly, a WWAN specifically configured to interact with a local group may interleave messages across multiple WWAN channels transmitted to the local group. Different WWAN channels

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may be transmitted and received by one base station or a plurality of base stations. This type of interleaving (at either the local group and the base station) may be determined by a network-management operator.

In another embodiment, a network-management operator may be configured to redundantly transmit data symbols over multiple slots or physical channels to reduce transmission power or to allocate more power to data.

A network-management operator may employ an authentication protocol to authenticate traffic between a base station and a MT. For example, a network-management operator may identify a particular WT in a local group to a base station. The base station may then verify that the WT has a legitimate subscription record with a service provider that utilizes the WWAN. Upon verification, the base station allows access to the air interface and the network-management operator (whose responsibilities may be transferred to the WT) signs access channel packets to prove it is the true owner of the session. In one exemplary embodiment of the invention, the WT and/or the network-management operator may use IS-856 Air Interface Authentication.

In one embodiment of the invention, a target WT includes a network-management operator that employs other WTs in its local group to interact with a WWAN. In this case, authentication may be performed only with the target WT. In an alternative embodiment, the network-management operator resides in at least one other WT, such as a network controller. Thus, authentication may be performed with a network-management operator in a single terminal that is configured to perform authentication for more than one WT.

A network-management operator may employ a key exchange protocol (e.g., a Diffie-Hellman algorithm) for exchanging security keys between a WT and a WWAN for authentication and encryption. Typically, there is some predetermined key exchange algorithm used within a particular WWAN. Public values are exchanged and then messages are exchanged between the WT and the WWAN to indicate that the session keys have been correctly calculated. The keys may be used by the WT and the WWAN in an encryption protocol to encrypt traffic.

In one embodiment of the invention, a network-management operator resides on a target WT that accesses the WWAN via multiple WTs in a local group. The network-

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management operator may be configured to encrypt and decrypt WWAN traffic for the target WT without vital security information being made available to WTs other than the target WT. In another embodiment, the network-management operator may reside in a network controller. In this case, the network-management operator may be configured to engage in security protocols for more than one WT in the local group. Network-management operators according to various embodiments of the invention may be configured to participate in security protocols used to provide crypto sync, time stamps, and other elements used in authentication and encryption protocols.

Some aspects provide a multicarrier protocol that controls interference relationships between the carriers. This control enables time domain signal shaping, which provides for low PAPR and adaptability to single-carrier waveforms. Disclosed aspects include Carrier Interferometry (CI).

In CI, subcarrier frequencies are selected to provide a predetermined spectral response. Polyphase codes are applied to each subcarrier to control the time-domain characteristics of the superposition signal, as well as provide for orthogonality between data symbols and/or users. In one aspect, a pulse (i.e., a constructive interference resulting from a zero-phase relationship between the subcarriers) is generated from a superposition of the coded signals. Time-offset replicas of the pulse are used to construct waveforms having a predetermined frequency-domain profile.

An objective may be to enable a communication protocol that provides frequency-diversity benefits of multicarrier modulation to single-carrier systems and provides the low-PAPR benefits of single-carrier modulation to multicarrier communication systems, and the ability to provide the benefits of both systems simultaneously.

Figure 15 illustrates a CI pulse shape characterized by an in-phase alignment (e.g., mode locking) of harmonic subcarriers 1505 at a specific time t_1. A composite signal 1530 results from a superposition (i.e., summation) of the carriers 1505. The composite signal 1530 shows a pulse envelope centered at a predetermined time instant t_1. In the case where there is no amplitude tapering (i.e., a rectangular window) and a plurality N of carriers have a uniform frequency separation f_s, a composite CI signal is:

$$e(t) = \sum_{n=1}^{N} e^{i[(\omega_c + n\omega_s)t + n\Delta\phi]}$$

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which is characterized by an envelope-magnitude function:

$$|e(t)| = \left| \frac{\sin(N(\omega_s t + \Delta\phi)/2)}{\sin((\omega_s t + \Delta\phi)/2)} \right|$$

where ω_c is related to a carrier frequency f_c (or equivalently, an offset frequency $f_o = f_c$) by the relationship $\omega_c = 2\pi f_c$. Similarly, ω_s is related to the separation frequency f_s by the relationship $\omega_s = 2\pi f_s$.

The phase offsets $\Delta\phi$ typically correspond to any of N orthogonal time offsets corresponding to N orthogonal pulse positions. A kth bit or data symbol a_k in a user's transmission s(t) modulated onto a particular CI pulse, or phase space is expressed as:

$$s_k(t) = e(t - kT_b)$$

where T_b is a time offset corresponding to the particular CI pulse. Orthogonal pulses are centered at intervals of $T_b = T_s/N$. A burst of bits or symbols may be transmitted onto a contiguous train of pulses, such as shown in Figure 16B. In this case, a transmission corresponding to a particular user is characterized by the following relationship:

$$s(t) = \sum_{k=1}^{N} a_k e(t - kT_b)$$

The time-shifted pulses are orthogonal to each other even though the pulses overlap in time:

$$\int_0^{T_s} e(t - kT_b) e(t - nT_b) \delta t \quad \underline{\quad} \quad (k \neq n)$$

Figure 16A illustrates an amplitude distribution of the CI carriers corresponding to the pulse train shown in Figure 16B. In some applications of the invention, carriers may be provided with complex weights to generate superposition signals corresponding to a predetermined sequence of code chips or data symbols.

Figure 17A illustrates individual CI pulses provided with code chips or data symbols, such as symbols $\beta_0(k)$ to $\beta_{14}(k)$. A pulse train 1795 shown in Figure 17B corresponds to the modulated pulses shown in Figure 17A.

In time-division multiplexing (e.g., in TDMA), the symbols modulated onto the pulses are typically data symbols corresponding to a particular user. In frequency-division multiplexing (e.g., in OFDM), data symbols corresponding to a particular user

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are modulated onto a pulse train (such as the pulse train shown in Figure 16B) constructed from a predetermined set of carrier frequencies allocated to that user. In direct sequence code division multiplexing (e.g., DS-CDMA) or direct sequence spread spectrum, data-bearing code symbols are modulated onto the pulse train. In coded multicarrier spreading (e.g., MC-CDMA or Spread OFDM), data-bearing code symbols are modulated directly onto the carriers.

The function e(t) is also characterized by an in-phase carrier component $\cos(\omega_c t)$ and a quadrature-phase component $\sin(\omega_c t)$. The in-phase and quadrature-phase components can correspond to N orthogonal pulse positions (i.e., phase spaces) and N pseudo-orthogonal pulse positions, respectively.

The CI signals are periodic with period $T_s = 1/f_s$ for an odd number of carriers N and with period $2/f_s$ for an even number of carriers N. In either case, data symbols of duration T_s are typically modulated onto the carriers (or pulses). The main lobe has duration $2/Nf_s$ and each of the N-2 side lobes has a duration $1/Nf_s$.

In Figure 16A, 20 carrier frequencies are allocated to a particular user and provided with complex weights to generate a train of CI pulse waveforms that convey information. Figure 16B shows 20 pulses orthogonally (and equally) positioned in time corresponding to data transmitted by (or to) that user. Each pulse waveform is a superposition of the 20 carriers provided with phases relative to the orthogonal positions in time. Predetermined sets of phase offsets are provided to the carriers to position the pulses orthogonally in time.

The cross correlation between the real parts of the pulse waveforms is illustrated by the following equation:

$$R_{k,j}(\tau) = \frac{1}{2f_s}\frac{\sin(2\pi N f_s \tau/2)}{\sin(2\pi f_s \tau/2)}\cos\left(\frac{(N-1)}{2}2\pi f_s \tau\right)$$

N equally spaced zeros occur over the time interval $T_s = 1/f_s$ as a result of the sinc-like term in the cross-correlation equation. This corresponds to each pulse waveform being centered at a particular time instant corresponding to a zero crossing (i.e., zero value) of all of the other orthogonal pulse waveforms.

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The cross-correlation equation expresses the Nyquist zero inter-symbol interference criteria. The Nyquist zero inter-symbol interference criteria requires a waveform to have zero crossings corresponding to positions of the other waveforms.

The spacing of the pulse positions (i.e., time instants) corresponds to zeroes in the cross-correlation function. The pulses are centered at equally spaced time instants k/Nf_s, where $k = 0,1,\ldots,N-1$, N is the number of carriers, and $f_s = 1/T_s$ is the frequency separation between the carriers. Thus, the time instants are defined by $0, T_s/N,\ldots, T_s(N-1)/N$.

CI waveforms may be implemented with contiguous or non-contiguous carriers. Contiguous carriers are defined as carriers allocated to one or more users characterized by a frequency separation f_s and symbol duration $T_s = 1/f_s$.

In the OFDM implementation of the invention, each user is provided with a unique set of carrier frequencies to eliminate multiple access interference (MAI). Similar frequency-division multiplexing may be provided to other CI-based transmission protocols to reduce or eliminate MAI. The real part of each user's OFDM transmission is expressed by

$$s(t) = \sum_{k=1}^{N}\sum_{i=1}^{N} a_k \cos\left(2\pi\left(f_c + if_s\right)t + mi2\pi / N\right)g(t)$$

where a_k is a kth data symbol (preferably a channel-coded data symbol) that is then spread over the N carriers allocated to the user. Since each data symbol is spread across all of the carriers, the full frequency diversity benefits of the channel can be achieved. Time interleaving may also be provided.

In one aspect, a received CI-OFDM signal for at least one user is separated into its orthogonal frequency components. Channel compensation (e.g., equalization) and combining are performed to provide estimates of the transmitted symbols. Inter-bit interference may be compensated via any combination of equalization and multi-user detection.

Carrier mixers or a carrier generator, as described herein, includes any type of system, method, or combination thereof adapted to perform at least one of a plurality of functions, including carrier generation, carrier selection, carrier allocation, and modulation. Carrier mixers imply the existence of a carrier generator (e.g., a multicarrier

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generator). Thus, carrier mixers and carrier generator can be equivalent terms as used herein. A carrier generator may include a carrier-mixer circuit. A carrier mixer may include any type of mixer, modulator, or equivalent device adapted to provide carrier selection and/or modulation. Carrier mixers/carrier generators may include local oscillators, harmonic signal generators, digital filters, invertible transform algorithms, quadratic mirror filters, sine wave look-up tables, etc. Carrier mixers may be interpreted as performing frequency-domain processes.

Carrier mixers or carrier generators may employ digital signal processing systems, such as microprocessors, may be employed. Consequently, Fourier transforms, such as DFT-based systems may be employed. For example, an IFFT or IDFT may be employed with one or more weight vectors applied to the frequency bins of the transform. A carrier mixer (or carrier generator) may include a weight-vector selector adapted to select predetermined frequency bins. A weight vector may include zero and non-zero values, such as to provide for carrier selection/allocation. Carrier mixers may include one or more carrier-allocation circuits. A carrier mixer allocates one or more carriers to one or more users. A carrier mixer may provide for modulation of data symbols onto the carriers. A carrier mixer may include a plurality of modulators or a modulator adapted to modulate at least one data symbol onto a plurality of carriers.

In this case, the frequencies of the CI carriers are incrementally spaced by a shift frequency f_s. However, non-uniform spacing of the frequencies may also be used to achieve certain benefits. The carrier frequencies are typically chosen to be orthogonal to each other:

$$\int_0^{T_C} \cos(\omega_i t + \phi_i)\cos(\omega_j t + \phi_j)dt = 0$$

where T_c is the chip duration, ω_i and ω_j are the ith and j^{th} carrier frequencies, and ϕ_i and ϕ_j are arbitrary phases. A signal in the jth frequency band does not cause interference in the ith frequency band.

The term carrier, as used herein with respect to a multicarrier signal or system, is equivalent to the terms subcarrier and tone. Orthogonal carriers may be characterized by constant-frequency carriers with orthogonal frequencies. Alternatively, orthogonal carriers may employ dynamically varying carrier frequencies, such as chirped or hopped

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carriers. For example, the frequency separation between a set of orthogonal carriers with dynamic frequencies may be constant or limited to integer multiples of an orthogonal frequency spacing f_s.

An input data source includes any input port adapted to receive data bits and/or data symbols, such as coded data bits and/or symbols. An input data source may include any apparatus and/or algorithm adapted to generate data, such as coded or uncoded data bits and/or symbols. An input data source may include at least one coder and/or coding algorithm. Channel coding may include any combination of well known channel coding techniques, such as trellis, block, convolutional, parity check (e.g., Gallagher coding or any other type of low-density parity check coding), and iterative soft-decision feedback (e.g., turbo) coding.

The phase of each CI signal is set with respect to at least one predetermined receiver time interval (i.e., phase space) in which the carriers constructively combine when received by a CI receiver. A set of incremental phase offsets $e^{in\Delta\phi_k}$ corresponding to at least one pulse position is applied to the CI carriers by one of a plurality N of interval delay (i.e., phase) systems. Each pulse's phase space is a set of carrier phases corresponding to the time instant at which the pulse is centered. Thus, each set of phase offsets maps a data symbol to a pulse centered at a particular instant in time.

Interval delay systems, or equivalently, phase-shift systems, include any type of phase shift module, delay module, temporal mapping module, polyphase code module, polyphase filter, etc., adapted to map data symbols to pulse positions. A pulse position is an instant in time at which a CI pulse is centered. A pulse, as used herein, typically refers to a single-pulse waveform generated from a superposition of selected carriers. Pulse waveforms may include a plurality of pulses, such as a pulse train. Delay systems are systems, algorithms, and/or devices adapted to provide time offsets (i.e., phase shifts) to individual carriers to generate carrier superpositions (pulse waveforms). Delay systems may provide phase offsets and/or time offsets to carriers and/or data symbols.

A delay system is typically configured to receive as input at least one of a data sequence and a set of carriers. The delay system directly maps data on modulated carriers to particular instants in time. The delay system may align carriers to produce pulse waveforms centered at one or more time instants and then modulation may be provided to

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the pulse waveforms. An interval delay system may include a polyphase coder adapted to provide polyphase codes to data symbols and/or carriers. A delay system may provide polyphase codes to frequency bins of an invertible transform, such as an IDFT or IFFT.

Although the apparatus diagrams illustrated herein illustrate the generation of CI transmission signals as step-by-step procedures, a preferred embodiment for accomplishing these processes may use digital signal-processing techniques, such as Discreet Fourier Transforms. The order of some of these processes may be switched. For example, modulation of each carrier by the input data may be the final step before combining.

Disclosed aspects may provide for any of various forms of duplexing, such as frequency division duplexing, code division duplexing, and time division duplexing (TDD). TDD allows for a highly efficient and cost-effective architecture, since the same frequency is used for both transmission and reception and the channel characteristics in both directions are virtually identical. In array-processing applications, the beam-forming weights can be determined from a base station antenna array for the reverse link and the same weights can be used on the forward link without requiring multiple antennas at the remote unit. This allows the system to deliver the capacity and interference mitigation benefits of adaptive beam forming for both the uplink and the downlink while keeping the complexity and cost of the remote unit very low. Furthermore, the TDD approach eliminates expensive diplexing filters and permits the use of a single RF chain, further reducing subscriber-unit costs.

Figure 18A is a functional diagram of a CI transmitter. An allocation step 1814 is performed by carrier mixers, which allocate a plurality of carrier frequencies (i.e., tones) to a particular user. A mapping step 1816 is performed by phase-shift/delay systems, which map each data symbol from data source 1812 to a particular pulse position. A pulse-generation step 1820' is performed by a combiner, which receives the allocated carriers as inputs and generates CI pulses at predetermined pulse positions. The resulting data-bearing CI waveform may be an analog or digital signal. If it is an analog signal, the waveform may optionally be sampled 1821.

The plurality of carrier mixers performs the allocation step that provides carrier frequencies used to generate at least one superposition signal for a particular user. The

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plurality of phase-shift/delay systems provides the mapping 1816 of each data symbol from the data source to a predetermined instant in time (i.e., pulse position). Each set of phase shifts applied to the information-modulated carriers by the phase-shift/delay system produces a phase alignment of the carriers (i.e., an interference pulse) at the predetermined instant in time. Thus, the combination of the phase-shift/delay systems and the data source produces a discrete signal of the mapped data symbols. The data symbols are typically provided with polyphase codes and modulated onto the individual CI carriers. Each polyphase code maps its associated data symbol to a particular instant in time.

A combining system, or combiner, as described herein, is any system, device or algorithm adapted to combine a plurality of allocated carriers (for transmission or reception) to produce a time-domain waveform. A combiner may be interpreted as a frequency-domain to time-domain converter. A combiner may be referred to as an interpolation circuit because it generates a time-domain waveform from a plurality of frequency-domain components. A combiner may include an inverse-Fourier transform, such as an IDFT or IFFT circuit or algorithm. Thus, one way to implement carrier generation and combining is to provide an IDFT. Consequently, carrier selection and data-symbol mapping may be performed by a polyphase coder adapted to generate a vector of frequency-bin weights.

The combining system (which may equivalently be an interpolation circuit) is adapted to perform pulse generation, as it combines the phase shifted carriers to produce one or more information-modulated pulses centered at the predetermined instants in time. A plurality of information-modulated pulses may be positioned contiguously in time (such as shown in Figures 16B and 17B) to provide a substantially uniform (low PAPR) signal over a predetermined interval (e.g., symbol period T_s or some multiple thereof). The pulse waveforms are functions that span the symbol duration T_s. In this case, a pulse waveform may be a digital or analog signal. The frequency response of the pulses includes sinusoids provided by the carrier mixers (i.e., allocation circuit).

Figure 18B illustrates a CI transmitter that includes a subcarrier allocation module 1814, a mapping module 1816, and an interpolation module 1820. The subcarrier allocation module 1816 performs the function of carrier mixers. Subcarrier allocation

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assigns a predetermined number N of carriers to one or more users wherein the carrier frequency spacing f_s and data symbol period T_s are selected to ensure orthogonality between the carriers. Orthogonality may be provided between the allocated carriers and unallocated carriers (e.g., carriers assigned to other users). For a number N of carriers, there are N orthogonal phase spaces (i.e., pulse positions). Thus, the number of users in an orthogonal CI system is less than or equal to the number N of carriers.

The carriers corresponding to each user may include contiguous carrier frequencies or uniformly spaced frequencies distributed over a broad frequency band. Each user may be allocated a unique set of carriers, thus providing for orthogonal frequency division multiple access. Alternatively, two or more users may share at least one set of carrier frequencies. Thus, CI may employ other multiple-access schemes, including time division and code division.

The mapping module 1816 is equivalently a multicarrier phase-shift module. The mapping module 1816 maps each data symbol from a data source to a predetermined instant in time. Incremental phase offsets applied to a plurality of carriers are equivalent to a time offset (e.g., delay) applied to a superposition of the carriers. Each set of phase offsets produces a phase alignment of the carriers (i.e., an interference pulse) at a predetermined instant in time, thus, mapping each data symbol to an instant in time.

The carriers are provided by the subcarrier allocation module 1814 (e.g., a plurality of carrier mixers) and modulated with one or more data symbols. Modulation may be performed at the carrier mixers. The combination of the phase-shift/delay systems and the data source produces a discrete signal consisting of the mapped data symbols.

The interpolation module 1820 can be expressed by a combining system. The interpolation module 1820 combines the phase-shifted carriers to produce one or more information-modulated pulses centered at the predetermined instants in time. The subcarrier allocation module 1814 provides the carriers from which the pulses are produced. Thus, the frequency response of the pulses may include only the sinusoids allocated by the subcarrier allocation module 1814 to a particular user. Since each user may be assigned a unique set of carriers, the pulse waveforms produced by the communication system can include non-zero sinusoids allocated to a particular user and zero-valued (i.e., an absence of) sinusoids allocated to other users.

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The CI transmitter components illustrated in Figure 18B, as well as other components in the transmitter, may be implemented as digital signal processing components. Consequently, the information-modulated pulses generated by a CI transmitter may be a digital signal sample vector.

Since the CI pulses are positioned orthogonally in time if the phase offsets are appropriately selected, signal characteristics (e.g., phase, amplitude, frequency, etc.) of each pulse at the pulse maxima conveys the data symbol value assigned to the corresponding phase space (i.e., instant in time at which the pulse is centered).

Figure 19 illustrates a CI transmitter. A set of carrier mixers 1914 (which typically includes a multicarrier signal generator) is adapted to allocate a set of carriers to a particular user. Thus, the carrier mixers 1914 perform the same function as a Discreet Fourier Transform (DFT) circuit combined with a zero-insertion circuit. For example, carriers corresponding to other users are removed, avoided, or otherwise set to zero.

A phase-shift/delay system 1916 is adapted to map each of a plurality of data symbols from a data source 1912 to a predetermined instant in time. The data source 1912 provides data symbols to any of the transmitter modules 1914, 1916, and/or 1920. Data symbols may be modulated directly onto individual carriers, data-bearing polyphase codes may be generated, or CI pulse waveforms may be modulated with data. The phase-shift/delay system 1916 applies sets of phase offsets to a plurality of carriers, which are provided by the carrier mixers 1914 and optionally modulated with one or more data symbols. Each set of phase offsets produces a phase alignment of the carriers (i.e., an interference pulse) at a predetermined instant in time, and thus, maps each data symbol to an instant in time. The combination of the phase-shift/delay systems 1916 and the data source 1912 produces a discrete signal of the mapped data symbols.

A combining system 1920 combines the modulated, phase-shifted carriers to produce information-modulated pulse waveforms. These pulse waveforms are inverse Fourier transforms of the carriers represented in the frequency domain. Thus, the combining system 1920 performs the same function as an Inverse-DFT circuit. Although not shown, a gain adjustment module or system (e.g., a pulse-shaping filter) may optionally be included in the transmitter.

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CI signal generator systems may include a transmission system, such as is known in the art with respect to single carrier and multicarrier communications. For example, a transmitter may include analog and/or digital components typically used to process a baseband signal for transmission into a communication channel.

Figure 20 illustrates a specific embodiment of a CI transmitter. A carrier generator/mixer circuit 2014 includes a pulse generator 2001 and a carrier-selection filter 2002. The pulse generator 2001 is adapted to generate pulse having a predetermined pulse-repetition frequency to provide a predetermined multicarrier output. Other pulse-generation parameters, such as pulse shape, may be selected and/or adapted to provide for desirable spectral characteristics.

A subcarrier processing module 2016 may be adapted to provide phase offsets to the selected carriers, provide polyphase coding to the carriers, modulate data (or coded data) symbols onto the carriers, and/or provide for carrier gain adjustments (e.g., pulse shaping, channel compensation, carrier selection, etc.). Accordingly, the subcarrier processing module 816 may include any combination of digital filters, modulators, coders, phase shifters, and channel-compensation circuits.

A combiner 2020 is optionally provided to generate a superposition of the carriers. A transmission module 2022 processes the baseband multicarrier signal and couples the processed signal into a communication channel. Although the combiner 2020 is shown coupled between the subcarrier processing module 816 and the transmission module 2022, in-channel combining may be provided. Accordingly, transmitter components (not shown), such as amplifiers, frequency converters, and guard-interval modules may be provided separately to each subcarrier.

A data source 2012 is coupled to at least one of the modules 2014, 2016, and 2020. The pulse generator 2014 may be modulated with data or otherwise adapted to generate information-modulated pulses. Alternatively, the subcarrier processing module 2016 may be adapted to modulate data onto the pulses or the selected individual carriers. In another embodiment of the invention, the combiner 2020 includes a modulator (not shown) adapted to modulate data symbols from data source 2012 onto the superposition signal.

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Some aspects may employ any of a number of techniques for providing channel estimating. For many of these methods, a block of pilot chips, tones, or other known signals may be inserted into the transmitted waveform. Known symbols may be mapped to CI phase spaces. Training symbols may be provided to individual subcarriers. In other embodiments, various types of coded training symbols may be transmitted. Blind adaptive estimation and equalization may be employed.

Figure 22A illustrates a plurality of CI pulse waveforms 2201 to 2209 orthogonally positioned in time. A plurality N of equally spaced carriers $f_1, f_2,\ldots,f_N$ are combined to generate the pulses 2201 to 2209. A set of carrier phases 2211, 2212,…, 2219 corresponds to each of the pulses 2201, 2202,…, 2209, respectively. Each set of carrier phases 2211, 2212,…, 2219 is an orthogonal polyphase CI code (or phase space) applied to the carriers to center a given pulse waveform at a corresponding instant in time.

A complex-valued data symbol (not shown) impressed onto a pulse (such as pulse 2201) may be characterized by an in-phase (e.g., real) part modulated onto pulse 2201 and a quadrature-phase (e.g., imaginary) part modulated onto a pulse waveform (not shown) centered equidistantly between pulses 2201 and 2202. Similarly, a first set of N real data symbols may be impressed onto a first set of N 9orthogonal pulses (such as the pulses 2201 to 2209). A second set of real data symbols may be impressed onto a quadrature-phase set of orthogonal pulses (not shown) centered equidistantly between adjacent pairs of the pulses 2201 to 2209.

Complex carrier weights corresponding to each of the carriers $f_1, f_2,\ldots,f_N$, represent a sum of the phase spaces 2211, 2212,…, 2219 multiplied by their corresponding data symbols. In particular, an nth (n = 1,2,…,N) carrier's complex weight equals the sum of each complex data symbol in the nth row of each phase space 2211, 2212,…, 2219 multiplied by the data symbol value (not shown) associated with that phase space 2211, 2212,…, 2219 (i.e., pulse position 2201, 2202,…, 2209).

Fogure 22B represents a CI waveform of the present invention. A plurality N of subcarriers 2221 to 2229 (e.g., sinusoids, or tones) are characterized by at least one predetermined set of complex subcarrier weights 2210. These weights 2210 align the sinusoids 2221 to 2229 to produce a train or sequence of information-modulated pulses

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2201 to 2209 in the time domain. These pulses 2201 to 2209 may be generated by applying the subcarrier weights 2210 to subcarriers (such as subcarriers 2221 to 2229) allocated to at least one user in a network.

A network may be characterized by various types of communication architectures having two or more users, or nodes, including point-to-point, point-to-multipoint, broadcast, multipoint-to-multipoint, multipoint-to-point, hierarchical, ad-hoc, peer-to-peer, multi-hop, and cellular. The invention is independent of the type of network. Accordingly, other network configurations may be employed. Similarly, the invention is independent of the propagation medium (i.e., communication channel) connecting the nodes.

Alternatively, multiple time-offset pulses are combined wherein each pulse 2201 to 2209 is generated from a superposition of predetermined subcarriers 2221 to 2229 and modulated with a corresponding data symbol. In some cases, time-domain waveforms are provided with frequency-domain processing (e.g., pulse-rate control, rise-time and roll-off control, pulse shaping, pulse-width control, frequency-selective filtering, windowing, and/or frequency masking) to generate pulse waveforms having predetermined spectral characteristics.

Variations of the disclosed pulse-generation techniques and/or multicarrier-generation techniques, as well as other techniques, may be employed in generating CI pulse waveforms. Pulse generators include circuits, systems, software, etc., adapted to generate pulse waveforms. Pulse generators can also include carrier-generation circuits, systems, software, etc. having some carrier-weighting apparatus or algorithm (e.g., CI coder, phase shifter, delay device, mode-locking system, etc.) adapted to produce a plurality of carriers having complex weights that shape a superposition of the carriers into one or more pulse waveforms. Since there are many techniques for generating CI waveforms, the invention is not limited to any specific embodiment for generating CI waveforms disclosed herein. Other techniques for generating CI waveforms will be evident to persons skilled in the art.

CI waveforms are typically impressed onto one or more carriers. CI subcarriers may be impressed onto multiple transmission carrier signals, such as carriers corresponding to different frequency bands. CI waveforms may be conveyed as analog

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waveforms (such as generated by a D/A converter or a bank of oscillators). CI waveforms may be digital signals (such as a digital output generated by an IDFT or other transform). Digital CI waveforms may be generated from an A/D conversion of at least one analog CI waveform. Digital CI waveforms may be generated by appropriately weighting and summing a predetermined set of digital sinusoids that are dynamically generated or stored in memory. Digital CI waveforms may include binary or M-ary (i.e., higher order) signals. Digital CI signals may be expressed as discreet or continuous modulation symbols, including, but not limited to, QAM, PSK, CPM, FSK, AM, FM, PAM, and TOM. The digital signals may be transmitted in any order.

Various interleaving and/or channel-coding techniques may be employed in the transmission of digital signals associated with CI waveforms. In one aspect of the invention, coding (which is not necessarily limited to channel coding) and/or interleaving are applied to data symbols prior to generating the CI waveforms. In another aspect of the invention, coding and/or interleaving are applied to digitized CI signals. In yet another embodiment, modulation symbols may be interleaved.

The offset frequency f_o represents the carrier frequency. In some applications, CI waveforms may be conveyed in their baseband form (i.e., a carrier frequency, or offset frequency f_o, having zero frequency). For example, baseband CI waveforms may be conveyed inside a digital signal processor or equivalent device, between storage devices (physical and/or virtual memory) and signal-processing devices (e.g., DSPs, microprocessors, CPUs), inside transmitter components, inside receiver components, and/or between transmitter and receiver components. CI waveforms may be conveyed in an intermediate-frequency (IF) form. For example, the multicarrier CI signal may be impressed on an IF carrier. Carriers having other frequencies, including optical, infra-red, and microwave, may be employed.

Complex subcarrier weights convey phase space (e.g., CI codes, phase-shift sets, carrier delays, pulse (time-) offset, or any other interpretation of carrier superposition signals resulting from carrier phase alignments at predetermined times) and information (e.g., data symbol) values. Complex subcarrier weights may be generated from a product of a vector or matrix of data symbols with a vector or matrix of phase space (i.e., CI code) values. Complex subcarrier weights may be generated from sums of information-

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modulated phase spaces. Complex subcarrier weights may be generated from a sum of products of each of a plurality of phase-shift sets corresponding to a particular phase space with data symbols corresponding to that particular phase space. Carrier weights may be generated by calculating or measuring subcarrier amplitudes and phases resulting from combining a plurality of information-modulated, time-offset pulse waveforms.

Subcarrier weights may optionally include channel compensation weights, array-processing weights, and/or coding (e.g., channel coding, multiple-access coding, spread-spectrum coding, etc.). The subcarrier weights may optionally provide for data interleaving.

In some aspects of the invention, subcarrier weights may be provided with at least one code (e.g., a complex-valued or real code) adapted to de-orthogonalize (e.g., provide time-domain spreading, and thus, overlapping of) the transmitted pulses. Upon reception, an appropriate derivative of the code (e.g., a complex-conjugate code) can be applied to the appropriate frequency-domain components to re-orthogonalize the pulse waveforms.

Figure 21 illustrates basic components of CI signal generation software residing on a computer-readable medium 2199. CI signal generation software is typically configured to control the function and transmission-signal output of a single carrier or multicarrier transmitter. In some cases, a CI transmission may be characterized as a single-carrier signal in the time domain having a plurality of predetermined frequency-domain (or spectral) components.

A subcarrier allocation source code segment 2191 is adapted to generate a plurality of subcarriers allocated to at least one user or allocate a plurality of input subcarriers (not shown) to a particular user. A subcarrier weighting source code segment 2192 is adapted to provide complex weights (e.g., CI codes) to a plurality of the allocated subcarriers. The weights are configured to map one or more input data symbols into one or more phase spaces.

The computer-readable medium 2199 may include any item of manufacture adapted to store or convey software and/or firmware. The source-code segments 2191 and 2192 may reside on a physical memory storage device, such as any magnetic, electrical, or optical device adapted to store data and/or computer command instructions. The source-code segments 2191 and 2192 may be implemented as gate configurations on

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a programmable or integrated circuit. Other means for arranging physical devices and/or electromagnetic phenomena may be employed to convey the function of the source-code segments 2191 and 2192. Accordingly, the computer-readable medium 2199 may include any combination of FPGAs, ASICs, transient memory, and persistent memory.

Subcarrier allocation may include generating subcarriers, providing for receiving input subcarriers, retrieving subcarriers or superposition waveforms from memory (e.g., a look-up table), or selecting non-zero (or equivalently, zero) valued input bin weights of an invertible transform, such as a DFT. In some applications, subcarrier allocation can include pulse shaping, controlling symbol durations, and/or selecting subcarrier frequency spacing. Some frequencies may be selected or avoided relative to channel conditions, bandwidth requirements, and/or interference.

The subcarrier allocation source code segment 2191 and subcarrier weighting source code segment 2192 may be implemented in one program. Similarly, other processing operations typically performed in a communication system transmitter may be implemented in, or in addition to, the source-code segments 2191 and 2192. It should be appreciated that subcarrier allocation, selection, and assignment can include providing subcarriers for system control and/or monitoring. Subcarrier allocation, as described throughout the specification may include providing for pilot tones, training sequences, and/or other subcarriers allocated to other system-control functions. Subcarrier weighting may include channel coding, source coding, spread-spectrum coding, formatting, multiple-access coding, multiplexing, encryption, array processing, and/or modulation. Systems and methods illustrated herein and described throughout the specification may be implemented as source-code segments residing on one or more computer-readable mediums.

Network control in CI communications may be adapted to enable users to share network resources (e.g., bandwidth). For example, channel resources in the form of phase spaces and/or subcarriers may be allocated to each user relative to their level of service. Bandwidth may be allocated to users relative to any combination of individual throughput requirements, purchased level of service, and availability of bandwidth. Circuit-switched processes may be implemented with respect to subcarrier allocations. Packet-switched

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processes may be implemented with respect to phase spaces. CI communications provides for the concurrent implementation of circuit switching and packet switching.

Figure 23A is a functional flow chart of a CI receiver. A receiver process 2301 couples at least one transmitted signal from a communication channel and converts it to an IF or baseband signal. Multicarrier receivers typically include various combinations of signal-processing components, such as amplifiers, filters, down converters, A/D converters, cyclic prefix removers, beam forming circuits, as well as other components. The receiver process 2301 may generate analog or digital signals.

A filtering process 2302 performs a time-domain to frequency-domain conversion of the received signal to produce a plurality of frequency-domain components. Filtering may remove one or more frequency components, or otherwise provide frequency-domain constraints such that the resulting frequency-domain components correspond to components of at least one desired transmit signal. The frequency-domain components may include subcarriers or complex weights corresponding to the magnitude and phase of each subcarrier. Time-domain to frequency-domain processes and frequency-domain to time-domain processes are commonly performed using Fourier transforms or cosine transforms.

An optional frequency domain equalization (FEQ) step 2303 may be provided. The FEQ step 2303 typically involves applying complex channel-compensation weights to the frequency-domain components. An equalizer, as used herein, is a digital hardware/software apparatus adapted to correct for the inter-symbol interference, fading, and/or other distortions of the received digitally-encoded signals so that the initial data can be recovered. Typically, an equalizer compensates for inter-symbol interference via several processes, such as linear equalization or decision feedback equalization. In linear equalization, the incoming signals are multiplied by the inverse of the inter-symbol interference, generally removing inter-symbol interference from the incoming signals. A drawback of linear equalization is that noise inherent in the data transmission is undesirably simultaneously amplified. Decision feedback equalization avoids the noise amplification problems of linear equalization, but runs the risk of error propagation since any decision errors that are made are fed back. Other types of equalization that may be

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included in the invention include maximum likelihood sequence estimation, iterative equalization, inter-symbol interference cancellation, and/or turbo equalization.

A combining process 2304 combines the selected frequency-domain components to produce a time-domain signal (e.g., a superposition signal or a sequence of data symbols). Thus, the combining process 2304 is equivalent to other frequency-domain to time-domain conversion processes. Combining 2304 may be followed by an optional time-domain equalization (TEQ) step 2305 and/or an optional multi-user detection (MUD) step 2306. A decision process 2307 is adapted to estimate the received data in order to recover transmitted data symbols. Various types of decision processing 2307 may be employed. An integration step (not shown) is typically provided with combining 2304 and/or decision processing 2307 to combine samples, or otherwise process the received signal, over one or more symbol durations T_s.

A decision system, as used herein, describes any combination of devices and/or algorithms adapted to process an input signal to provide at least one estimate of the input signal's value. Hard and/or soft decisions may be employed. A decision system may provide for various signal-processing techniques (e.g., decoding, feedback, as well as various adaptive routines), such as are typically associated with receivers and reception techniques. A decision system may employ some reference, such as a reference symbol constellation.

Figure 23B illustrates a receiver method and apparatus similar to that shown in Figure 23A with the addition of a CI phase space decoder step 2310. A plurality of CI phase spaces (i.e., time intervals) can be selected by the same transversal filter described with respect to the TEQ 2305. In this case, data symbols impressed onto different phase spaces are separated by applying the appropriate incremental delays (i.e., phase offsets) to the individual carriers prior to combining 2304. If the components are complex values (e.g., output-bin values of a discreet Fourier transform), a complex conjugate of each CI code used to map a data symbol to a particular phase space may be employed to recover the corresponding mapped symbol.

Figure 24A shows an embodiment of a CI receiver that includes a receiving module 2301, a filter bank 2302, a delay system (or phase-shifter bank) 2310, a combiner 2304, and a decision module 2307. Received signals are processed by the receiving

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module 2301 prior to processing at the filter bank 2302. The filter bank 2302 may include a plurality of filters, such as a plurality of analysis filters. The filter bank 2302 is typically a complementary system with respect to a carrier synthesizer (not shown) employed on the transmit side to generate CI signals. Alternatively, the filter bank 2302 may include a transform operation that is complementary (e.g., inverted) relative to an associated transform function in a corresponding CI transmission process. For example, the filter bank 2302 may be adapted to perform a Fourier transform operation (e.g., a DFT implemented with a fast transform algorithm, such as a fast Fourier transform). Alternatively, the filter bank 2302 may be adapted to perform matched filtering. In any of these cases, the function of the filter bank 2302 is to convert an input time-domain signal into a plurality of frequency-domain components.

The delay system 2310 is adapted to provide incremental delays to a plurality of subcarrier waveforms generated by the filter bank 2302. Equivalently, the delay system 2310 may provide incremental phase offsets to frequency-bin values or equivalent complex values corresponding to carrier magnitudes and phases. It is well known that there is a linear relationship between carrier time offsets τ and carrier phase offsets ϕ related to a given carrier frequency f_n: $\phi = 2\pi f_n \tau$. The delay system 2310 typically provides a complementary or inverse set of delays (or equivalently, phase shifts) to the component waveforms. Accordingly, the delay system 2310 is adapted to provide complementary phase offsets (or time offsets) that are complex conjugates of terms corresponding to each predetermined phase space, such as the phase spaces 2211, 2212,…, 2219 shown in Figure 22A.

The combiner 2304 is adapted to combine one or more sets of the delayed (or phase offset) carrier components. Combining may include equalization, such as frequency-domain equalization. Similarly, some form of time-domain equalization and/or multi-user detection may be performed after combining. Consequently, the combiner 2304 may include at least one equalizer (not shown).

The combiner 2304 combines the frequency-domain components to generate a time-domain sequence, such as a reconstructed CI pulse waveform or a sequence of symbol values corresponding to the transmitted data. A CI pulse waveform typically includes a plurality of orthogonally positioned CI pulses (i.e., a pulse train, such as

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illustrated in Figures 16B and 17B) wherein each pulse conveys (e.g., is modulated with) a data symbol. Thus, the combiner 2304 generates signal values from data symbols that were mapped to predetermined instants in time (i.e., phase spaces, or pulse positions centered at equally spaced time instants) by at least one transmitter.

The decision module 2307 processes the signal values to generate estimated data symbols. Methods of formatting information symbols, such as mapping a constellation of data symbols to a constellation of modulation levels, and the reverse operation, are typically understood to be a process within a symbol-estimation step or decision step. Such as in which information symbols are converted to waveform symbols at a transmitter and the reverse conversion is performed at a receiver. A decoder may perform symbol-to-bit mapping. Digital data may be mapped into a signal point sequence with respect to a predetermined code, and an inverse mapping produces an estimated data sequence from a received signal point sequence. An inverse-mapping device (not shown), which may be part of the decision module 2307, produces an estimated data sequence from a received signal point sequence. Receivers may employ channel estimation. Channel estimation in multicarrier systems is typically regarded as part of an equalization process.

Figure 24B illustrates a CI receiver. A DFT 2302 functions as a filter bank. A delay system 2310 is implemented as a plurality M of phase-space modules 2310.1 to 2310.M. Each phase-space module 2310.1 to 2310.M, such as phase-space module 2310.1, is adapted to generate a plurality N of phase offsets, such as 2310.11 to 2310.1N corresponding to a particular phase space. Phase-shifted values or time-offset carriers generated by each phase-space module 2310.1 to 2310.M are coupled to a corresponding combiner of a plurality M of combiners 2304.1 to 2304.M. A decision module 2307 is adapted to process combined symbols or waveforms to generate at least one data estimate. A decision module or a delay system may include at least one decoder (not shown) adapted to perform any necessary decoding, such as channel decoding, multiple-access decoding, demultiplexing, de-spreading, decryption, etc.

Figure 25A illustrates a CI reception method and functional components of a CI receiver. A receiver module 2501 is adapted to process transmissions from a communication channel to generate one or more received signals for baseband or IF

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processing. A projection module 2502 is adapted to project the received signals onto at least one orthonormal basis corresponding to at least one user's transmissions. A combining module 2504 is adapted to combine the projections and optionally perform equalization. Combined signals are processed in a decision module 2507 adapted to generate one or more estimated data symbol values.

In particular, the steps of performing time-domain to frequency-domain conversion and filtering the frequency-domain signal may be achieved by projecting the received signal onto the orthonormal basis of the transmitted signals (such as indicated by the projection module 2502). Projecting a received multicarrier signal onto an orthonormal basis of a particular user's transmitted signal produces frequency-domain signal components $r = (r_0, r_1, \ldots, r_{N-1})$ corresponding to that user's assigned carriers. Equivalently, the projection of a received signal onto an orthonormal basis excludes signals (e.g., carriers and/or phase spaces) that do not correspond to that orthonormal basis.

Figure 25B illustrates a CI receiver method and system. A receiver module 2501 is adapted to process and couple one or more transmitted signals from a communication channel to a matched filter 2502. The receiver module 2501 is adapted to perform various types of signal processing (e.g., amplification, filtering, down conversion, A/D conversion, guard-interval removal, beam forming, and/or other types of signal processing) to modify a received signal into an appropriate format for baseband or IF signal processing. The modified signal may include an analog or digital signal.

The matched filter 2502 is typically matched to one or more signal characteristics (e.g., subcarriers, phase spaces, time intervals, codes, etc.) of at least one user or data stream. Different users and/or transmitted data symbols are typically characterized by at least one set of unique diversity parameter values, such as carrier frequencies, phase spaces, time intervals, codes, subspaces, polarizations, or combinations thereof. Other diversity parameters may be used to characterize different users and/or data streams. The matched filter 2502 may include one or more matched-filter elements.

The output(s) of the matched filter 2502 typically characterizes the degree of matching (e.g., correlation) of the filter 2502 with the received signal(s). Measured variations in the degree of matching can indicate the transmitted symbol values. Thus,

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these measurements may be mapped to a predetermined symbol constellation. The temporal characteristics (e.g., synchronization and duration) of these measurements are typically selected in an integrator 2504. The integrator's 2504 function is typically optimized relative to the probability of error (or BER) of the symbol estimates generated by a decision module 2507.

Integration represents combining in the time domain. Consequently, integration may be part of a combining process (not shown). Frequency-domain combining is typically performed in the matched filter 2502. For example, matching of a particular phase space includes carrier selection, and accordingly, a combining of the appropriately phase-shifted carriers. Alternatively, the matched filter 2502 simply matches components of a signal space corresponding to a particular user or data channel. In this case, the integrator 2504 produces values corresponding to the components over a predetermined time interval, and the decision module 2507 combines the component values to generate symbol estimates. Thus, the matched filter 2502 may employ polyphase codes corresponding to CI phase spaces as part of its matching function. Similarly, the decision module 2507 may employ polyphase CI codes as part of a combining process.

The decision module 2507 may be adapted to perform any of various functions related to data-symbol processing. For example, the decision module 2507 may perform any combination of channel decoding, demodulation, spread-spectrum decoding, de-interleaving, demultiplexing, multiple-access decoding, and formatting. Equalization may be performed by one or more receiver modules 2502, 2504, and/or 2507.

Figure 26A illustrates a CI receiver apparatus and method of the invention. A receiver module or system 2501 is adapted to receive and process at least one transmitted signal to provide a digital or analog time-domain signal to a first software module 2502. The first software module 2502 is adapted to project the received signal onto the orthonormal basis of the transmitted signals. This achieves a combined time-domain to frequency-domain transform and tone filtering.

The first software module 2502 includes a plurality N of multipliers 2511.1 to 2511.N adapted to multiply the received signal by reference signals having orthogonal carrier frequencies $f_n = f_o + nf_s$ (n=0,…,N-1) and at least one predetermined phase relationship $n\Delta\Phi_k$,. Software module 2502 also includes a plurality N of integrators

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2504.1 to 2501.N adapted to integrate the products over each symbol interval T_s. The outputs of the first module 2502 are frequency-domain signal components $r = (r_0, r_1, \ldots, r_{N-1})$ corresponding to a particular user's assigned carriers. The first module 2502 is typically adapted to generate phase offsets $\Delta\Phi$ corresponding to a plurality of phase spaces (i.e., time offsets).

A second software module 2514 takes the form of a combiner, which performs a frequency-domain to time-domain transform. Equalization (not shown) may be performed by either or both first and second modules 2502 and 2514, respectively. Time-domain equalization and/or frequency-domain equalization may be employed. Various combining techniques, such as any appropriate optimal-combining technique may be employed. The combined frequency-domain components produce a time-domain signal, such as shown in FIGS. 1, 2B, and 3B. The time-domain signal may include an analog or digital waveform. Alternatively, a time-domain signal may include a sequence of digital symbol values.

Each set of phase offsets $\Delta\Phi$ corresponds to a particular phase space or time offset. Each received data symbol is characterized by a data-modulated pulse centered at a particular time instant. The inclusion of phase selection in the reference signals used in the multipliers 2511.1 to 2511.N of the first software module 2502 provides for selection of signal values at predetermined instants in time. Thus, the process of combining 2514 the phase-offset signals generated in the first module 2502 is part of a time-instant to symbol-mapping process. Decision processing 2507 provides for estimation of the received data. Decision processing 2507 is a mapping process that maps received signal values corresponding to each pulse (i.e., equally spaced instants in time used to transmit symbol values) into decision variables (i.e., estimated signal values).

Figure 26B illustrates a CI receiver, including a receiver module 2501, a matched filter or projection module 2502, a plurality M of integrators 2504.1 to 2504.M, and a decision device 2507. The projection module 2502 includes a discreet Fourier transform (e.g., FFT 2512). Equivalently, other types of filters may be included, such as to select one or more subcarrier components allocated to a particular user. N frequency-domain components generated by the FFT 2512 are phase shifted by a plurality M of phase-shift systems (e.g., interval delay systems) 2510.1-2510.M. The N signal components

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corresponding to each phase-shift system 2510.1-2510.M are combined in an associated combiner 2514.1 to 2514.M to generate a time-domain signal.

A plurality M of time-domain signals is output from the projection module 2502. Each of the M time-domain signals is integrated over each symbol interval T_s by the integrators 2504.1 to 2504.M. Signal values generated by the integrators 2504.1 to 2504.M are processed by the decision module 2507 to generate a sequence of estimated data symbols.

Various embodiments may include variations in system configurations and the order of steps in which methods are provided. For example, the order of frequency-domain combining (illustrated by the combiners 2514.1 to 2514.M) and time-domain combining (illustrated by the integrators 2504.1 to 2504.M) may be switched. Multiple steps and/or multiple components may be consolidated.

Figure 26C illustrates a subcarrier weighting source code segment 2591 and a CI combining source code segment 2592 residing on a computer-readable medium 2599. Source code segment 2591 is adapted to process one or more received channel measurements (such as frequency-domain or time-domain measurements) for generating a plurality of subcarrier weights. These weights are adapted to compensate for one or more channel effects, including, but not limited to, multipath, dispersion, and co-channel interference. The weights may be adapted to provide CI decoding. The weights may be adapted relative to one or more channel and/or data-quality measurements. The weights may be configured relative to data-processing measurements, such as hard-decision, soft-decision, and/or iterative feedback decision processing. The weights are typically applied to a plurality of subcarriers, such as frequency components produced by a filter bank or an FFT. Subcarrier weighting may include filtering, such as providing for acquiring subcarrier frequencies allocated to at least one predetermined user. Consequently, subcarrier weights may include both zero and non-zero values. Subcarrier weighting may include channel decoding, source decoding, spread-spectrum decoding, formatting, multiple-access decoding, demultiplexing, decryption, array processing, and/or modulation.

Source-code segment 2592 is adapted to combine the received and weighted carriers to generate a processed signal output, which is typically a sequence of symbols.

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At least one type of optimal combining may be provided. Code segment 2592 is adapted to receive as input at least one received signal, such as a sequence of data symbols. The received signal may be impressed onto the weights, weighted subcarriers, or waveforms generated from one or more superpositions of the weighted subcarriers. The weights are configured to map one or more input data symbols into one or more phase spaces. In some applications, data-modulated weights may be generated in source-code segment 2591. In this case, source-code segment 2591 is adapted to process the received signal to generate at least one set of information-bearing weights.

Figure 27A illustrates a number M of CI receiver branches. A plurality of input couplers (e.g., antenna elements) 2701.1 to 2701.M couple signals from a communications medium (e.g., a free-space channel, a waveguide, etc.) and process the signals. The input couplers 2701.1 to 2701.M are typically adapted to perform any combination of front-end receiver-side processing, including amplification, filtering, frequency conversion, and/or A/D conversion. Other types of processing may be performed. For example, a plurality of optional guard interval (e.g., cyclic prefix) removal circuits 2702.1 to 2702.M may be incorporated in the input couplers 2701.1 to 2701.M. Similarly, each of a plurality M of serial-to-parallel converters 2703.1 to 2703.M may be included in the input couplers 2701.1 to 2701.M or in each of a plurality M of invertible-transform (e.g., FFT) circuits 2704.1 to 2704.M.

Each of the invertible-transform circuits 2704.1 to 2704.M transforms an input time-domain signal into a plurality N of frequency-domain components. The components are weighted with at least one set of CI combining weights $\alpha_m(n)$, where m = 1,…,M and n = 1,…,N, by a plurality M of component-weighting modules 2705.1 to 2705.M. In the case where MMSE combining is employed, the weights $\alpha_m(n)$ are expressed by:

$$\alpha_m(n) = h_m^*(n) \Big/ \left(N|h_m(n)|^2 + \sigma^2 \right)$$

where $h_m(n)$ is the channel response for the nth frequency channel of the mth spatial subchannel, and σ^2 is the noise power. Other types and combinations of combining may be employed.

A plurality M of combiners, such as IFFTs 2706.1 to 2706.M, combine the weighted frequency-domain components to generate a plurality of time-domain signals.

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Time-domain outputs of the IFFTs 2706.1 to 2706.M are coupled to beam-forming modules 2707.1 to 2707.M, which are adapted to provide beam-forming weights that cancel co-channel interference in a plurality of combiners 2708.1 to 2708.M. Each combiner 2708.1 to 2708.M may include a summing circuit, an adder, an accumulator, an integrator, or any appropriate invertible transform.

The beam-forming modules 2707.1 to 2707.M and the combiners 2708.1 to 2708.M may be adapted to perform any of various types and combinations of adaptive combining. In some applications, maximal ratio combining may be employed. Other combining schemes may be employed. Combining may include interference cancellation, multi-user detection, null steering, spatial interferometry multiplexing, etc. In some cases, space-time processing may be employed. Successive interference cancellation, as well as other multi-level cancellation techniques, can be used. In other cases, space-frequency processing may be provided. Channel decoding weights may be provided by either or both the component-weighting modules 2705.1 to 2705.M and the beam-forming modules 2707.1 to 2707.M. Symbols output by the combiners 2708.1 to 2708.M are converted to a data stream by a parallel-to-serial converter 2709 prior to being demodulated and decoded 2710.

In some disclosed aspects, the subcarriers may be selected for a particular user, such as in an orthogonal frequency division multiple access system. Subcarriers allocated to a particular user may be interleaved in frequency with subcarriers allocated to one or more other users. In another aspect of the invention, a different set of subcarriers is selected for each of a plurality of data symbols or data symbol groups transmitted by and/or to a particular user. A plurality of users may share a common set of subcarriers, yet share the channel via time division multiple access (TDMA), code division multiple access (CDMA), and/or space division multiple access (SDMA). Other multiple-access schemes may be employed. Similarly, different data symbols corresponding to a particular user may share the channel relative to the previously mentioned multiple-access schemes.

In one aspect, a signal generator or transmitter includes a subcarrier allocator, a pulse generator, a modulator, and a sequential pulse positioner. The subcarrier allocator assigns a predetermined set of subcarriers to a particular data symbol, user, or group of

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users. The pulse generator produces a plurality of pulses wherein the spectrum of each pulse or group of pulses is characterized by the set of subcarriers. The modulator modulates the pulses or subcarriers with at least one data symbol. The pulse positioner sequentially positions the modulated pulses.

A transmitter may include a polyphase, poly-amplitude code generator, a subcarrier allocator, a subcarrier weighting module, and a subcarrier combiner. The code generator produces at least one of a set of polyphase, poly-amplitude codes configured to produce a predetermined time-domain signal, such as a direct sequence coded signal. The transmitter may include a modulator adapted to modulate data onto the codes, the subcarriers, or the time-domain signal. The subcarrier weighting module impresses the polyphase, poly-amplitude codes onto a predetermined set of orthogonal subcarriers selected by the subcarrier allocator. The combiner combines the subcarriers to produce the time-domain signal.

A CI decoder may include receiver components illustrated in the figures and described throughout the specification and incorporated references. For example, a CI decoder may include an equalizer (such as a time-domain equalizer and/or a frequency-domain equalizer), a de-mapper, a de-interleaver, a decoder, a de-scrambler, a filter (such as a matched filter), an integrator, and/or a decision module.

CI receivers may be adapted to process either or both single-carrier and multicarrier signals. Frequency-domain analysis and processing of single-carrier signals may be performed relative to pulse characteristics. For example, number of subcarriers, subcarrier spacing, and window durations in receiver processing may be selected relative to physical signal parameters, such as pulse width, pulse shape, and pulse spacing.

In one aspect, a received signal is separated into a plurality of orthogonal subcarrier components by a time-domain to frequency-domain converter. The output of the converter is characterized by orthogonal poly-amplitude (and polyphase) coded data. The converter may be adapted to perform a Fourier transform, such as an FFT or a DFT. A combiner performs frequency-domain equalization and provides CI decoding of the coded data.

Functional aspects are described with respect to signal-waveform illustrations and corresponding descriptions. For example, Figure 27B illustrates a block transmission

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characterized by symbol duration T_s, and includes four orthogonal sinc-like pulse waveforms 341, 342, 343, and 344. Each pulse waveform (such as pulses 341, 342, 343, and 344) may be impressed with a unique data symbol.

A preceding block transmission includes orthogonal pulse waveforms 331, 332, 333, and 334 and a following block transmission includes orthogonal pulse waveforms 351, 352, 353, and 354. Block transmissions are characteristic of multicarrier operation. For example, OFDM employs subcarrier blocks defined by uniform start and end times for each subcarrier, the difference in times typically being equal to the symbol duration T_s, or the symbol duration T_s plus a cyclic prefix. Cyclic prefixes, cyclic "post-fixes", or some other guard interval may be included in the signal plots, such as between the blocks shown in Figure 27B.

Since the pulse waveforms 341, 342, 343, and 344 have the same starting and ending times, the waveform shapes 341, 342, 343, and 344are different from each other. For example, waveform 341 has all of its sidelobes to the right of its main lobe, whereas all of the sidelobes of waveform 344 occur to the left of the main lobe. This tends to increase the interference in systems that perform time-domain equalization and Rake reception. In particular, inter-pulse interference is not limited to nearby pulses because the side-lobe structure is periodic, or cyclic, over the symbol duration T_s. For example, the side-lobe amplitude (and thus, interference) of waveform 341 diminishes across pulse 342 and increases across pulse 344. In this particular example, the pulse waveforms may be generated from four orthogonal subcarrier frequencies, which are not shown.

Figure 28A illustrates a CI transmitter that includes a CI coder 2802, an IDFT (such as IFFT 2804), a polyphase filter 2809, and a transmission system 2807. The CI coder 2802 is adapted to map multiple input data symbols onto a plurality of subcarriers. This is achieved via CI coding. The IFFT 2804 is adapted to receive the plural sub-channel signals and transform them into plural time-domain signals. The polyphase filter 2809 receives the time-domain signals and outputs a plurality of filtered signals. The polyphase filter 2809 may be adapted to provide the filtered signals with a predetermined spectral profile of selected subcarriers. Polyphase filters operate by multiplying selected phases, or samples, of a filter impulse response with samples of one or more input signals.

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Figure 28B illustrates a CI reception method that implies an apparatus for carrying out the method. A receiver step 2851 processes transmissions from a communication channel to generate received signals. Time-domain to frequency-domain conversion and filtering the resulting frequency-domain signal is achieved by projecting the received signal onto an orthonormal basis of the transmitted signals (such as indicated by a projection step 2852). Projecting a received multicarrier signal onto an orthonormal basis of a particular user's transmitted signal produces frequency-domain signal components $r = (r_0, r_1, \ldots, r_{N-1})$ corresponding to that user's assigned subcarriers. Equivalently, the projection of a received signal onto an orthonormal basis excludes signals (e.g., carriers and/or phase spaces) that do not correspond to that orthonormal basis.

Frequency-domain to time-domain conversion is achieved by combining 2854 the received frequency-domain components produced by either band-pass filtering or projection onto a predetermined orthonormal basis. The combined frequency-domain components produce a time-domain signal. The step of recovering symbols is provided in the decision process 2857.

Figure 28C illustrates a CI receiver including a receiver module 2861, a matched filter or projection module 2862, a plurality M of integrators 2864.1 to 2864.M, and a decision device or module 2867. The projection module 2862 includes a DFT, such as an FFT 2872. Equivalently, other types of filters may be included, such as to select one or more subcarrier components allocated to a particular user. N frequency-domain components generated by the FFT 2872 are phase shifted by a plurality M of phase-shift systems (e.g., interval-delay systems) 2870.1 to 2870.M. The N signal components corresponding to each phase-shift system 2870.1 to 2870.M are combined in an associated combiner 2874.1 to 2874.M to generate a time-domain signal.

A plurality M of time-domain signals is output from the projection module 2862. Each of the M time-domain signals is integrated over each symbol interval T_s, by the integrators 2864.1 to 2864.M. Signal values generated by the integrators 2864.1 to 2864.M are processed by the decision module 2867 to generate a sequence of estimated data symbols.

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Various embodiments of the invention may include variations in system configurations and the order of steps in which methods are provided. Multiple steps and/or multiple components may be consolidated.

Figure 29A illustrates a block waveform including a set of N orthogonal CI pulse waveforms 2941 to 2949 having a duration of T_s. CI pulse waveforms (such as pulse 2941 to 2949) may be generated from a superposition of orthogonal subcarriers. Each of the pulse waveforms 2941 to 2949, which represents a CI phase space, is modulated with one of a plurality of data symbols d_1 to d_N, respectively. In one aspect of the invention, each data symbol d_1 to d_N includes a code chip of an orthogonal code, such as Hadamard-Walsh (Walsh) code or a Walsh code multiplied by a long code. Pseudo-orthogonal coding may be employed. Other codes, including Gold codes, Barker codes, Kasami codes, CI codes, and/or DeBot codes, may be modulated onto the pulses 2941 to 2949. The subcarrier weights resulting from the application of these time-domain codes provide orthogonal or pseudo-orthogonal CI codes expressed as frequency-domain codes, which are characterized by low PAPR in multicarrier synthesis.

Figure 29B illustrates a plurality of CI subcarrier weights w_1 to w_N generated from a set of data symbols d_1 to d_N mapped to a number N of orthogonal CI phase spaces. A CI code matrix of dimension NXN containing polyphase code chips is multiplied by a set of data vectors or a data matrix. In particular, each column of the CI code matrix (such as column 2951) is multiplied by a corresponding data symbol (such as symbol d_2). In some cases, the CI code matrix and an NXN data matrix (not shown) may be provided with an element-by-element multiplication. Each row of a product matrix resulting from the product of the data symbols d_1 to d_N with the CI code matrix are summed to produce the subcarrier weights w_1 to w_N. For example, elements in row 2953, after multiplication by the data symbols d_1 to d_N, are summed to generate weight w_2. Since rows and columns of the basic CI code matrix resemble the vectors of complex values used in DFTs, the subcarrier weights w_1 to w_N can be calculated using a fast transform algorithm.

Figure 30A illustrates transmitter apparatus and method embodiments of the present invention. An input data stream is serial-to-parallel converted and processed in a subcarrier-weighting module 3002. The weighting module 3002 provides one or more orthogonal poly-amplitude codes to the subcarriers. The codes may also be characterized

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by polyphase values. The codes are typically indicative of the data and are used as subcarrier weights. In this case, block codes are provided. The weights may be used to synthesize at least one predetermined direct-sequence (e.g., DSSS or DS-CDMA) waveform. The weights are converted to at least one time-domain waveform in a frequency-domain to time-domain converter 3004, such as an inverse Fourier transform.

The time-domain output of the converter 3004 is processed in a transmission system 3006, which may optionally provide a guard interval or cyclic prefix (and/or postfix), perform digital-to-analog conversion, up convert the signal, provide amplification, optionally filter the signal, and provide for coupling the signal into a communication channel. Other transmitter-side signal-processing operations may be provided, including MIMO (e.g., array) processing. This transmitter embodiment may be adapted to generate multicarrier signals configured to appear as a single-carrier signal in the time domain.

Figure 30B shows a receiver apparatus and method of the invention. A receiver system 3001 couples single-carrier and/or multicarrier transmissions from a communication channel, and adapts the received signals for baseband or IF processing. In particular, the receiver system 3001 may perform filtering, amplification, down conversion, analog-to-digital conversion, cyclic-prefix removal, and/or other receiver processing operations that are well known in the art. The receiver system 3001 may be adapted to perform MIMO (e.g., array) processing. A received signal is separated into a plurality of orthogonal subcarrier components by a time-domain to frequency-domain converter 3003, such as a Fourier transform. Frequency-domain equalization and decoding of the orthogonal poly-amplitude codes is performed in a combiner 3005. The combiner 3005 multiplies the frequency bin values output by the converter 3003 with a complex conjugate of at least one of poly-amplitude code. A decision module 3007 is adapted to process the combined signal values using any combination of hard-decision and soft-decision processing.

In one aspect, a received signal for at least one user is separated into orthogonal frequency components. Channel compensation (e.g., equalization) and combining are performed to provide estimates of the transmitted symbols. ISI may be compensated via any combination of equalization and multi-user detection.

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Embodiments may employ any of a number of techniques for providing channel estimating. For many of these methods, a block of pilot chips, tones, or other known signals may be inserted into the transmitted waveform. Known symbols may be mapped to CI phase spaces. Training symbols may be provided to individual subcarriers. In other embodiments, various types of coded training symbols may be transmitted. Blind adaptive estimation and equalization may be employed.

Figure 31A illustrates a communication method of the invention. A plurality of orthogonal polyphase / poly-amplitude codes are generated 3061 in a transmitter. The codes are modulated 3062 with different data symbols. A-frequency-domain to time-domain conversion 3063 of the modulated codes is provided to generate a time-domain output. A cyclic prefix or guard interval is optionally prepended 3064 to the time-domain output, followed by transmission processing 3065 adapted to process the signal for transmission into a communication channel 99.

A receiver process 3071 couples the transmission from the channel 99 and performs receiver system processes typically performed to convert a received signal to a digital or analog baseband or IF signal. An optional cyclic-prefix removal 3072 may be performed as necessary prior to time-domain to frequency-domain conversion 3073. Interfering frequency-domain signals are separated in an interference-cancellation process 3074, which may optionally employ frequency-domain and/or time-domain equalization. Separated signal values are then post processed, which may include decision processing 3075.

Figure 31B illustrates a method of receiving single-carrier or multicarrier signals, including providing for receiver-system processing 3151 of received signals, performing a time-domain to frequency-domain conversion 3153 of the received signals to produce a plurality of orthogonal subcarrier values, providing for frequency-domain-equalization of the subcarrier values, providing for CI decoding 3157 (which includes combining), and providing for decision processing 3159.

Figure 32 illustrates a sub-space/subcarrier processor receiver of the invention. A plurality M of receiver systems 3251 to 3259 is adapted to couple a plurality of interfering single-carrier or multicarrier signals from a communication channel. M receiver branches are provided for frequency-domain analysis of received signals.

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Optional cyclic prefix removal modules 3261 may be provided. A set of M time-domain to frequency-domain converters, such as DFTs 3271 to 3279, separate received signals in each branch into a plurality N of subcarrier values. Each of a plurality of sub-space processors 3281 to 3289 processes the subcarrier values. For example, N sub-space processors 3281 to 3289 can process M signals at a time that were mapped into each of the N subcarrier frequencies.

The output of each sub-space processor 3281 to 3289 is characterized by up to M sub-space values. Each of a plurality of CI decoders 3291 to 3299, such as CI block decoders or CI sliding window decoders, combine subcarrier values corresponding to a particular subspace.

Figure 33A illustrates basic components of CI signal generation software residing on a computer-readable medium 3399. CI signal generation software is typically configured to control the function and transmission-signal output of a single carrier or multicarrier transmitter. In some cases, a CI transmission may be characterized as a single-carrier signal in the time domain having a plurality of predetermined frequency-domain (or spectral) components.

A subcarrier allocation source code segment 3301 is adapted to generate a plurality of subcarriers allocated to at least one user or allocate a plurality of input subcarriers (not shown) to a particular user. A subcarrier weighting source code segment 3302 is adapted to provide complex weights (e.g., CI codes) to a plurality of the allocated subcarriers. The weights are configured to map one or more input data symbols into one or more phase spaces.

The computer-readable medium 3399 may include any item of manufacture adapted to store or convey software and/or firmware. The source-code segments 3301 and 3302 may reside on a physical memory storage device, such as any magnetic, electrical, or optical device adapted to store data and/or computer command instructions. The source-code segments 3301 and 3302 may be implemented as gate configurations on a programmable or integrated circuit. Other means for arranging physical devices and/or electromagnetic phenomena may be employed to convey the function of the source-code segments 3301 and 3302. Accordingly, the computer-readable medium 3399 may include any combination of FPGAs, ASICs, transient memory, and persistent memory.

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Subcarrier allocation may include generating subcarriers, providing for receiving input subcarriers, retrieving subcarriers or superposition waveforms from memory (e.g., a look-up table), or selecting non-zero (or equivalently, zero) valued input bin weights of an invertible transform, such as a DFT. In some applications, subcarrier allocation can include pulse shaping, controlling symbol durations, and/or selecting subcarrier frequency spacing. Some frequencies may be selected or avoided relative to channel conditions, bandwidth requirements, and/or interference.

The subcarrier allocation source code segment 3301 and subcarrier weighting source code segment 3302 may be implemented in one program. Similarly, other processing operations typically performed in a communication system transmitter may be implemented in, or in addition to, the source-code segments 3301 and 3302. It should be appreciated that subcarrier allocation, selection, and assignment can include providing subcarriers for system control and/or monitoring. Subcarrier allocation, as described throughout the specification may include providing for pilot tones, training sequences, and/or other subcarriers allocated to other system-control functions. Subcarrier weighting may include channel coding, source coding, spread-spectrum coding, formatting, multiple-access coding, multiplexing, encryption, modulation, and/or array processing. Systems and methods illustrated herein and described throughout the specification may be implemented as source-code segments residing on one or more computer-readable mediums.

Network control in CI communications may be adapted to enable users to share network resources (e.g., bandwidth). For example, channel resources in the form of phase spaces and/or subcarriers may be allocated to each user relative to their level of service. Bandwidth may be allocated to users relative-to any combination of individual throughput requirements, purchased level of service, and availability of bandwidth.

Figure 33B illustrates a subcarrier weighting source code segment 3391 and a CI combining source code segment 3392 residing on a computer-readable medium 3399. Source code segment 3391 is adapted to process one or more received channel measurements (such as frequency-domain or time-domain measurements) for generating a plurality of subcarrier weights. These weights are adapted to compensate for one or more channel effects, including, but not limited to, multipath, dispersion, and co-channel

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interference. The weights may be adapted to provide CI decoding. The weights may be adapted relative to one or more channel and/or data-quality measurements. The weights may be configured relative to data-processing measurements, such as hard-decision, soft-decision, and/or iterative feedback decision processing. The weights are typically applied to a plurality of subcarriers, such as frequency components produced by a filter bank or an FFT. Subcarrier weighting may include filtering, such as providing for acquiring subcarrier frequencies allocated to at least one predetermined user. Consequently, subcarrier weights may include both zero and non-zero values. Subcarrier weighting may include channel decoding, source decoding, spread-spectrum decoding, formatting, multiple-access decoding, demultiplexing, decryption, array processing, and/or modulation.

Source-code segment 3392 is adapted to combine the received and weighted carriers to generate a processed signal output, which is typically a sequence of symbols. At least one type of optimal combining may be provided. Code segment 3392 is adapted to receive as input at least one received signal, such as a sequence of data symbols. The received signal may be impressed onto the weights, weighted subcarriers, or waveforms generated from one or more superpositions of the weighted subcarriers. The weights are configured to map one or more input data symbols into one or more phase spaces. In some applications, data-modulated weights may be generated in source-code segment 3391. In this case, source-code segment 3391 is adapted to process the received signal to generate at least one set of information-bearing weights.

All publications and patent applications mentioned in this specification are herein incorporated by reference to the same extent as if each individual publication or patent application was specifically and individually incorporated by reference.

Various embodiments of the invention may include variations in system configurations and the order of steps in which methods are provided. In many cases, multiple steps and/or multiple components may be consolidated.

The method and system embodiments described herein merely illustrate the principles of the invention. It should be appreciated that those skilled in the art will be able to devise various arrangements, which, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and

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scope. Furthermore, all examples and conditional language recited herein are intended to be only for pedagogical purposes to aid the reader in understanding the principles of the invention. This disclosure and its associated references are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

It should be appreciated by those skilled in the art that the block diagrams herein represent conceptual views of illustrative circuitry, algorithms, and functional steps embodying the principles of the invention. Similarly, it should be appreciated that any flow charts, flow diagrams, signal diagrams, system diagrams, codes, and the like represent various processes which may be substantially represented in computer-readable medium and so executed by a computer or processor, whether or not such computer or processor is explicitly shown.

The functions of the various elements shown in the drawings, including functional blocks labeled as “processors” or “systems,” may be provided through the use of dedicated hardware as well as hardware capable of executing software in association with appropriate software. When provided by a processor, the functions may be provided by a single dedicated processor, by a shared processor, or by a plurality of individual processors, some of which may be shared. Moreover, explicit use of the term "processor" or "controller" should not be construed to refer exclusively to hardware capable of executing software, and may implicitly include, without limitation, digital signal processor (DSP) hardware, read-only memory (ROM) for storing software, random access memory (RAM), and non-volatile storage. Other hardware, conventional and/or custom, may also be included. Similarly, the function of any component or device described herein may be carried out through the operation of program logic, through dedicated logic, through the interaction of program control and dedicated logic, or even manually, the particular technique being selectable by the implementer as more specifically understood from the context.

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Any element expressed herein as a means for performing a specified function is intended to encompass any way of performing that function including, for example, a combination of circuit elements which performs that function or software in any form, including, therefore, firmware, micro-code or the like, combined with appropriate circuitry for executing that software to perform the function. The invention as defined herein resides in the fact that the functionalities provided by the various recited means are combined and brought together in the manner which the operational descriptions call for. Applicant regards any means which can provide those functionalities as equivalent as those shown herein.

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Patent Application of:	Docket No.: CBF-006.C3.2
Steve Shattil	Confirmation No.: 5226
Application No.: 17105576	Group Art Unit:
Filed: 26-NOV-2020	Examiner:

For: **TRANSMIT PRE-CODING**

Commissioner for Patents
P.O. BOX 1700
Alexandria, VA 22313-1700

PRELIMINARY AMENDMENT

Sir:

Prior to examination on the merits, please amend the above-identified application as follows.

Amendments to the Specification begin on page 2 and include both an attached Substitute Specification and an annotated Specification showing changes in accordance with 37 C.F.R. 1.125.

The listing of **Claims** begins on page 3.

Amendments to the **Drawings** begin on page 11 and include additional drawing sheets.

Remarks begin on page 12.

AMENDMENTS TO THE SPECIFICATION

Please REPLACE the Specification with the attached Substitute Specification. An annotated Specification showing changes in accordance with 37 C.F.R. 1.125 is also attached.

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CLAIMS

The following is a complete list of all claims in this application.

1. (Original) A method for receiving an Orthogonal Frequency Division Multiplexing (OFDM) signal transmitted by a user device in a wireless network, the method comprising:

determining a plurality of subcarrier frequencies allocated to the user device;

converting the OFDM signal to a plurality of frequency-domain values corresponding to the plurality of subcarrier frequencies; and

decoding the plurality of frequency-domain values to recover a plurality of data symbols encoded by the user device on the plurality of subcarrier frequencies;

wherein decoding employs a plurality of codes that are inverse to, complex-conjugate of, or complementary to a set of complex-valued codes that the user device employs to shape the OFDM signal into a superposition of cyclic-shifted pulse waveforms that each has one of the plurality of data symbols modulated thereon.

2. (Original) The method of claim 1, wherein each of the plurality of codes employed for decoding comprises a different vector of linear phase offsets.

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3. (Original) The method of claim 1, wherein the cyclic-shifted waveforms have cyclic shifts that cause the cyclic-shifted waveforms to be orthogonal, and each of the plurality of codes employed for decoding comprises a set of linear phase offsets that corresponds to one of the cyclic shifts.

4. (Original) The method of claim 1, wherein the complex-valued codes cause the cyclic-shifted waveforms to be Sinc waveforms, and the plurality of codes is configured to decode the Sinc waveforms.

5. (Original) The method of claim 1, wherein the plurality of subcarrier frequencies has a frequency spacing f_s, and the plurality of cyclic-shifted waveforms are periodic over a symbol interval $T_s = 1/f_s$.

6. (Original) The method of claim 1, wherein converting the OFDM signal to a plurality of frequency-domain values uses a discrete Fourier transform.

7. (Original) The method of claim 1, further comprising removing at least one of a guard interval, a cyclic prefix, and a cyclic postfix from the OFDM signal before converting the OFDM signal to the plurality of frequency-domain values.

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8. (Original) The method of claim 1, wherein converting the OFDM signal to the plurality of frequency-domain values provides for orthogonal frequency division multiple access for the user device and at least one other user device.

9. (Original) The method of claim 1, wherein an mth one of the plurality of codes is expressed as a set of N code chips for a set of integers n = {0,..., N-1}, wherein each code chip is expressed by $e^{i2\pi nm/N}$, wherein *i* is the square root of -1, and π is Pi.

10. (Original) An apparatus for receiving an Orthogonal Frequency Division Multiplexing (OFDM) signal transmitted by a user device in a wireless network, the apparatus comprising:

at least one processor; and

a non-transitory computer-readable memory communicatively coupled to the at least one processor, the non-transitory computer-readable memory including a set of instructions stored thereon and executable by the at least one processor for:

determining a plurality of subcarrier frequencies allocated to the user device;

converting the OFDM signal to a plurality of frequency-domain values corresponding to the plurality of subcarrier frequencies; and

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decoding the plurality of frequency-domain values to recover a plurality of data symbols encoded by the user device on the plurality of subcarrier frequencies;

wherein decoding employs a plurality of codes that are inverse to, complex-conjugate of, or complementary to a set of complex-valued codes that the user device employs to shape the OFDM signal into a superposition of cyclic-shifted pulse waveforms that each has one of the plurality of data symbols modulated thereon.

11. (Original) The apparatus of claim 10, wherein each of the plurality of codes employed for decoding comprises a different vector of linear phase offsets.

12. (Original) The apparatus of claim 10, wherein the cyclic-shifted waveforms have cyclic shifts that cause the cyclic-shifted waveforms to be orthogonal, and each of the plurality of codes employed for decoding comprises a set of linear phase offsets that corresponds to one of the cyclic shifts.

13. (Original) The apparatus of claim 10, wherein the complex-valued codes cause the cyclic-shifted waveforms to be Sinc waveforms, and the plurality of codes is configured to decode the Sinc waveforms.

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14. (Original) The apparatus of claim 10, wherein the plurality of subcarrier frequencies has a frequency spacing f_s, and the plurality of cyclic-shifted waveforms are periodic over a symbol interval $T_s = 1/f_s$.

15. (Original) The apparatus of claim 10, wherein converting the OFDM signal to a plurality of frequency-domain values uses a discrete Fourier transform.

16. (Original) The apparatus of claim 10, wherein the non-transitory computer-readable memory further includes instructions stored thereon and executable by the at least one processor for removing at least one of a guard interval, a cyclic prefix, and a cyclic postfix from the OFDM signal before converting the OFDM signal to the plurality of frequency-domain values.

17. (Original) The apparatus of claim 10, wherein converting the OFDM signal to the plurality of frequency-domain values provides for orthogonal frequency division multiple access for the user device and at least one other user device.

18. (Original) The apparatus of claim 10, wherein an mth one of the plurality of codes is expressed as a set of N code chips for a set of integers n = {0,..., N-1}, wherein each code chip is expressed by $e^{i2\pi nm/N}$, wherein *i* is the square root of -1, and π is Pi.

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19. (Original) A computer program product for receiving an Orthogonal Frequency Division Multiplexing (OFDM) signal transmitted by a user device in a wireless network, the computer program product comprising a non-transitory computer readable storage device having computer readable program code stored therein, said program code containing instructions executable by one or more processors of a computer system for:

determining a plurality of subcarrier frequencies allocated to the user device;

converting the OFDM signal to a plurality of frequency-domain values corresponding to the plurality of subcarrier frequencies; and

decoding the plurality of frequency-domain values to recover a plurality of data symbols encoded by the user device on the plurality of subcarrier frequencies;

wherein decoding employs a plurality of codes that are inverse to, complex-conjugate of, or complementary to a set of complex-valued codes that the user device employs to shape the OFDM signal into a superposition of cyclic-shifted pulse waveforms that each has one of the plurality of data symbols modulated thereon.

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20. (Original) The computer program product of claim 19, wherein each of the plurality of codes employed for decoding comprises a different vector of linear phase offsets.

21. (Original) The computer program product of claim 19, wherein the cyclic-shifted waveforms have cyclic shifts that cause the cyclic-shifted waveforms to be orthogonal, and each of the plurality of codes employed for decoding comprises a set of linear phase offsets that corresponds to one of the cyclic shifts.

22. (Original) The computer program product of claim 19, wherein the complex-valued codes cause the cyclic-shifted waveforms to be Sinc waveforms, and the plurality of codes is configured to decode the Sinc waveforms.

23. (Original) The computer program product of claim 19, wherein the plurality of subcarrier frequencies has a frequency spacing f_s, and the plurality of cyclic-shifted waveforms are periodic over a symbol interval $T_s = 1/f_s$.

24. (Original) The computer program product of claim 19, wherein converting the OFDM signal to a plurality of frequency-domain values uses a discrete Fourier transform.

25. (Original) The computer program product of claim 19, wherein the non-transitory computer-readable storage device further includes instructions stored therein and

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executable by the one or more processors for removing at least one of a guard interval, a cyclic prefix, and a cyclic postfix from the OFDM signal before converting the OFDM signal to the plurality of frequency-domain values.

26. (Original) The computer program product of claim 19, wherein converting the OFDM signal to the plurality of frequency-domain values provides for orthogonal frequency division multiple access for the user device and at least one other user device.

27. (Original) The computer program product of claim 19, wherein an mth one of the plurality of codes is expressed as a set of N code chips for a set of integers n = {0,…, N-1}, wherein each code chip is expressed by $e^{i2\pi nm/N}$, wherein *i* is the square root of -1, and π is Pi.

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AMENDMENTS TO THE DRAWINGS

Please ADD the attached Drawing Sheets 18 to 32 to the current drawing sheets.

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REMARKS

By this amendment, the additional Drawings and the amendments to the Specification constitute an insertion of material that was previously incorporated by reference in this application in accordance with 37 C.F.R. 1.57(f). Specifically, the additional Drawings and the inserted text in the Specification consists of the same material in published patent appl. nos. 20040086027 and 20030147655, which were previously incorporated by reference in the current application. Applicant respectfully contents that no issue of new matter has been added by this amendment.

No amendment was made to the claims.

If the Examiner believes, for any reason, that personal communication will expedite prosecution of this application, the Examiner is invited to telephone the undersigned at the number provided.

Prompt and favorable consideration of this Reply is respectfully requested.

Respectfully Submitted,

/Steven J Shattil/

Steven J Shattil
Reg. No. 40170

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Doc Code: TRACK1.REQ
Document Description: TrackOne Request

PTO/AIA/424 (04-14)

CERTIFICATION AND REQUEST FOR PRIORITIZED EXAMINATION UNDER 37 CFR 1.102(e) (Page 1 of 1)

First Named Inventor:	Steve Shattil	Nonprovisional Application Number (if known):	
Title of Invention:	Transmit Pre-Coding		

APPLICANT HEREBY CERTIFIES THE FOLLOWING AND REQUESTS PRIORITIZED EXAMINATION FOR THE ABOVE-IDENTIFIED APPLICATION.

1. The processing fee set forth in 37 CFR 1.17(i)(1) and the prioritized examination fee set forth in 37 CFR 1.17(c) have been filed with the request. The publication fee requirement is met because that fee, set forth in 37 CFR 1.18(d), is currently $0. The basic filing fee, search fee, and examination fee are filed with the request or have been already been paid. I understand that any required excess claims fees or application size fee must be paid for the application.

2. I understand that the application may not contain, or be amended to contain, more than four independent claims, more than thirty total claims, or any multiple dependent claims, and that any request for an extension of time will cause an outstanding Track I request to be dismissed.

3. The applicable box is checked below:

I. ☑ Original Application (Track One) - Prioritized Examination under § 1.102(e)(1)

i. (a) The application is an original nonprovisional utility application filed under 35 U.S.C. 111(a). This certification and request is being filed with the utility application via EFS-Web.

---OR---

(b) The application is an original nonprovisional plant application filed under 35 U.S.C. 111(a). This certification and request is being filed with the plant application in paper.

ii. An executed inventor's oath or declaration under 37 CFR 1.63 or 37 CFR 1.64 for each inventor, **or** the application data sheet meeting the conditions specified in 37 CFR 1.53(f)(3)(i) is filed with the application.

II. ☐ Request for Continued Examination - Prioritized Examination under § 1.102(e)(2)

i. A request for continued examination has been filed with, or prior to, this form.
ii. If the application is a utility application, this certification and request is being filed via EFS-Web.
iii. The application is an original nonprovisional utility application filed under 35 U.S.C. 111(a), or is a national stage entry under 35 U.S.C. 371.
iv. This certification and request is being filed prior to the mailing of a first Office action responsive to the request for continued examination.
v. No prior request for continued examination has been granted prioritized examination status under 37 CFR 1.102(e)(2).

Signature /Steven J Shattil/	Date 11/26/2020
Name (Print/Typed) Steven J Shattil	Practitioner Registration Number 40170

Note: *This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4(d) for signature requirements and certifications. Submit multiple forms if more than one signature is required.**

☐ *Total of 1 forms are submitted.

Privacy Act Statement

The **Privacy Act of 1974 (P.L. 93-579)** requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (*i.e.*, GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

PTO/AIA/14 (12-13)
Approved for use through 01/31/2014. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76.
This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.

Secrecy Order 37 CFR 5.2

☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)

Inventor Information:

Inventor 1 — Remove

Legal Name

Prefix	Given Name	Middle Name	Family Name	Suffix
	Steve		Shattil	

Residence Information (Select One) ● US Residency Non US Residency Active US Military Service

City	Cheyenne	State/Province	WY	Country of Residence	US

Mailing Address of Inventor:

Address 1	PO Box 17355
Address 2	

City	Boulder	State/Province	CO
Postal Code	80308	Country	US

All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the **Add** button. Add

Correspondence Information:

Enter either Customer Number or complete the Correspondence Information section below.
For further information see 37 CFR 1.33(a).

☐ **An Address is being provided for the correspondence Information of this application.**

Customer Number	74284		
Email Address	genghiscomm@gmail.com	Add Email	Remove Email

Application Information:

Title of the Invention	Transmit Pre-Coding		
Attorney Docket Number	CBF-006.C3.2	Small Entity Status Claimed	☒
Application Type	Nonprovisional		
Subject Matter	Utility		
Total Number of Drawing Sheets (if any)	17	Suggested Figure for Publication (if any)	8A

Filing By Reference :

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

Only complete this section when filing an application by reference under 35 U.S.C. 111(c) and 37 CFR 1.57(a). Do not complete this section if application papers including a specification and any drawings are being filed. Any domestic benefit or foreign priority information must be provided in the appropriate section(s) below (i.e., "Domestic Benefit/National Stage Information" and "Foreign Priority Information").

For the purposes of a filing date under 37 CFR 1.53(b), the description and any drawings of the present application are replaced by this reference to the previously filed application, subject to conditions and requirements of 37 CFR 1.57(a).

Application number of the previously filed application	Filing date (YYYY-MM-DD)	Intellectual Property Authority or Country

Publication Information:

☐ Request Early Publication (Fee required at time of Request 37 CFR 1.219)

☒ **Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32).
Either enter Customer Number or complete the Representative Name section below. If both sections are completed the customer Number will be used for the Representative Information during processing.

Please Select One:	● Customer Number	US Patent Practitioner	○ Limited Recognition (37 CFR 11.9)
Customer Number	74284		

Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78.
When referring to the current application, please leave the application number blank.

Prior Application Status	Pending		Remove
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
	Division of	14727769	2015-06-01
Prior Application Status	Patented		Remove

Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)	Patent Number	Issue Date (YYYY-MM-DD)
14727769	Continuation of	14276309	2014-05-13	9048897	2015-06-02

Prior Application Status	Patented	Remove

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)	Patent Number	Issue Date (YYYY-MM-DD)
14276309	Continuation of	12545572	2009-08-21	9042333	2015-05-26
Prior Application Status	Patented			Remove	
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)	Patent Number	Issue Date (YYYY-MM-DD)
12545572	Division of	11187107	2005-07-22	8670390	2014-03-11
Prior Application Status	Expired			Remove	
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)		
11187107	Claims benefit of provisional	60598187	2004-08-02		

Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the **Add** button. Add

Foreign Priority Information:

This section allows for the applicant to claim priority to a foreign application. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(d). When priority is claimed to a foreign application that is eligible for retrieval under the priority document exchange program (PDX)[i] the information will be used by the Office to automatically attempt retrieval pursuant to 37 CFR 1.55(h)(1) and (2). Under the PDX program, applicant bears the ultimate responsibility for ensuring that a copy of the foreign application is received by the Office from the participating foreign intellectual property office, or a certified copy of the foreign priority application is filed, within the time period specified in 37 CFR 1.55(g)(1).

Remove

Application Number	Country[i]	Filing Date (YYYY-MM-DD)	Access Code[i] (if applicable)

Additional Foreign Priority Data may be generated within this form by selecting the **Add** button. Add

Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications

☐ This application (1) claims priority to or the benefit of an application filed before March 16, 2013 and (2) also contains, or contained at any time, a claim to a claimed invention that has an effective filing date on or after March 16, 2013.
NOTE: By providing this statement under 37 CFR 1.55 or 1.78, this application, with a filing date on or after March 16, 2013, will be examined under the first inventor to file provisions of the AIA.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

Authorization to Permit Access:

☐ Authorization to Permit Access to the Instant Application by the Participating Offices

If checked, the undersigned hereby grants the USPTO authority to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the World Intellectual Property Office (WIPO), and any other intellectual property offices in which a foreign application claiming priority to the instant patent application is filed access to the instant patent application. See 37 CFR 1.14(c) and (h). This box should not be checked if the applicant does not wish the EPO, JPO, KIPO, WIPO, or other intellectual property office in which a foreign application claiming priority to the instant patent application is filed to have access to the instant patent application.

In accordance with 37 CFR 1.14(h)(3), access will be provided to a copy of the instant patent application with respect to: 1) the instant patent application-as-filed; 2) any foreign application to which the instant patent application claims priority under 35 U.S.C. 119(a)-(d) if a copy of the foreign application that satisfies the certified copy requirement of 37 CFR 1.55 has been filed in the instant patent application; and 3) any U.S. application-as-filed from which benefit is sought in the instant patent application.

In accordance with 37 CFR 1.14(c), access may be provided to information concerning the date o f filing this Authorization.

Applicant Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Applicant 1 Remove

If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.

Clear

● Assignee	Legal Representative under 35 U.S.C. 117	Joint Inventor
Person to whom the inventor is obligated to assign.	Person who shows sufficient proprietary interest	

If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:

Name of the Deceased or Legally Incapacitated Inventor :	
If the Applicant is an Organization check here. ☒	
Organization Name	Genghiscomm Holdings, LLC

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

Mailing Address Information For Applicant:			
Address 1	PO Box 17355		
Address 2			
City	Boulder	State/Province	CO
Country[i]	US	Postal Code	80308
Phone Number	7202344351	Fax Number	
Email Address	genghiscomm@gmail.com		

Additional Applicant Data may be generated within this form by selecting the Add button. Add

Assignee Information including Non-Applicant Assignee Information:

Providing assignment information in this section does not subsitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Assignee 1

Complete this section if assignee information, including non-applicant assignee information, is desired to be included on the patent application publication . An assignee-applicant identified in the "Applicant Information" section will appear on the patent application publication as an applicant. For an assignee-applicant, complete this section only if identification as an assignee is also desired on the patent application publication.

Remove

If the Assignee or Non-Applicant Assignee is an Organization check here. ☒

Organization Name	Genghiscomm Holdings, LLC

Mailing Address Information For Assignee including Non-Applicant Assignee:			
Address 1	PO Box 17355		
Address 2			
City	Boulder	State/Province	CO
Country[i]	US	Postal Code	80308
Phone Number	7202344351	Fax Number	
Email Address	genghiscomm@gmail.com		

Additional Assignee or Non-Applicant Assignee Data may be generated within this form by selecting the Add button. Add

Signature:

Remove

NOTE: This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4 for signature requirements and certifications.

Signature	/Steven J Shattil/	Date (YYYY-MM-DD)	2020-11-26

PTO/AIA/14 (12-13)
Approved for use through 01/31/2014. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	CBF-006.C3.2
	Application Number	
Title of Invention	Transmit Pre-Coding	

First Name	Steven	Last Name	Shattil	Registration Number	40170

Additional Signature may be generated within this form by selecting the Add button. Add

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

Privacy Act Statement

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5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent C o o p eration Treaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.

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9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

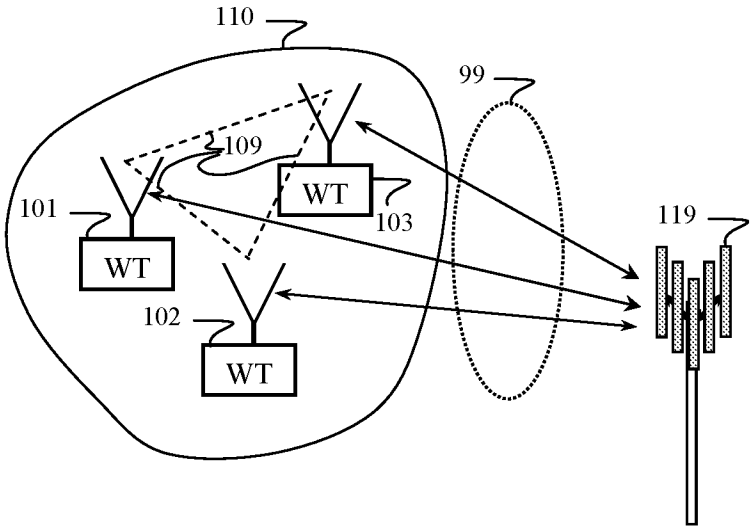


FIGURE 1A

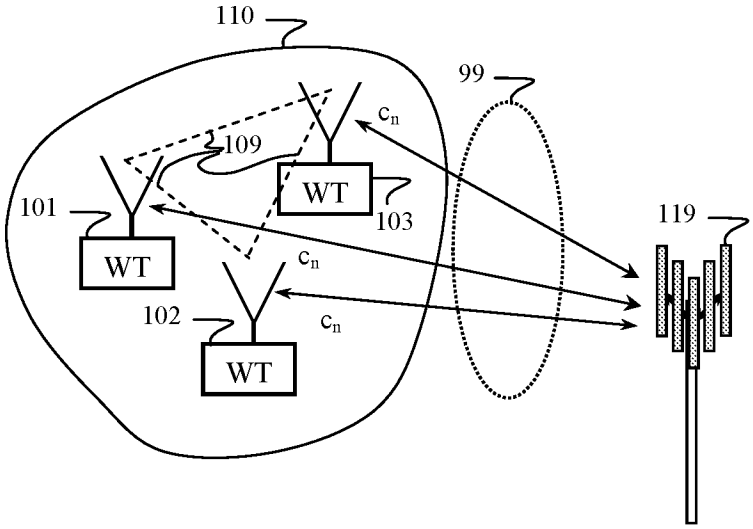


FIGURE 1B

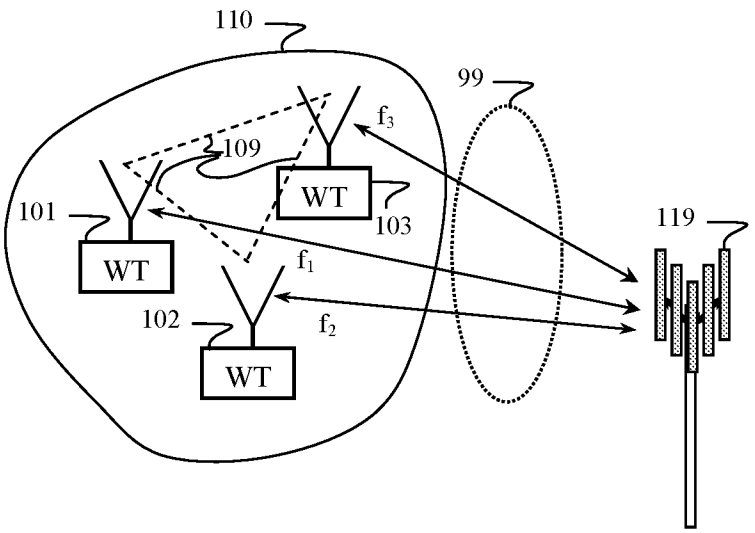


FIGURE 1C

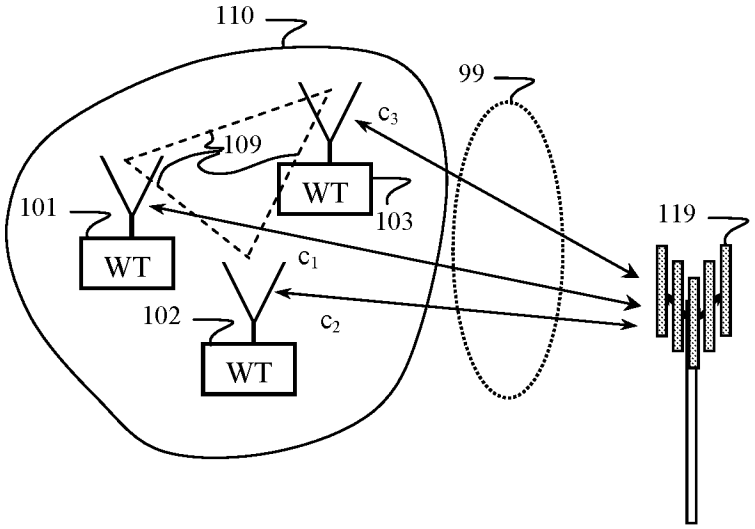


FIGURE 1D

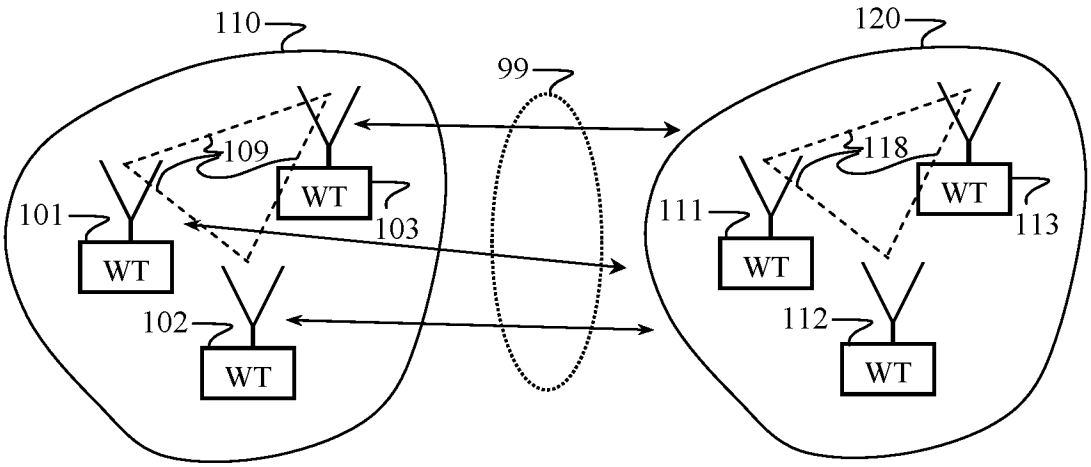


FIGURE 1E

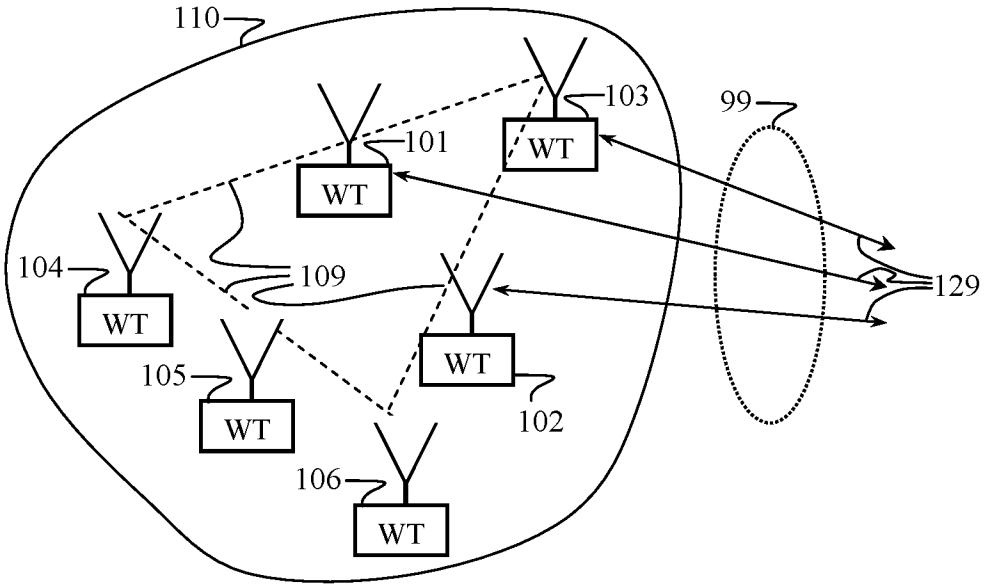


FIGURE 1F

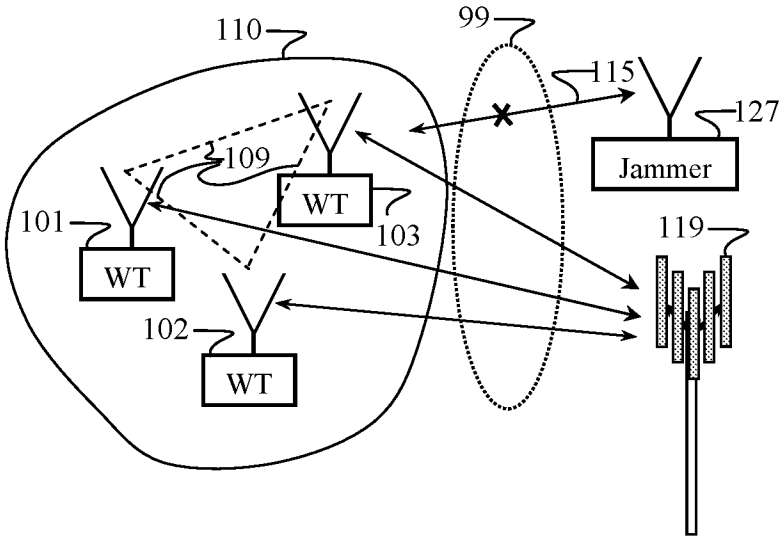


FIGURE 1G

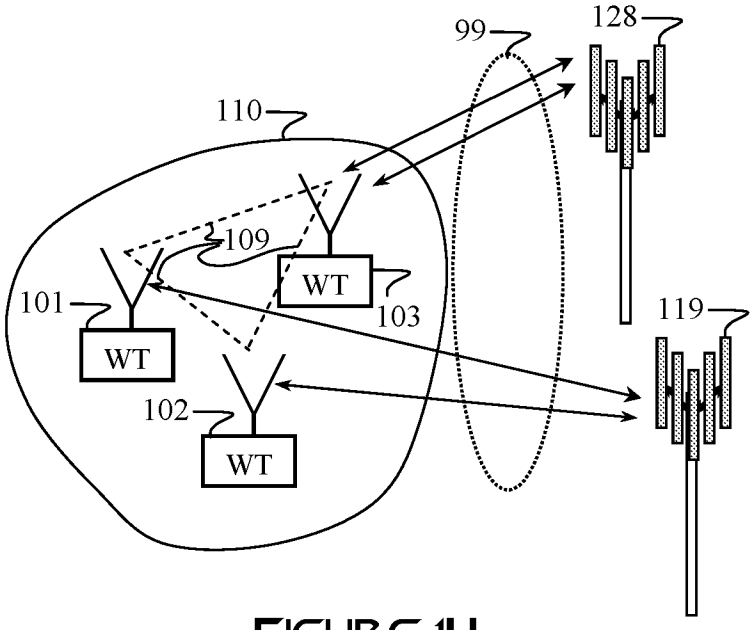


FIGURE 1H

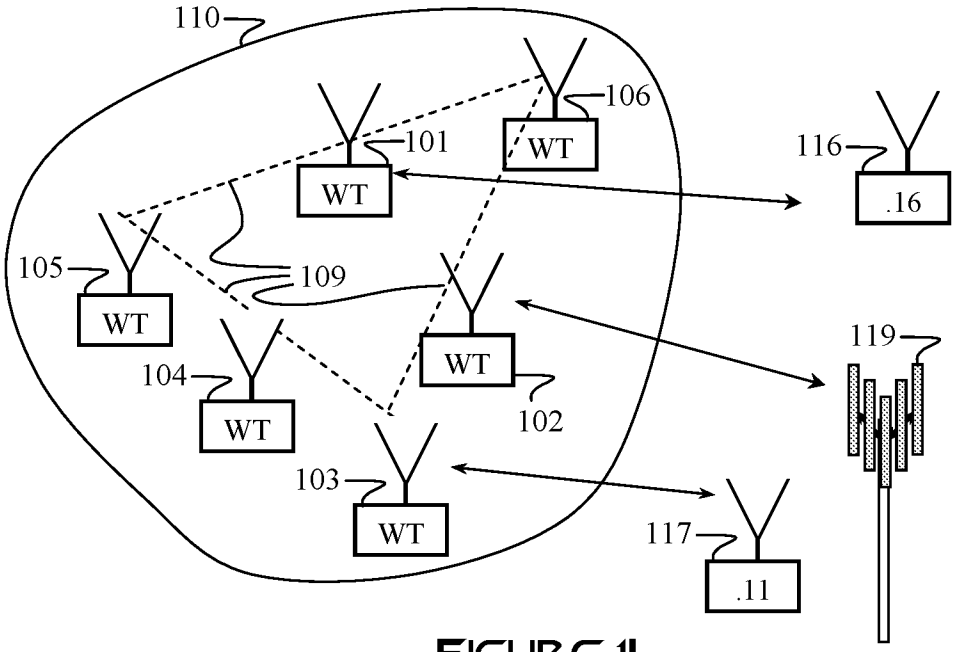


FIGURE 1I

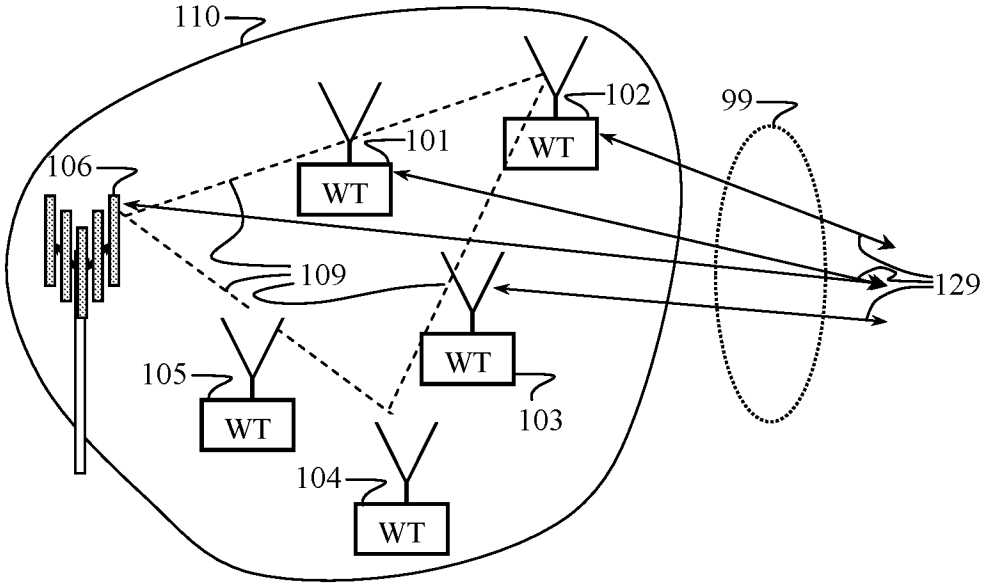


FIGURE 1J

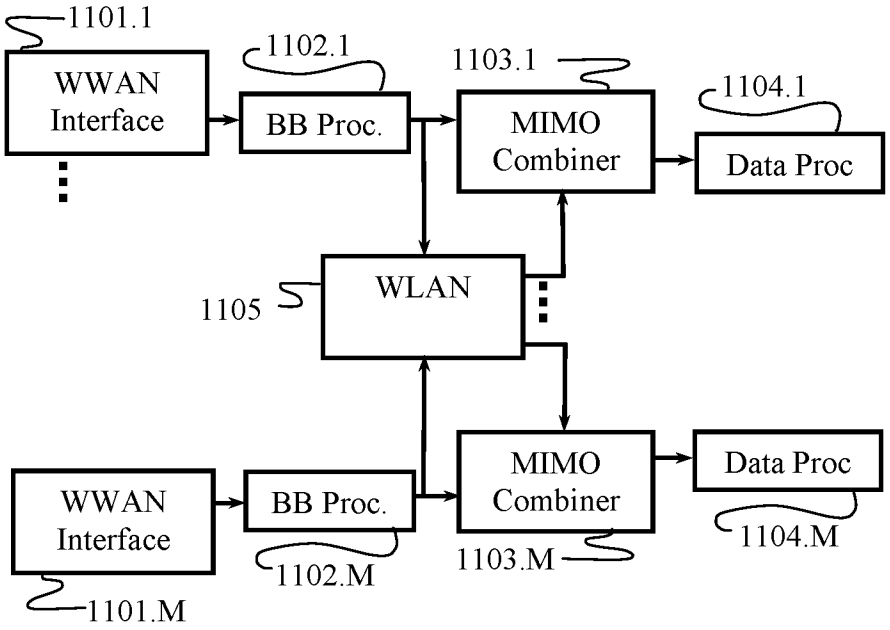


FIGURE 2A

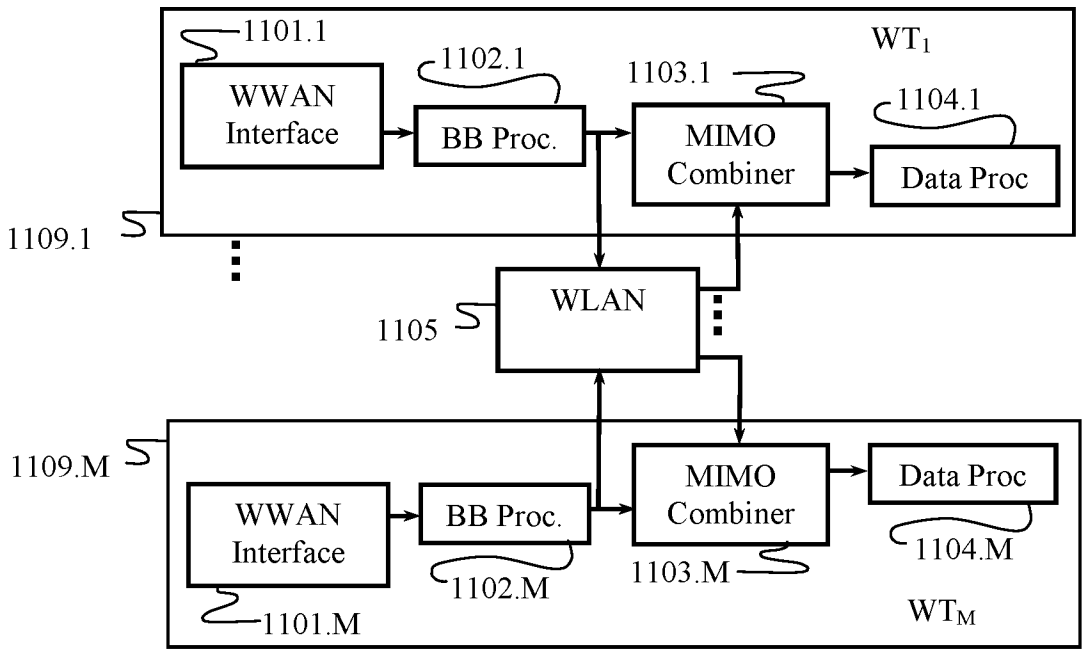


FIGURE 2B

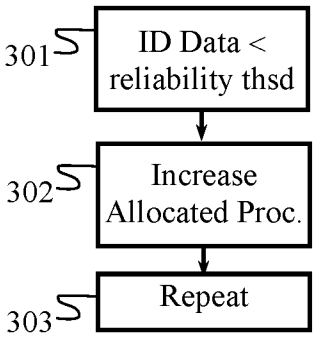


FIGURE 3A

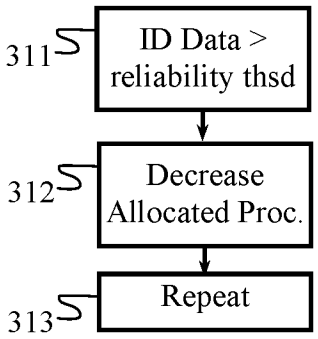


FIGURE 3B

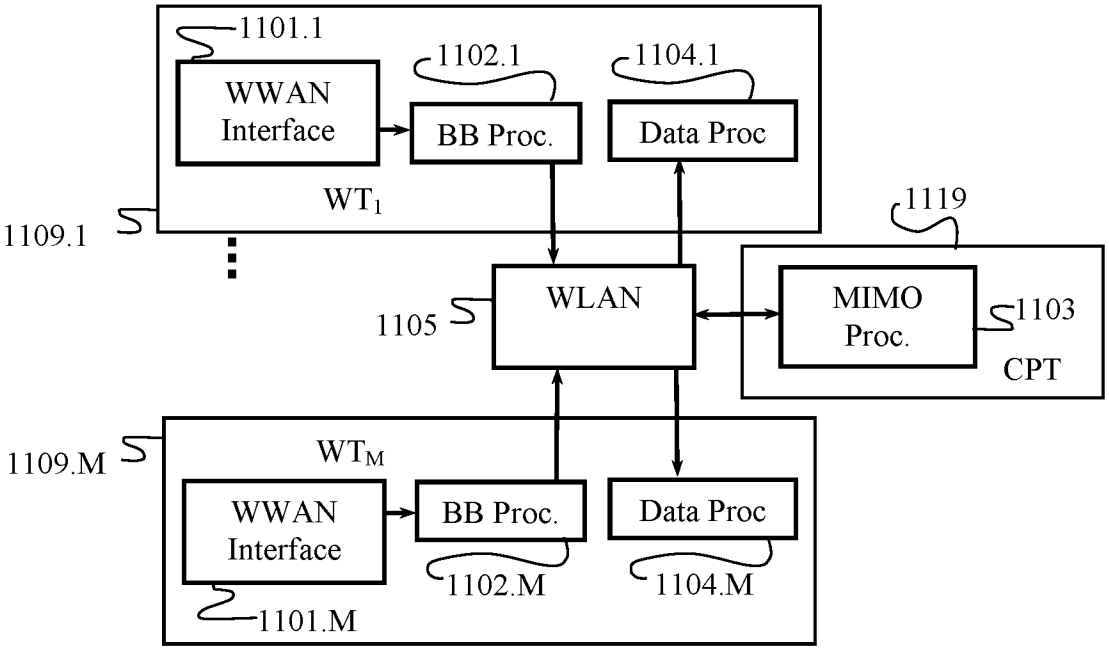


FIGURE 4A

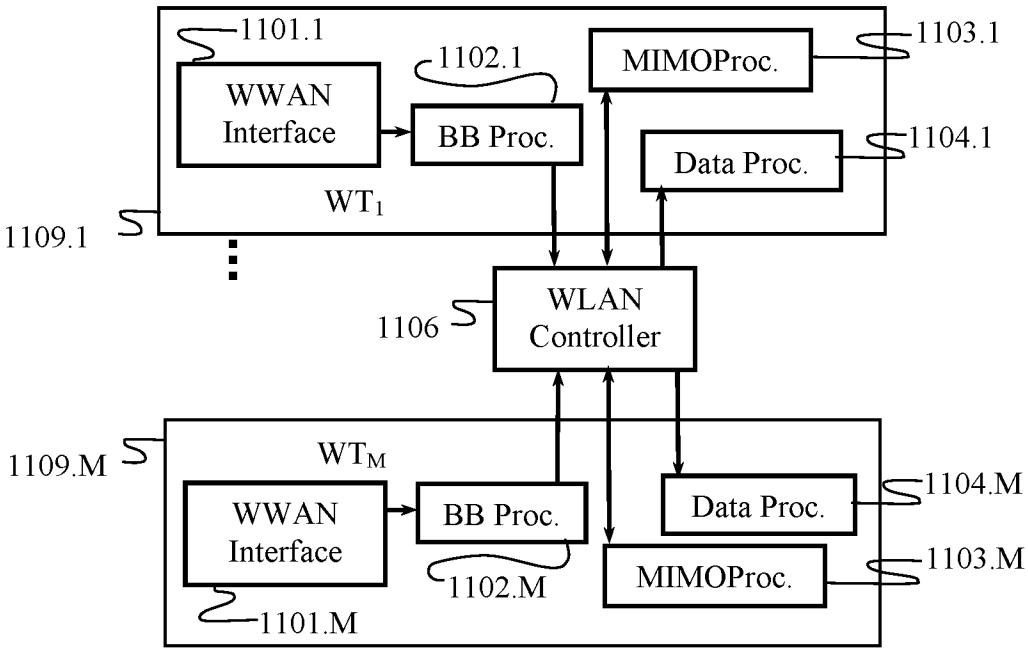


FIGURE 4B

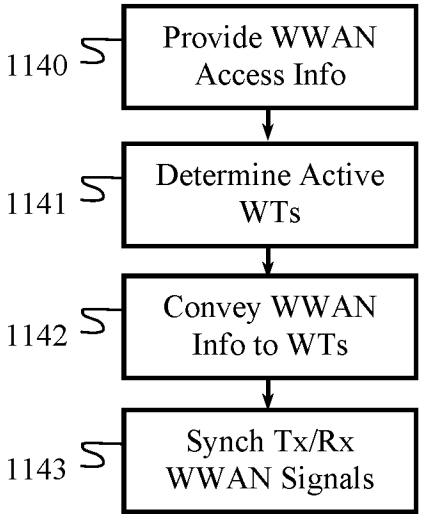


FIGURE 4C

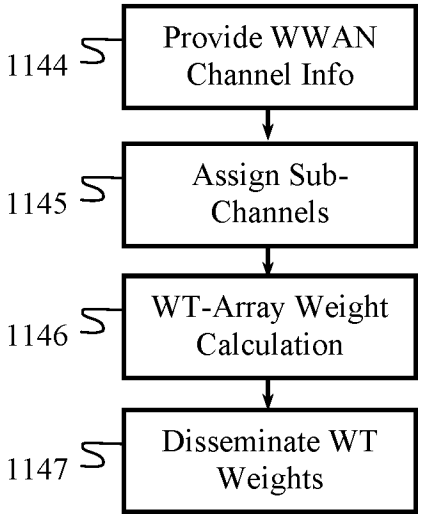


FIGURE 4D

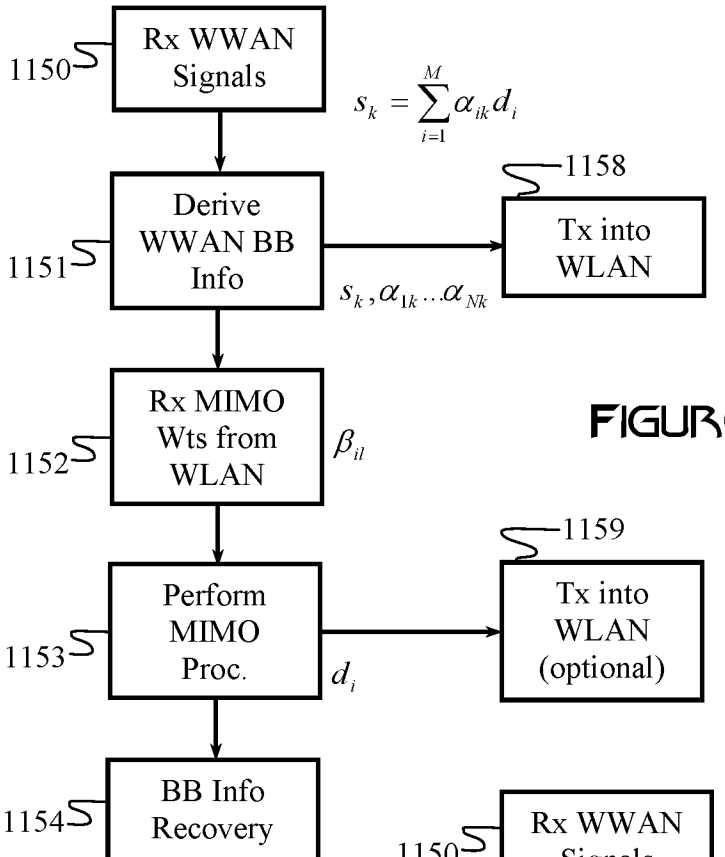


FIGURE 5A

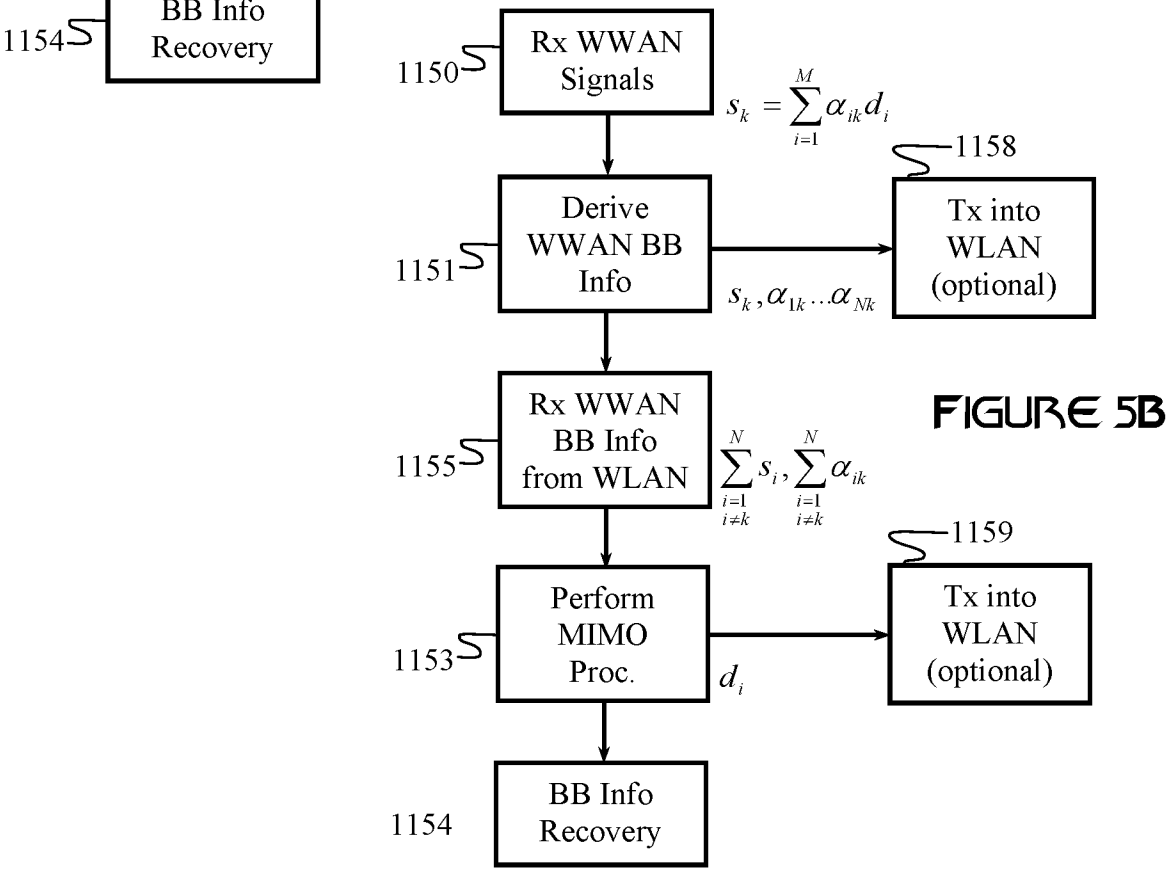


FIGURE 5B

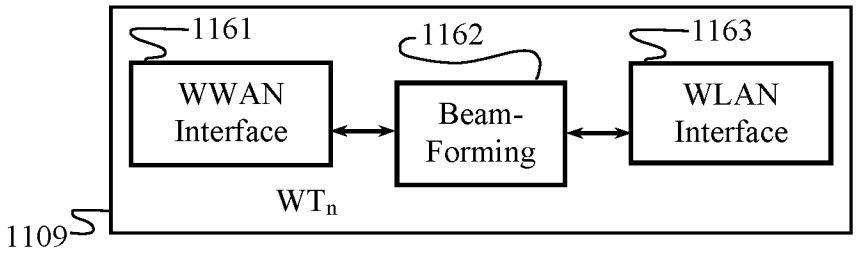


FIGURE 6A

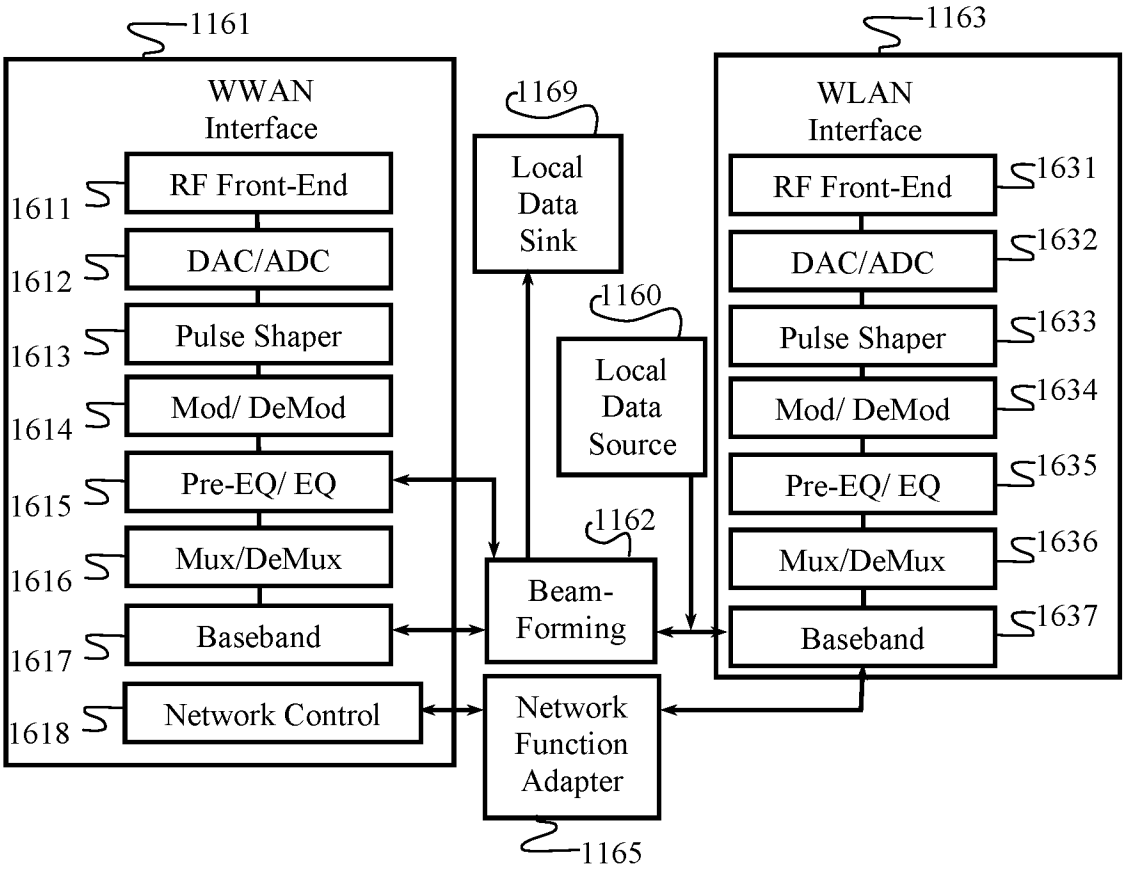


FIGURE 6B

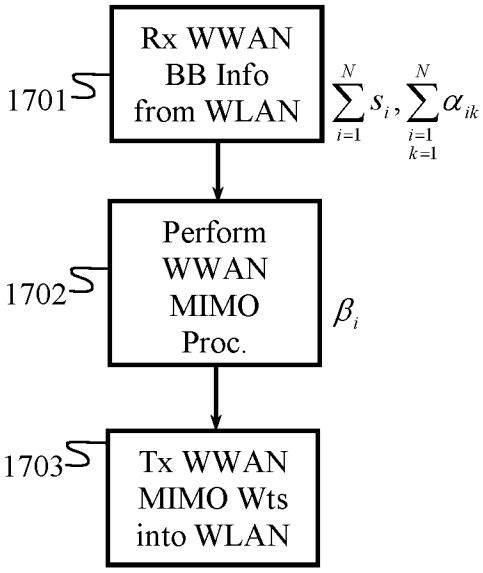


FIGURE 7A

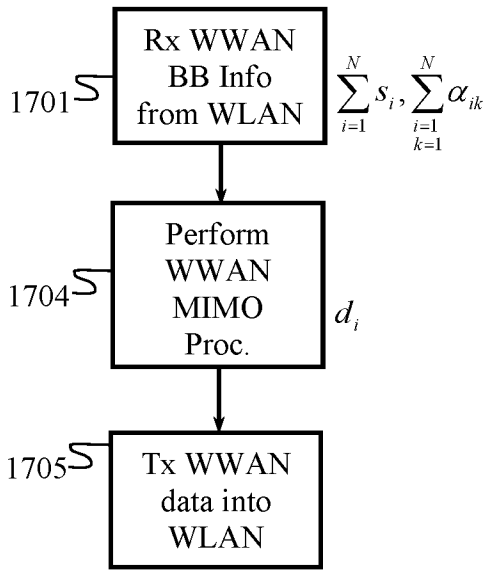


FIGURE 7B

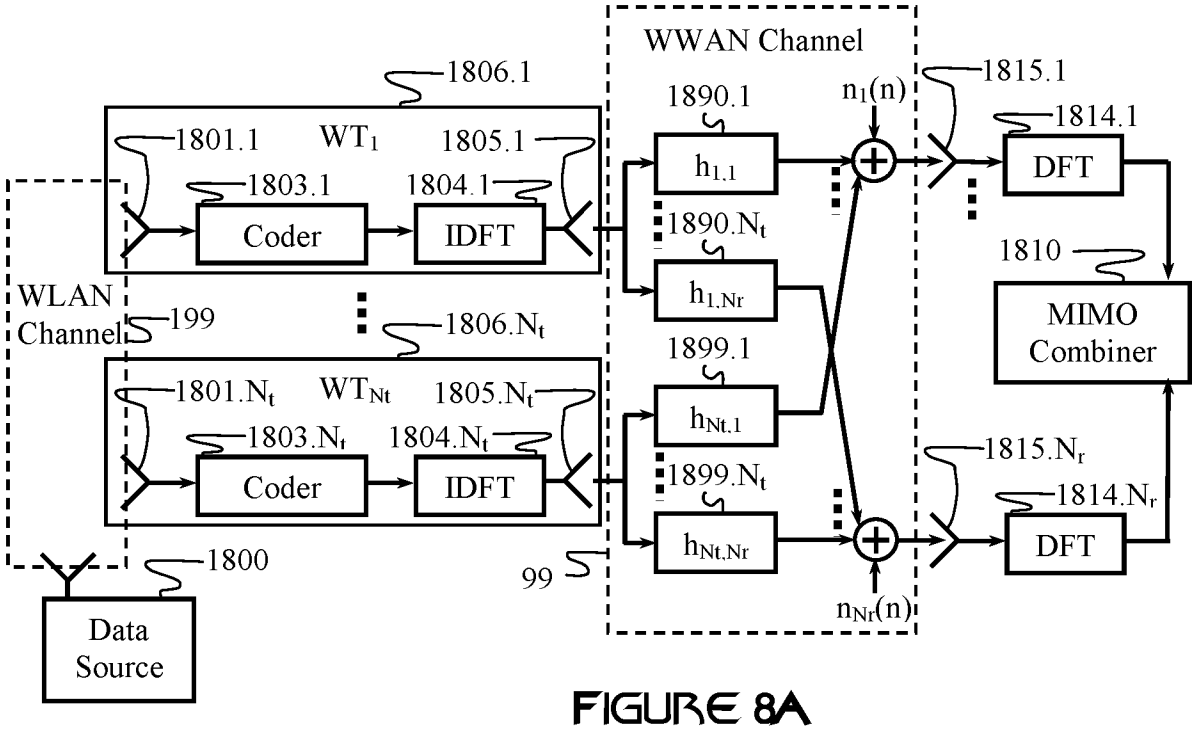


FIGURE 8A

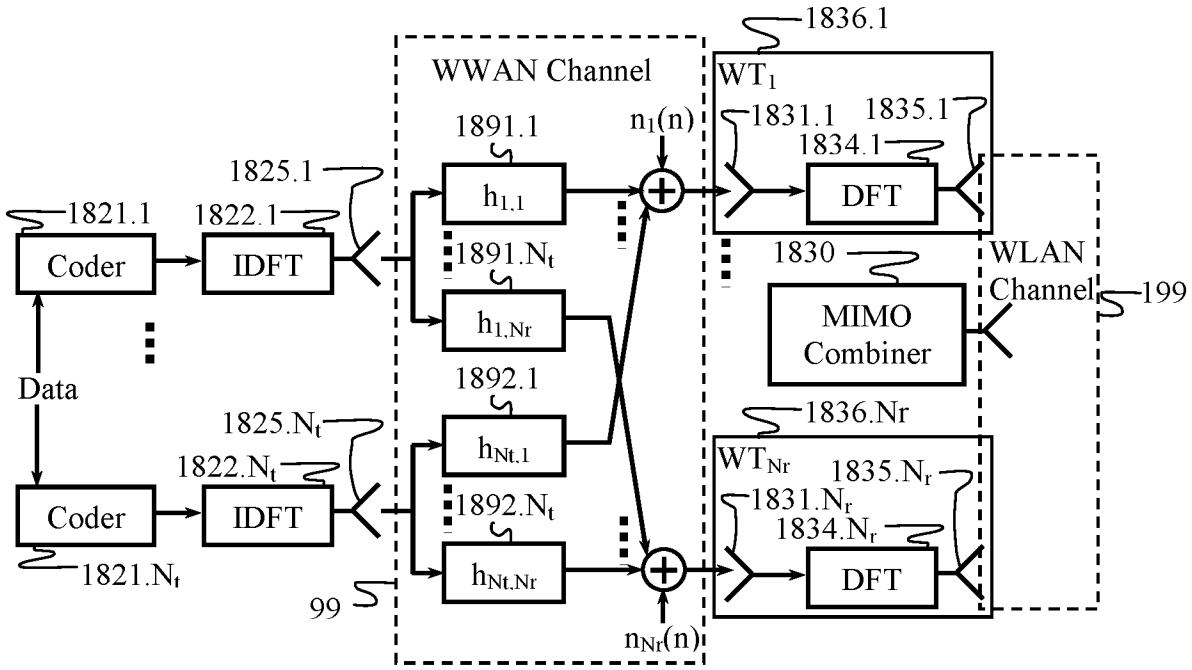


FIGURE 8B

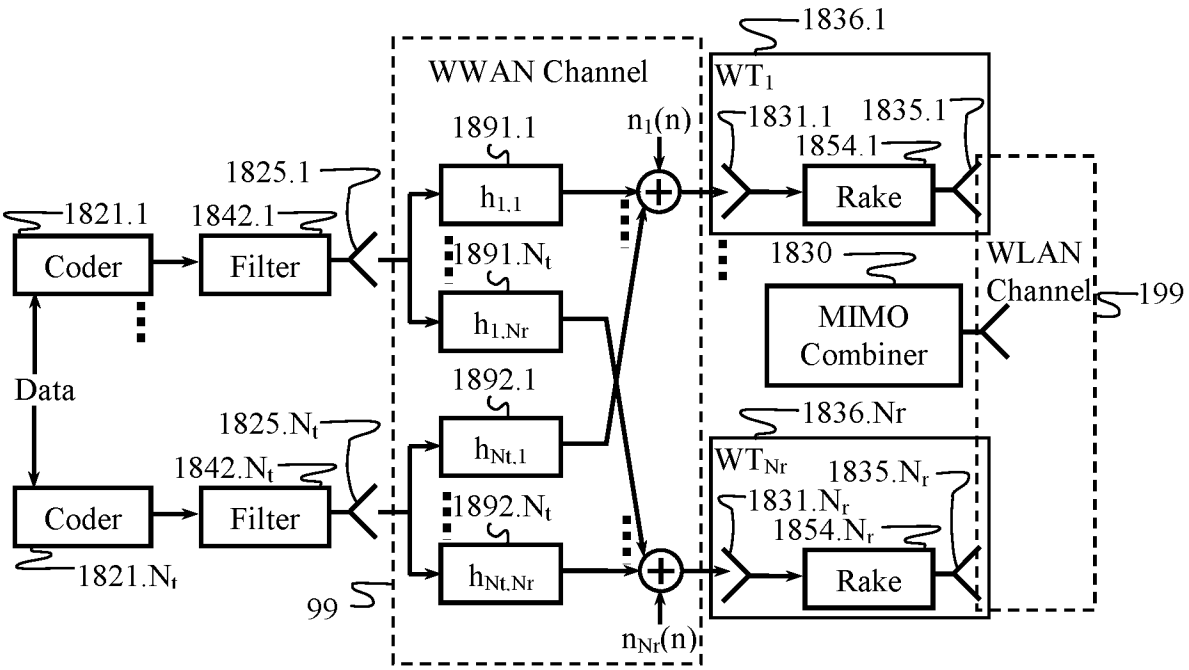

1836.1
WWAN Channel
WT1
1891.1
n1(n)
1831.1
1835.1
1854.1
1825.1
h1,1
Rake
1821.1
1842.1
Coder
Filter
1891.Nt
1830
WLAN
h1,Nr
MIMO
Channel
199
Combiner
Data
1892.1
1836.Nr
1825.Nt
hNt,1
WTNr
1835.Nr
1842.Nt
1831.Nr
1892.Nt
1854.Nr
Coder
Filter
Rake
1821.Nt
hNt,Nr
99
nNr(n)

FIGURE 8C

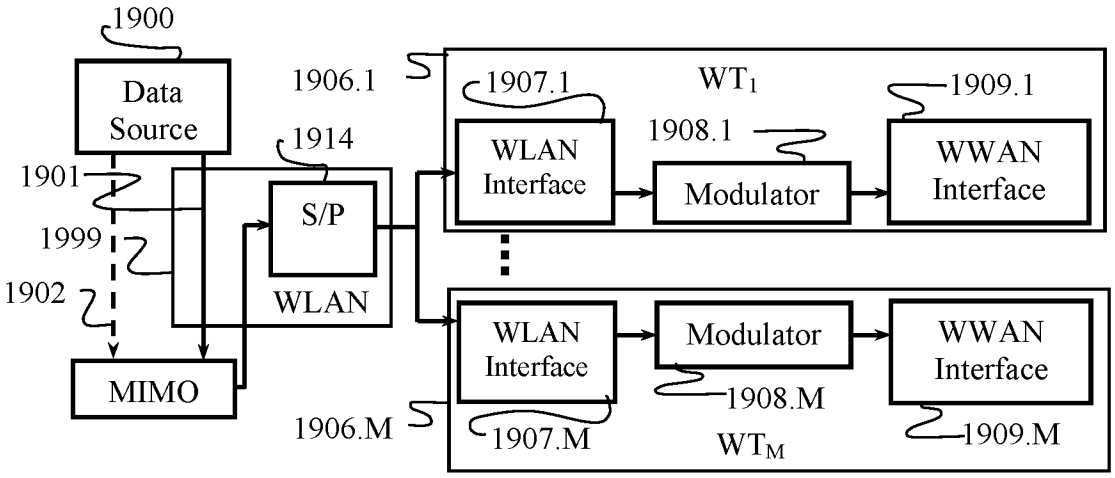


FIGURE 9A

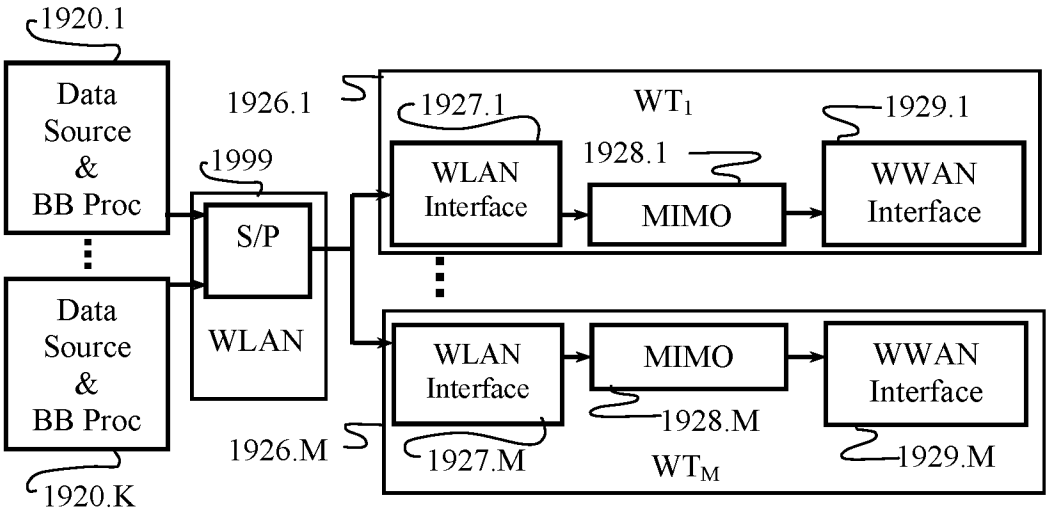


FIGURE 9B

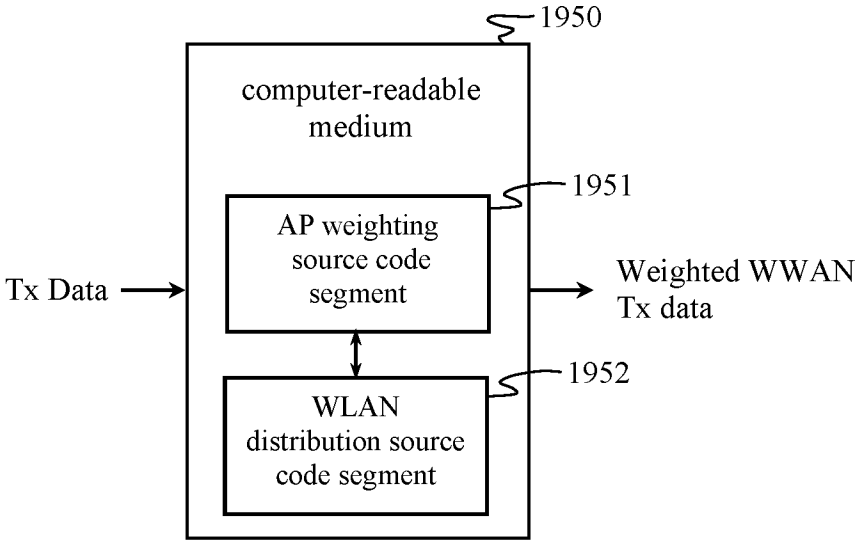


FIGURE 10A

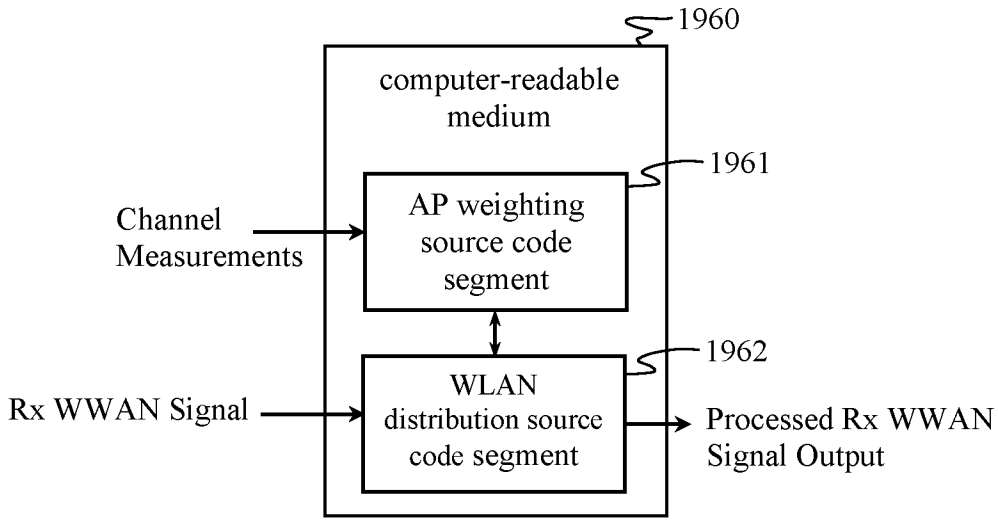


FIGURE 10B

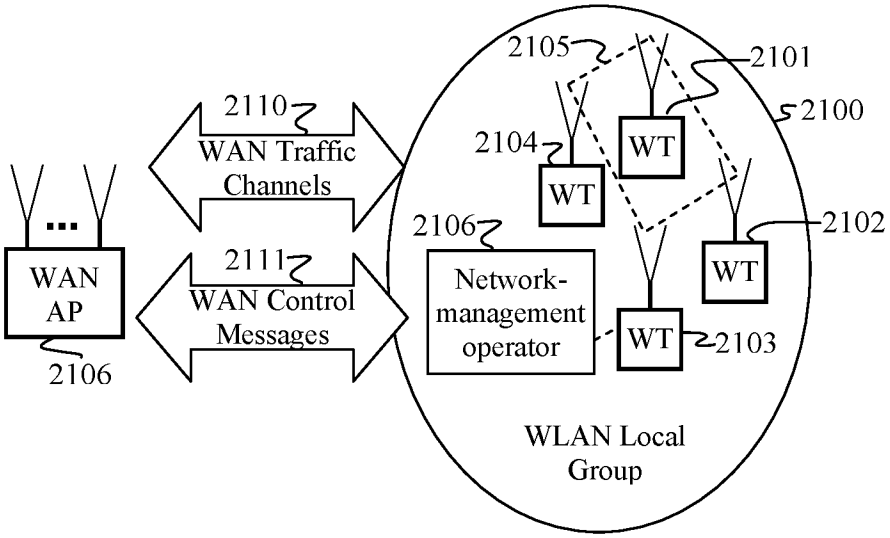

2105
2101
2100
2110
WAN Traffic Channels
2104
WT
WT
2106
2102
WT
2111
WAN Control Messages
WAN AP
Network-management operator
WT
2103
2106
WLAN Local Group

FIGURE 11

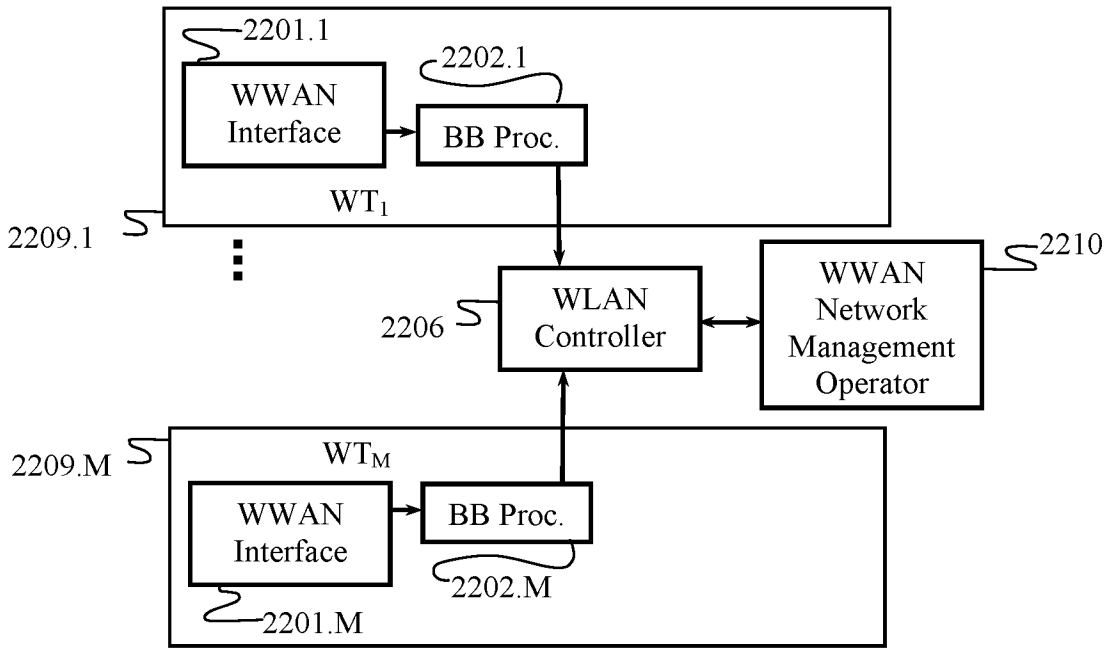


FIGURE 12

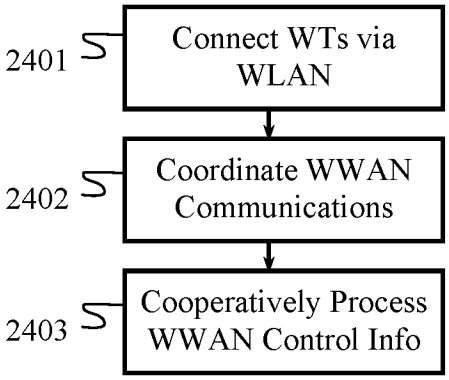


FIGURE 14

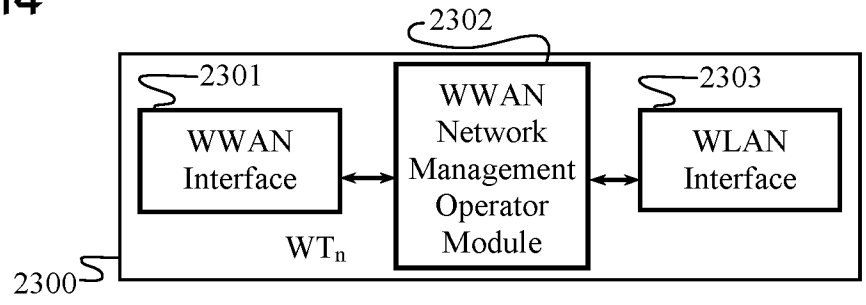


FIGURE 13

Abstract

A method for receiving an Orthogonal Frequency Division Multiplexing (OFDM) signal transmitted by a user device in a wireless network comprises determining which subcarrier frequencies are allocated to the user device; converting the OFDM signal to a frequency-domain values corresponding to the subcarrier frequencies; and decoding the frequency-domain values to recover data symbols encoded by the user device on the subcarrier frequencies. The decoding employs codes that are inverse to, complex-conjugate of, or complementary to a set of complex-valued codes employed by the user device to shape the OFDM signal into a superposition of cyclic-shifted pulse waveforms, wherein each of the pulse waveforms has one of the data symbols modulated thereon.

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Patent Application

of

Steve Shattil

for

Transmit Pre-Coding

RELATED APPLICATIONS

This application is a Continuation of U.S. Pat. Appl. No. 14/727,769, filed June 1, 2015, which is a Continuation of U.S. Pat. Appl. No. 14/276,309, filed May 13, 2014, now U.S. Pat. No. 9,048,897, which is a Continuation of U.S. Pat. Appl. No. 12/545,572, filed August 21, 2009, now U.S. Pat. No. 9,042,333, which is a Divisional of U.S. Pat. Appl. No. 11/187,107, filed on July 22, 2005, now U.S. Pat. No. 8,670,390, which claims priority to Provisional Appl. No. 60/598,187, filed August 2, 2004, all of which are incorporated by reference in their entireties.

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BACKGROUND

I. Field

Disclosed aspects relate generally to antenna-array processing and ad-hoc networking, and particularly to providing cooperative signal processing between a plurality of wireless terminal devices, such as to improve network access.

II. Background

Wireless data service is an emerging market with high growth potential. However, market growth requires higher bandwidth and better coverage than cellular technologies can provide. Furthermore, state-of-the-art wireless network technologies are mainly focused on the server side, rather than using mobile wireless terminals to extend the network infrastructure.

A peer-to-peer mode of communication is expected to offer distinct performance benefits over the conventional cellular model, including better spatial-reuse characteristics, lower energy consumption, and extended coverage areas. The key advantage of the peer-to-peer network model is the increase in spatial reuse due to its short-range transmissions. Although peer-to-peer networking shows some promise, there are significant drawbacks that prevent conventional peer-to-peer networks from being a technically and commercially viable solution.

Recent analyses of multi-hop networks compared to cellular networks have indicated that the spatial reuse improvement in the peer-to-peer network model does not translate into greater throughput. Rather, the throughput is lower than that observed in the cellular network model. This observation is explained in three parts:

- *Multi-hop Routes:* Although the spatial reuse is increased, since a flow traverses multiple hops in the peer-to-peer network model, the end-to-end throughput of a flow, while directly proportional to the spatial reuse, is also inversely proportional to the hop-length. Moreover, since the expected hop-length in a dense network is of the order of $O(\sqrt{n})$, a tighter bound on the expected per-flow throughput is $O(1/\sqrt{n})$. While this bound is still higher than that of the dense cellular network model ($O(1/n)$), the following two reasons degrade the performance even more.
- *Base-Station Bottleneck:* The degree of spatial reuse and expected per-flow throughput of the peer-to-peer network model is valid for a network where all flows

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have destinations within the same cell. In this case, the base station is the destination for all flows (e.g., it is the destination of the wireless path). Thus, any increase in spatial reuse cannot be fully realized as the channel around the base-station becomes a bottleneck and has to be shared by all the flows in the network. Note that this is not an artifact of the single-channel model. As long as the resources around the base-station are shared by all the flows in the network (irrespective of the number of channels), the performance of the flows will be limited to that of the cellular network model.

- *Protocol Inefficiencies:* The protocols used in the cellular network model are both simple and centralized, with the base station performing most of the coordination. Cellular protocols operate over a single hop, leading to very minimal performance degradation because of protocol inefficiencies. However, in the peer-to-peer network model, the protocols (such as IEEE 802.11 and DSR) are distributed, and they operate over multiple hops. The multi-hop path results in more variation in latency, losses, and throughput for TCP. These inefficiencies (which arise because of the distributed operation of the medium access and routing layers) and the multi-hop operation at the transport layer translate into a further degraded performance.

Similarly, antenna-array processing has demonstrated impressive improvements in coverage and spatial reuse. Array-processing systems typically employ multiple antennas at base stations to focus transmitted and received radio energy and thereby improve signal quality. In cellular communications, improvements in signal quality lead to system-wide benefits with respect to coverage, service quality and, ultimately, the economics of cellular service. Furthermore, the implementation of antenna arrays at both ends of a communication link can greatly increase the capacity and performance benefits via Multiple Input Multiple Output (MIMO) processing. However, power, cost, and size constraints typically make the implementation of antenna arrays on mobile wireless terminals, such as handsets or PDAs, impractical.

In cooperative diversity, each wireless terminal is assigned an orthogonal signal space relative to the other terminals for transmission and/or reception. In particular, both multiplexing and multiple access in cooperative diversity are orthogonal. In antenna-array processing, either or both multiplexing and multiple access are non-orthogonal.

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Specifically, some form of interference cancellation is required to separate signals in an array-processing system because transmitted and/or received information occupies the same signal space.

Applications and embodiments relate to ad-hoc networking and antenna-array processing. Embodiments may address general and/or specific needs that are not adequately serviced by the prior art, including (but not limited to) improving network access (e.g., enhancing range, coverage, throughput, connectivity, and/or reliability). Applications of certain embodiments may include tactical, emergency response, and consumer wireless communications. Due to the breadth and scope of the present invention, embodiments may be provided for achieving a large number of objectives and applications, which are too numerous to list herein. Therefore, only some of the objects and advantages of specific embodiments are discussed in the Summary and in the Detailed Description.

SUMMARY

Some of the exemplary embodiments of the disclosure are summarized as follows. Embodiments include beam-forming systems configured to enable spatially separated wireless terminals (WTs) to perform beam-forming operations in a wireless wide area network (WWAN). A wireless local area network (WLAN) couples together the WTs, which may be configured to share WWAN data, access, and control information. A beam-forming system may comprise the WTs, which function as elements of an antenna array. WWAN network access functions (such as monitoring control channels and exchanging control messages with the WWAN) may be provided in a centralized or a distributed manner with respect to the WTs.

Embodiments also include systems and methods configured for allocating network resources among the WTs, load balancing, distributed computing, antenna-switching diversity, WWAN diversity, interference mitigation, hand off, power control, authentication, session management, ad-hoc network control, error correction coding, and interference mitigation. Other embodiments and variations thereof are described in the Detailed Description.

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In one embodiment, a computer program comprises a beam-forming weight calculation source code segment adapted to calculate at least one set of beam-forming weights for signaling between at least one group of WTs and at least one WWAN, and a WLAN information-distribution source code segment adapted to distribute at least one of a set of signals between the at least one group of WTs, the set of signals including a plurality of received WWAN signals, a plurality of WWAN transmission data, and the at least one set of beam-forming weights.

In another embodiment. a computer program comprises a beam-forming weight source code segment adapted to calculate at least one set of beam-forming weights for signaling between at least one group of WTs and at least one WWAN, and a MIMO combining source code segment adapted to combine a plurality of weighted received WWAN signals, at least one of the beam-forming weight source code segment and the MIMO combining source code segment including WLAN information-distribution source code adapted to distribute at least one of a set of signals between the at least one group of wireless terminals, the set of signals including a plurality of received WWAN signals, a plurality of WWAN transmission data, at least one channel estimate, and the at least one set of beam-forming weights.

A receiver embodiment of the invention comprises a plurality of WWAN interfaces, wherein each WWAN interface is adapted to receive at least one transmitted WWAN signal; a plurality of baseband processors wherein each baseband processor is coupled to at least one WWAN interface in the plurality of WWAN interfaces, the plurality of baseband processors adapted to generate a plurality of WWAN baseband signals; at least one WLAN coupled to the plurality of baseband processors; and at least one MIMO combiner adapted to receive at least one WWAN baseband signal from the WLAN, the at least one MIMO combiner adapted to perform MIMO combining of a plurality of WWAN baseband signals.

A transmitter embodiment of the invention comprises a plurality of WWAN interfaces wherein each WWAN interface is adapted to transmit at least one WWAN signal; at least one data source adapted to generate at least one data signal for transmission into at least one WWAN; at least one WLAN adapted to couple the at least one data signal to the plurality of WWAN interfaces for generating a plurality of WWAN

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data signals; and at least one MIMO processor adapted to generate a plurality of complex weights for weighting the plurality of WWAN data signals.

A wireless terminal according to one aspect of the invention comprises at least one WWAN interface; at least one WLAN interface; and at least one cooperative beam-forming system coupled between the WWAN interface and the WLAN interface and adapted to perform beamforming with information received from the WLAN interface.

Receivers and cancellation systems described herein may be employed in subscriber-side devices (e.g., cellular handsets, wireless modems, and consumer premises equipment) and/or server-side devices (e.g., cellular base stations, wireless access points, wireless routers, wireless relays, and repeaters). Chipsets for subscriber-side and/or server-side devices may be configured to perform at least some of the receiver and/or cancellation functionality of the embodiments described herein.

Additional embodiments, objects, and advantages are described and inferred from the following detailed descriptions and figures. Although particular embodiments are described herein, many variations and permutations of these embodiments fall within the scope and spirit of the invention. Although some benefits and advantages of the preferred embodiments are mentioned, the scope of the invention is not intended to be limited to particular benefits, uses, or objectives. Rather, embodiments of the invention are intended to be broadly applicable to different wireless technologies, system configurations, networks, and transmission protocols, some of which are illustrated by way of example in the figures and in the following detailed description. The detailed description and drawings are merely illustrative of the invention rather than limiting, the scope of the invention being defined by the appended claims and equivalents thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A illustrates an application of various embodiments of the invention to a cellular network.

Figure 1B illustrates an embodiment of the invention in which transmitted and/or received data between a WLAN group and a WWAN terminal occupies parallel, redundant channels c_n.

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Figure 1C illustrates an embodiment of the invention in which a WLAN group comprising a plurality of Wireless Terminals (WTs) is adapted to communicate with at least one WWAN node.

Figure 1D illustrates an embodiment of the invention in which communications between a WWAN node and a plurality of WTs are characterized by different, yet complementary, code spaces c_1, c_2, and c_3.

Figure 1E illustrates an embodiment of the invention in which a first WLAN group is adapted to communicate with a second WLAN group via at least one WWAN channel or network.

Figure 1F shows an embodiment of the invention wherein a WLAN group includes a plurality of WWAN-active WTs and at least one WWAN-inactive WT.

Figure 1G illustrates a cooperative beam-forming embodiment of the invention that functions in the presence of a desired WWAN terminal and a jamming source.

Figure 1H illustrates a cooperative beam-forming embodiment of the invention that functions in the presence of a plurality of desired WWAN terminals.

Figure 1I illustrates an embodiment of the invention adapted to provide a plurality of WTs in a WLAN group with access to a plurality of WWAN services.

Figure 1J illustrates an embodiment of the invention in which a WLAN group includes at least one WWAN terminal.

Figure 2A illustrates a functional receiver embodiment of the invention that may be realized in both method and apparatus embodiments.

Figure 2B illustrates a functional receiver embodiment of the invention that may be realized in both method and apparatus embodiments.

Figure 3A illustrates an embodiment of the invention in which a WLAN controller for a WLAN group allocates processing resources based on WWAN-link performance.

Figure 3B illustrates an alternative embodiment of the invention in which a WLAN controller for a WLAN group allocates processing resources based on WWAN-link performance.

Figure 4A illustrates a MIMO receiver embodiment of the invention.

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Figure 4B illustrates a functional embodiment of the invention in which MIMO processing operations are distributed over two or more WTs.

Figure 4C illustrates a functional embodiment of the invention for transmission and reception of WWAN signals in a distributed network of WTs.

Figure 4D illustrates a functional embodiment of the invention adapted to perform cooperative beamforming.

Figure 5A illustrates a receiver embodiment of the invention that may be implemented by hardware and/or software.

Figure 5B illustrates an alternative receiver embodiment of the invention.

Figure 6A illustrates functional and apparatus embodiments of the present invention pertaining to one or more WTs coupled to at least one WWAN and at least one WLAN.

Figure 6B illustrates a preferred embodiment of the invention that may be employed as either or both apparatus and functional embodiments of one or more WTs.

Figure 7A illustrates a functional embodiment of the invention related to calculating MIMO weights in a cooperative-beamforming network.

Figure 7B illustrates a functional embodiment of the invention adapted to calculate transmitted data symbols received by a cooperative-beamforming network.

Figure 8A illustrates a preferred transmitter embodiment of the invention.

Figure 8B illustrates a preferred receiver embodiment of the invention.

Figure 8C illustrates an embodiment of the invention in which a plurality of WTs is adapted to perform time-domain processing.

Figure 9A illustrates an optional transmission embodiment of the present invention.

Figure 9B illustrates a functional flow chart that pertains to transmitter apparatus and method embodiments of the invention.

Figure 10A illustrates software components of a transmission embodiment of the invention residing on a computer-readable memory.

Figure 10B illustrates software components of a receiver embodiment of the invention residing on a computer-readable memory.

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Figure 11 shows a WWAN comprising a WWAN access point (e.g., a base station) and a local group comprising a plurality of wireless terminals communicatively coupled together via a WLAN. A network-management operator is configured to handle WWAN-control operations within the local group.

Figure 12 is a block diagram of a communication system comprising a WLAN for communicatively coupling a plurality of mobile wireless terminals to a WLAN controller, and a network-management operator for cooperatively processing WWAN-control messages for the mobile wireless terminals.

Figure 13 is a block diagram of a mobile wireless terminal in accordance with an aspect of the invention in which a WWAN network management operator module is communicatively coupled to at least one other mobile wireless terminal via a WLAN and communicatively coupled to the WWAN.

Figure 14 illustrates a method in accordance with an aspect of the invention in which WWAN communications for a group of wireless terminals are cooperatively processed.

DETAILED DESCRIPTION

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the exemplary embodiments are not intended to limit the invention to the particular forms disclosed. Instead, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

Figure 1A illustrates how some embodiments of the invention may be employed in a cellular network. Each wireless terminal (WT) of a plurality of WTs 101-103 is in radio contact with at least one wireless wide area network (WWAN) terminal, which may also be referred to as a WWAN node, such as cellular base station 119. The cellular base station 119 may include one or more antennas (e.g., an antenna array). WWAN signals transmitted between the base station 119 and the WTs 101-103 propagate through a WWAN channel 99, which is typically characterized by AWGN, multipath effects, and may include external interference.

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The WTs 101-103 represent a wireless local area network (WLAN) group 110 (or local group) if they are currently connected or are capable of being connected via a WLAN 109. Accordingly, the WTs may be adapted to connect to at least one WWAN and to at least one WLAN. The WLAN group 110 may consist of two or more WTs in close enough proximity to each other to maintain WLAN communications. A given WWAN may include one or more WLAN groups, such as WLAN group 110.

In an exemplary embodiment of the present invention, the WTs 101-103 may be configured to transmit data $d_t(n)$ over a WWAN channel to the base station 119. The WTs 101-103 may also be configured to receive data $d_r(n)$ on a WWAN channel from the base station 119. The received data $d_r(n)$ is shared by the WTs 101-103 via the WLAN 109. Similarly, the transmitted data $d_t(n)$ may be distributed to the WTs 101-103 via the WLAN 109. The WLAN 109 typically comprises the wireless-communication resource between the WTs 101-103 and the associated physical-layer interface hardware. The WLAN 109 is differentiated from a WWAN by its relatively shorter range. For example, a Bluetooth or UWB system functioning within an IEEE 802.11 network would be referred to as a WLAN, whereas the 802.11 network would be referred to as a WWAN. A WLAN may operate in a different frequency band than the WWAN. Alternatively, other orthogonalizing techniques may be employed for separating WLAN and WWAN signals from each other. WLANs and WWANs, as defined herein, may employ any type of free-space transmissions, including, but not limited to, ultra-low frequency, RF, microwave, infrared, optical, and acoustic transmissions. WLANs and WWANs may employ any type of transmission modality, including, but not limited to, wideband, UWB, spread-spectrum, multi-band, narrowband, or dynamic-spectrum communications.

The WLAN 109 may also comprise the WLAN network-control functionality commonly associated with a WLAN, and the WWAN-access control functionality required to distribute necessary WWAN-access parameters (e.g., node addresses, multiple-access codes, channel assignments, authentication codes, etc.) between active WTs 101-103. The distribution of WWAN-access parameters between multiple WTs 101-103 enables each WT 101-103 to be responsive to transmissions intended for a particular WT in the local group and/or it enables a plurality of WTs 101-103 to function as a single WT when transmitting signals into the WWAN channel 99.

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Particular embodiments of the invention provide for adapting either or both the transmitted data $d_t(n)$ and the received data $d_r(n)$ in order to perform beamforming. Specifically, the group of WTs 110 may be adapted to perform antenna-array processing by linking the individual WTs together via WLAN links 109 and employing appropriate antenna-array processing on the transmitted and/or the received data, $d_t(n)$ and $d_r(n)$, respectively.

Ad-hoc wireless networks (e.g., multi-hop and peer-to-peer networks) may employ intermediate relay nodes to convey transmissions from a source to a destination. Relays reduce the transmission power requirements for sending information over a given distance. This indirectly increases the spatial-reuse factor, thus enhancing system-wide bandwidth efficiency. For this reason, ad-hoc wireless networking works particularly well with unlicensed spectrum, which is characterized by restrictive power limitations and high path loss compared to cellular bands. Similarly, for certain embodiments of the invention, it may be preferable to employ high-loss (e.g., high-frequency) channels for the WLAN connections 109.

The capacity of wireless ad-hoc networks is constrained by interference caused by the neighboring nodes, such as shown in P. Gupta and P.R. Kumar, "The Capacity of Wireless Networks," IEEE Trans. Info. Theory, vol. IT-46, no. 2, Mar. 2000, pp. 388-404 and in A. Agarwal and P. R. Kumar, ``Improved capacity bounds for wireless networks." Wireless Communications and Mobile Computing, vol. 4, pp. 251-261, 2004, both of which are incorporated by reference herein. Using directional antennas (such as antenna arrays) reduces the interference area caused by each node, which increases the capacity of the network. However, the use of directional antennas and antenna arrays on the WTs 101-103 is often not feasible, especially when there are size constraints, power restrictions, cost constraints, and/or mobility needs. Thus, some embodiments of the present invention may provide for enabling WTs to form groups that cooperate in network-access functions. This provides each member of a given WLAN group with greater network access, as well as other benefits.

Antenna-array processing is generally categorized as multiple-input, single-output (MISO), single-input, multiple-output (SIMO) or multiple input, multiple output (MIMO). Array processing often employs beam forming in at least one predetermined

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signal space or signal sub-space. For example, phased-array processing involves coherent beam-forming of at least one transmitted signal frequency. Sub-space processing often employs some form of baseband interference cancellation or multi-user detection. Other variations of phased-array and sub-space processing also exist and may be implemented in embodiments of the present invention.

Sub-space processing is commonly employed via space-time processing (e.g., Rake receivers are employed in a frequency-selective channel) and/or space-frequency processing (e.g., frequency-domain processing is employed to provide for multiple flat-fading channels). Similarly, sub-space processing may employ other diversity parameters and combinations thereof, including (but not limited to) polarization processing and code-space processing.

MIMO systems have been shown to significantly increase the bandwidth efficiency while retaining the same transmit power budget and bit-error-rate (BER) performance relative to a single input, single output (SISO) system. Similarly, for a given throughput requirement, MIMO systems require less transmission power than SISO systems. MIMO technology is useful for enabling exceptionally high bandwidth efficiency. However, many spatial-multiplexing techniques require rich scattering. Increased path loss and poor scattering are major problems for MIMO systems operating above 2.4GHz. For these reasons, lower (e.g., cellular) frequencies are often preferred for MIMO applications. However, some MIMO benefits can also be achieved at higher frequencies.

Figure 1B illustrates an embodiment of the present invention in which transmitted and/or received data between the WLAN group 110 and the WWAN terminal 119 occupies parallel, redundant channels c_n. This approach is distinct from typical cooperative-diversity implementations in which WWAN data transmissions are conveyed over a plurality of orthogonal channels. Rather, each of the WTs 101-103 transmits and/or receives on a common channel c_n. This enables many well-known types of array processing to be performed.

The WLAN group 110 may function as either or both a transmitting array and a receiving array. The signal received at an antenna array is a noisy superposition of the n transmitted signals:

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$$y(n) = \sqrt{\frac{E_s}{M_t}} Hs(n) + v(n)$$

where $\{s(n)\}_{n=0}^{N-1}$ is a sequence of transmitted vectors, E_s corresponds to the transmit energy assuming that $E_{sn}||s_n|| = 1$ for $n = 1,\ldots,M_t$, $v(n)$ represents AWGN with zero mean and variance, and H is an $M_r \times M_t$ matrix channel (where M_r is the number of receiver elements and M_t is the number of transmitter elements), which is assumed constant over N symbol periods. The nominal rank of a rational matrix H is the order of the largest minor of H that is not identically zero, such as shown in T. Kailath, Linear Systems, Prentice-Hall, Inc., 1980, (especially Sec. 6.5), which is incorporated by reference.

Channel characterization involves finding a set of channel realizations (e.g., functions) that indicate channel quality with respect to some performance metric (e.g., error probability or asymptotic criteria). In the MIMO channel, several variables contribute to the channel quality (and thus, to the optimization of channel quality), including the choice of space-time codes, receiver-terminal selection, and receiver algorithm(s) employed.

In one embodiment of the invention, a subset of WTs in a WLAN group may be selected such as to provide optimal WWAN transmission and/or reception within at least one predetermined constraint, such as an optimal or maximum number of active WWAN transceivers within the WLAN group. Such predetermined constraints may be established to optimize some combination of WWAN link performance and resource use within the WLAN group. In one embodiment, WTs experiencing the best WWAN channel conditions may be selected. Techniques employing antenna selection, such as may be used for diversity processing with antenna arrays, may be used in embodiments of the present invention. In one aspect of the invention, resource conservation may focus on WT battery power, MIMO processing complexity, and/or WLAN bandwidth.

Certain embodiments of the invention may distinguish between circuit power (e.g., power used to perform signal processing) versus transmission power. Other embodiments of the invention may provide consideration for the total battery power (e.g., processing power plus transmission power) budget, such as to provide power (e.g., battery usage) load balancing between WTs. Thus, embodiments of the invention may

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optimize a balance of signaling parameters, including (but not limited to) transmission power, channel-coding (and decoding) complexity, modulation, signal processing and the complexity associated with cooperative array processing parameters (e.g., number of active array elements, number of channels, number of WTs employed to perform signal processing, number of WTs in a WLAN group, type of array-processing operations, etc.).

Any combination of various channel-characterization functions may be employed as a measure of link performance. Example functions including, but not limited to, the following may be employed. Possible functions include the average signal strength:

$$P(\mathrm{H}) = \frac{1}{N}\sum_{n=0}^{N-1}\left\|H^{(n)}\right\|_F^2$$

the average mutual information:

$$\bar{I}(\mathrm{H}) = \frac{1}{N}\sum_{n=0}^{N-1}\log\det\left(I_{M_r} + \frac{E_s}{N_o M_t}H^{(n)}H^{(n)\mathrm{H}}\right)$$

and the normalized average mutual information:

$$\bar{I}(\mathrm{H}) = \frac{1}{N}\sum_{n=0}^{N-1}\log\det\left(I_{M_r} + \frac{E_s}{N_o}\frac{1}{\alpha}H^{(n)}H^{(n)\mathrm{H}}\right)$$

where $\alpha = \frac{1}{NM_tM_r}\sum_{n=0}^{N-1}\left\|H^{(n)}\right\|_F^2$ is an estimate of the path loss.

Theoretical capacity in a MIMO channel is typically expressed as:

$$C = \log_d \det\left[I_{M_r} + \rho/M_t HH^*\right]$$

where ρ is the average SNR.

A preferred embodiment of the invention may employ error-correcting codes to add structured redundancy to the information bits. This can be done to provide diversity, such as temporal diversity, spatial diversity, and/or frequency diversity. Embodiments of the invention may employ spreading codes, which are well known in the art. In addition to collaborative MIMO operations, the WTs may engage in collaborative decoding. In particular, a WLAN group may be provided with functionality that directs the WTs to coordinate WWAN information exchange and decoding via the WLAN.

In yet another embodiment of the invention, a WWAN terminal may be adapted to receive channel information (and/or even received data) from WTs, perform array-

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processing (e.g., MIMO) computations, and then upload the resulting array-processing weights to the WTs. The WTs may simply apply the weights to their transmitted and/or received WWAN signals, and perform any other related operations, such as combining.

Figure 1C illustrates a WLAN group 110 comprising a plurality of WTs 101-103 adapted to communicate with at least one WWAN node 119. A WWAN channel 99 expresses distortions, interference, and noise that affect WWAN transmissions between the WTs 101-103 and the WWAN node 119. Channel estimation characterizes propagation characteristics (e.g., multipath, shadowing, path loss, noise, and interference) in the WWAN channel.

In one embodiment of the invention, a given WWAN transmission is separated into spectral components (such as denoted by f_1, f_2, and f_3) by the WLAN group 110. For example, each of the WTs 101-103 may be adapted to receive predetermined spectral components f_1, f_2, and f_3 of a given transmission intended for a particular WT. Alternatively, each of the WTs 101-103 may be adapted to transmit one or more associated predetermined spectral components to the WWAN node 119.

The selection of spectral components f_1, f_2, and f_3 and their association with particular WTs 101-103 is typically performed to optimize WWAN system performance relative to the current WWAN channel 99. For example, since the frequency-dependent fading profile in a scattering-rich environment tends to be unique for each spatially separated WT 101-103 channel, the spectral components f_1, f_2, and f_3 are preferably selected to minimize the effects of deep fades and/or interference. Spectral-component selection may be selected and/or adapted to optimize one or more WWAN link-performance metrics, including, but not limited to, SNR, BER, PER, and throughput. Spectral-component selection may be performed to achieve other objectives, such as to distribute processing loads across the WLAN group 110.

The spectral components f_1, f_2, and f_3 may be characterized by overlapping or non-overlapping frequency bands. Spectral components f_1, f_2, and f_3 may each include continuous or discontinuous (e.g., frequency interleaved) frequency-band components. Spectral components f_1, f_2, and f_3 may comprise similar or different bandwidths. Furthermore, the spectral components f_1, f_2, and f_3 may include gaps or notches, such as

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to notch out interference or deep fades. Accordingly, an aggregate signal derived from combining the spectral components f_1, f_2, and f_3 may include gaps or notches.

WWAN communication signals may include multicarrier (e.g., OFDM) or single-carrier signals. In the case of single-carrier signals, the WTs 101-103 can be adapted to perform frequency-domain synthesis and/or decomposition, such as described in published patent appl. nos. 20040086027 and 20030147655, which are hereby incorporated by reference in their entireties.

Figure 1D illustrates a similar communication-system embodiment to that shown in Figure 1C, except that the transmissions between the WWAN node 119 and the WTs 101-103 are characterized by different, yet complementary, code spaces c_1, c_2, and c_3. In this case, the term complementary means that the coded transmissions corresponding to the code spaces c_1, c_2, and c_3 can sum to produce at least one predetermined WWAN coded data sequence. This may be a weighted sum due to the given channel conditions. A predetermined WWAN coded data sequence may employ a code that would ordinarily (in view of the prior art) be employed in whole. That is, it would not ordinarily be partitioned into sub-codes to be transmitted by different transmitters or received by different receivers.

In one embodiment of the invention, the code spaces c_1, c_2, and c_3 correspond to direct-sequence codes, such as may be used to provide for spreading and/or multiple access. A superposition of signals transmitted across the code spaces c_1, c_2, and c_3 may provide at least one predetermined WWAN coded data sequence received by at least one WWAN node 119. Similarly, a superposition of signals received by the WTs 101-103 and mapped onto the code spaces c_1, c_2, and c_3 may provide at least one predetermined WWAN coded data sequence that would ordinarily (in view of the prior art) be intended for a single WT. Preferred embodiments of the invention may provide for channel corrections (e.g., pre-distortion and/or receiver-side channel compensation) by either or both the WLAN group 110 and the WWAN node 119. Accordingly, the code spaces c_1, c_2, and c_3 may be adapted to account for channel conditions.

In another embodiment of the invention, the code spaces c_1, c_2, and c_3 may correspond to direct-sequence codes having predetermined spectral characteristics. It is well known that different time-domain data sequences may be characterized by different

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spectral distributions. Accordingly, embodiments of the invention may provide for selecting complementary codes c_1, c_2, and c_3 having predetermined spectral characteristics with respect to WWAN channel conditions affecting the links between the WTs 101-103 and the WWAN node 119. Thus, the codes c_1, c_2, and c_3 may be selected according to the same criteria employed for selecting the spectral components f_1, f_2, and f_3.

Figure 1E illustrates an embodiment of the invention in which a first WLAN group 110 (such as comprising WTs 101-103 connected via WLAN 109) is adapted to communicate with a second WLAN group 120 (such as comprising WTs 111-113 connected via WLAN 118) via WWAN channel 99. Applications of this embodiment may be directed toward peer-to-peer and multi-hop networks. Specifically, antenna-array processing (e.g., MIMO operations) may be performed by both WLAN groups 110 and 120. Each WLAN group (such as WLAN groups 110 and 120) may function as a single node in an ad-hoc network, a peer-to-peer network, or a multi-hop network. For example, any communication addressed to (or routed through) a particular node (such as one of the WTs 101-103) may be advantageously processed by one or more of the WTs 101-103 in the WLAN group 110. In one embodiment, each active WT 101-103 in the WLAN group 110 may be responsive to communications addressed to itself and to at least one other WT 101-103 in the WLAN group 110.

The WLAN 109 may be used to inform individual WTs 101-103 which node address(es) (or multiple-access channel assignments) to be responsive to. Similarly, the WLAN 109 may convey information to WTs 101-103 in order to spoof node addresses and/or multiple-access information and otherwise help WTs 101-103 assume channelization information related to a particular WT identity prior to transmitting signals into the WWAN. Thus, the WLAN 109 can be used to assist in synchronizing WT interactions with the WWAN. The functionality of providing for sharing WWAN-access information between WTs 101-103 may be coordinated and controlled with respect to cooperative-array (e.g., MIMO) processing.

Figure 1F shows an embodiment of the invention wherein a WLAN group 110 includes a plurality of WWAN-active WTs 101-103 and at least one WWAN-inactive WT, such as WTs 104-106. The WWAN-active WTs 101-103 may be configured to

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directly transmit and/or receive WWAN communication signals 129. WWAN-inactive WTs 104-106 are defined as WLAN-connected terminals that do not directly communicate with the WWAN. Rather, the WWAN-inactive WTs 104-106 may be in a sleep or standby mode.

In a preferred embodiment of the invention, signals routed to and from a particular WT 101-103 may be provided with beam-forming weights that allow for phased-array and/or sub-space processing. Calculation of the weights may be facilitated via distributed computing (e.g., as a load-balancing measure) across a plurality of the WTs (101-106). This allows the WLAN group 110 to scale the effective throughput of the WWAN link and coordinate system throughput with local area load balancing. In particular, the efficiency of the WWAN link is proportional to the smaller of the number of array elements at the WWAN terminal (not shown) and the number of WWAN-active transceiver antennas linked by the WLAN 109. When an equal number N of antennas is employed on both sides of the link, up to an N-fold increase in the link throughput is possible. Channel coding can be employed to exchange this increase for improved probability-of-error performance, increased range, and/or lower transmission power.

Although the capacity of a MIMO channel increases with the number of antennas employed at both ends of the link, the complexity of the transmission and reception algorithms increases accordingly. For example, the sphere decoder has a typical complexity of $O(M_T^6)$, where M_T is the number of transmitting antennas, and V-Blast has a typical complexity of $O((M_R M_T)^3)$, where M_R and M_T are respectively the number of receiving and transmitting antennas. However, the computational power increases only linearly with respect to the number of WTs (assuming each WT has identical processing capability). Thus, the aggregate processing power of the WTs may determine the maximum number of active antennas that a WLAN group 110 can support.

One solution to the disparity between required processing power and the number of WT processors in a given WLAN group 110 is to ensure that the total number of WTs exceeds the number of MIMO channels in the group 110. This approach enables at least two significant processing advantages:

1) The processing load may be spread over a larger number of mobile-terminal processors, and

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2) A form of antenna-switching diversity can be used to optimize performance and throughput in the MIMO channel.

Antenna switching is a well-known technique that switches between various antennas and selects ones having the best signal outputs. This can be done to reduce correlation between antennas, thereby improving MIMO performance. Antenna switching is described in G.J. Foschini, M.J. Gans, "On limits of wireless communication in a fading environment when using multiple antennas," *Wireless PersonalCommunications*, vol. 6, no. 3, pp. 311-335, March 1998, which is incorporated by reference. In some embodiments of the invention, WTs having the most favorable WWAN channel characteristics may be selected to improve MIMO performance without any increase in processing complexity.

In some embodiments of the invention, one or more WWAN-inactive WTs 104-106 may be employed for WLAN-based functions, such as (but not limited to) WLAN network control, distributed-computing applications, and WWAN-interface control. For example, WLAN network control may include any of the well-known network-control functions, such as terminal identification, authentication, error correction, routing, synchronization, multiple-access control, resource allocation, load balancing, power control, terminal-state management, hand-offs, etc.

The WLAN 109 may employ distributed computing across a plurality of the WTs. Distributed computing may be employed simply to achieve increased processing power. Alternatively, distributed computing may include other objectives, such as balancing computational processing loads or balancing power consumption across the WTs 101-106 in the WLAN group 110. Computational loads on the WLAN group can potentially include any WWAN-related computations, such as WWAN channel estimation, WWAN channel compensation, diversity combining, WWAN channel coding/decoding, and cooperative array processing (e.g., MIMO weight calculation, interference cancellation, multi-user detection, matrix operations, and other smart antenna array processing operations).

WWAN-interface control may include distributing WWAN data and control information between the WTs 101-106. In one exemplary embodiment of the invention, at least one of the WTs 101-106 comprises a data source that distributes its data to at least

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one other WT 101-106 for transmission into the WWAN. In a similar embodiment of the invention, received WWAN signals intended for a particular WT 101-106 are received by a plurality of WWAN-active WTs 101-103. The received WWAN signals may optionally be processed by one or more WTs 101-106 prior to being routed to the intended WT 101-106. Accordingly, WWAN channel-access information may be routed to a plurality of WWAN-active WTs 101-103 such that they function together as a single WT 101-106.

The determination of which WTs 101-106 are active is typically performed by decision processing within the WLAN group 110 that determines which WTs 101-106 have the highest quality WWAN channel(s). The number of WWAN-active WTs (such as WTs 101-103) may be determined by one or more factors, including WT channel quality, array-processing complexity, available computational resources within the WLAN group 110, load balancing, and information-bandwidth requirements. In an alternative embodiment of the invention, the WWAN assigns cooperative channel-access information to the WTs 101-103 and may optionally determine which WTs 101-106 are active.

Some embodiments of the invention may take into consideration not only the MIMO complexity at the WTs, but also the added complexity associated with distributing the computational loads over WTs in a given WLAN group. Both MIMO and distributed computing overheads can be characterized as a function of the number of WTs in a WLAN group. Furthermore, the information bandwidth of a given WLAN channel limits the rate of information exchange between WTs. Accordingly, local channel conditions within the WLAN may affect throughput and range, and thus limit the number of WTs within the WLAN group. Either the WLAN capacity or the computational capability of each WT may set a practical limit on the number of WTs in a WLAN group and the overall frequency-reuse factor.

Another important factor that can impact the WLAN group size is the channel rate-of-change, which may be due to motion of the WTs and/or other objects in the WWAN environment. In particular, rapidly changing channel conditions may necessitate frequent updates to the MIMO computations, thus increasing the computational load on WLAN group and potentially increasing the required data transfer across the WLAN.

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Similarly, local channel conditions may dictate the flow of data if distributed computing is employed.

MIMO systems experience substantial degradation in data transfer rates in mobile channels. Time-varying multipath-fading profiles commonly experienced in a mobile wireless network exhibit deep fades that often exceed 30dB. Commercial viability of some embodiments of the present invention requires the ability to tolerate a rapidly changing channel. A promising approach to this problem is to employ diversity to reduce the channel rate-of-change. In a wideband system, or equivalently, in a system comprised of a number of narrowband subcarriers distributed (e.g., interleaved) over a wide frequency band, deep fades affect only a portion of the total channel bandwidth. Therefore, frequency and/or spatial diversity may be employed to reduce the likelihood of deep fades in a multipath environment. Similarly, alternative forms of diversity may be employed. In a mobile environment, this translates into reducing the channel rate-of-change.

Figure 1G illustrates a cooperative beam-forming embodiment of the invention that functions in the presence of a desired WWAN terminal 119 and an external interference source (or jammer) 118. WTs 101-103 in a WLAN group 110 may coordinate their received aggregate beam pattern(s) to null out a jamming signal 115. Array-processing operations performed on signals received from the WTs 101-103 may take the form of phased-array processing, which minimizes the array's sensitivity to signals arriving from one or more angles. Alternatively, array processing may employ baseband (or intermediate-frequency) interference cancellation. Similarly, beam-forming operations may be employed to cancel emissions transmitted toward one or more terminals (such as jammer 118).

Figure 1H illustrates a cooperative beam-forming embodiment of the invention configured to function in the presence of a plurality of desired WWAN terminals 119 and 127. In one embodiment of the invention, the WWAN terminals 119 and 127 may be common to a particular WWAN, and the configuration illustrated in Figure 1H may include a soft hand-off in which redundant transmissions are transmitted between the WLAN group 110 and the WWAN terminals 119 and 127. In this case, the WLAN group may be distributed geographically over a plurality of WWAN sectors or cells. In one

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aspect of the invention, the WLAN group 110 may adapt its connectivity with the WWAN to transition to the cell or sector offering the optimal aggregate WWAN channel quality. Accordingly, the WLAN group may adapt its selection of WWAN-active WTs in response to a hand off.

In another embodiment of the invention, the WLAN group 110 may employ a first WWAN connection (such as illustrated by a connection between WTs 101 and 102, and WWAN terminal 119) and a second WWAN connection (such as illustrated by a connection between WT 103 and WWAN terminal 127) to transmit and/or receive one or more data streams. The WLAN group 110 may employ a plurality of WWAN user channels in a given WWAN. Similarly, the WLAN group 110 may employ connections to a plurality of different WWANs.

Figure 1I illustrates an embodiment of the invention that provides a plurality of WTs 101-106 in a WLAN group 110 with access to a plurality of WWAN services (i.e., WWANs). For example, WT 101 is provided with a communication link with an IEEE 802.16 access-point terminal 116 in an IEEE 802.16 network, WT 102 maintains access capabilities to a 3G-cellular terminal 119, and WT 103 has connectivity to an IEEE 802.11 access point 117. WLAN connectivity 109 is adapted to enable any of the WTs 101-106 in the WLAN group 110 to access any of the plurality of WWAN (802.16, 3G, and 802.11) services.

The WLAN 109 may include a WWAN-access controller (not shown), which may take the form of WLAN-control software residing on a physical device, such as one or more WTs 101-106. Connectivity of the WTs 101-106 to the available WWAN services may be performed with respect to a combination of technical rules and business rules. For example, WWAN access is typically managed using technical rules, such as network load balancing, power conservation, and minimizing computational processing loads. However, WWAN access can also be influenced by business rules, such as enabling a predetermined cost/service ratio for individual WTs 101-106. For example, the WWAN-access controller (not shown) can anticipate the economic cost of particular WWAN services to the user, as well as user communication needs, when assigning WWAN access to individual WTs 101-106. Each WT 101-106 may provide the WWAN-access controller (not shown) with a cost tolerance, which can be updated relative to the type of

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communication link desired. For example, high-priority communication needs (such as particular voice communications or bidding on an online auction) may include permissions to access more expensive WWAN connections in order to ensure better reliability.

The overall goal of WWAN access may be to achieve optimal connectivity with minimum cost. Accordingly, WWAN-access algorithms may include optimization techniques, including stochastic search algorithms (like multi-objective genetic algorithms). Multi-objective optimization are well known in the art, such as described in E.Zitzler and L.Thiele," Multiobjective evolutionary algorithms: A comparative case study and the strength pareto approach," *IEEE Tran. on Evol. Comput.*, vol. 3, no. 4, Nov 1999, pp. 257-271 and J.D. Schaffer, "Multiple objective optimization with vector evaluated genetic algorithms," *Proceedings of 1st International Conference on Genetic Algorithms*, 1991, pp. 93-100, both of which are incorporated by reference.

A WWAN-access controller (not shown) preferably ensures an uninterrupted session when transitioning from one WWAN to another. In particular, the transition between different WWANs should be invisible to the user. This requires that the WWAN-access controller (not shown) be adapted to store user state information (e.g., save browser pages or buffer multimedia data streams). Furthermore, back-end systems may preferably be employed to manage cooperative WWAN access in order to consolidate different WWAN-access charges into a single bill for the user.

In Figure 1J, a plurality of WTs 101-106 in a WLAN group 110 includes at least one WWAN terminal 106. The WTs 101-105 may contribute beam-forming capabilities to the WWAN terminal 106, such as to increase range, increase spatial reuse, reduce transmission power, and/or achieve any of other various beamforming objectives.

In one embodiment of the invention the WTs 101-105 function as lens for WWAN signals transmitted and received by the WWAN terminal 106. For example, the WTs 101-106 may collect received WWAN signals and then focus retransmitted WWAN signals at the WWAN terminal 106. Similarly, the WTs 101-105 may assist in the transmission of WWAN signals from the WWAN terminal 106 to one or more remote sources. In essence, the WTs 101-105 may function like a radio relay, but with

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directionality and focusing capabilities. In this embodiment, the WLAN connectivity of WTs 101-105 with the WWAN terminal 106 may not be necessary.

In another embodiment of the invention, one or more of the WTs 101-106, such as WWAN terminal 106, may be adapted to process the majority (or entirety) of necessary beam-forming computations. In this case, WT 106 is designated as a computer-processing terminal. The computer-processing terminal 106 is adapted to include specific computational resources for processing WWAN signals received by other WTs (such as WTs 101-103), which are then relayed via the WLAN 109 to the computer-processing terminal 106. Similarly, the computer-processing terminal 106 may be adapted to perform signal-processing operations associated with WWAN transmission. Computational operations associated with other WWAN signal-processing operations (e.g., coding, decoding, channel estimation, network-access control, etc.) may be provided by the computer-processing terminal 106.

Figure 2A illustrates a functional embodiment of the invention that may be realized in both method and apparatus embodiments. A plurality *M* of WWAN Interfaces 1101.1-1101.M is provided for coupling WWAN signals to and/or from at least one WWAN. In one functional embodiment, WWAN Interfaces 1101.1-1101.M may include WWAN transceivers adapted to convert received WWAN signals into received baseband signals. A plurality of WWAN baseband processors 1102.1-1102.M are optionally provided for performing baseband processing (such as, but not limited to, channel compensation, A/D conversion, frequency conversion, filtering, and demultiplexing) on the received baseband signals. Alternatively, the function of the WWAN baseband processors 1102.1-1102.M may be performed by the WWAN Interfaces 1101.1-1101.M.

Baseband outputs from the WWAN baseband processors 1102.1-1102.M are coupled into a plurality of array processors, such as MIMO combiners 1103.1-1103.M. In a MIMO channel, the received WWAN signals (and thus, the baseband outputs) are characterized by a plurality of overlapping (i.e., interfering) signals. Although MIMO combiners 1103.1-1103.M are shown, any type of array processor may be employed. The number of array processors may be less than, equal to, or greater than the number *M* of WWAN Interfaces 1101.1-1101.M. Baseband outputs may also be coupled into a WLAN 1105, which is coupled to the plurality of MIMO combiners 1103.1-1103.M. Each

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MIMO combiner 1103.1-1103.M may be adapted to receive baseband outputs from two or more baseband processors 1102.1-1102.M wherein at least one of those baseband outputs is coupled to the MIMO combiner 1103.1-1103.M via the WLAN 1105.

A particular m^{th} MIMO combiner 1103.m need not process data from a corresponding (m^{th}) WWAN Interface 1101.m. Rather, the mth MIMO combiner 1103.m may process baseband signal outputs from a plurality of WWAN Interfaces 1101.p {p = 1,...,M, where $p \neq m$}.

The WLAN 1105 comprises at least one WLAN channel between at least one baseband output (e.g., baseband processor 1102.1-1102.M outputs) and at least one array processor, such as the MIMO combiners 1103.1-1103.M. The WLAN 1105 may include WLAN interfaces (not shown) and associated WLAN-control hardware and/or software (not shown).

The MIMO combiners 1103.1-1103.M may be adapted to separate the overlapping signals and output at least one desired transmission therefrom. Outputs of the MIMO combiners 1103.1-1103.M are optionally processed by secondary data processors 1104.1-1104.M, which may provide coupling into the WLAN 1105. The secondary data processors 1104.1-1104.M may be adapted to perform demodulation, error-correction decoding, data formatting, and/or other related baseband-processing functions.

In some embodiments of the invention, MIMO combiner 1103.1-1103.M outputs may be coupled via the WLAN 1105 to other MIMO combiners 1103.1-1103.M and/or secondary data processors 1104.1-1104.M. For example, embodiments of the invention may employ an iterative cancellation process, such as successive interference cancellation (which is well-known in the art), involving the use of strongest-signal estimates, and then next-strongest-signal estimates to cancel known interference in weaker signals. Alternatively, embodiments may employ parallel cancellation.

Figure 2B illustrates an embodiment of the invention including a plurality M of WTs 1109.1-1109.M, each comprising a corresponding combination of a WWAN Interface 1101.1-1101.M, an optional WWAN baseband processor 1102.1-1102.M, a combiner (such as a MIMO combiner 1103.1-1103.M), and a secondary data processor 1104.1-1104.M. The WTs 1109.1-1109.M are coupled together by a WLAN 1105, which

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is configured to convey data between the WTs 1109.1-1109.M in order to enable cooperative antenna-array processing.

A WT, such as any of the WTs 1109.1-1109.M, includes any system or device provided with communicative connectivity means to a WLAN 1105. Two or more WTs 1109.1-1109.M are preferably provided with WWAN interfaces, such as WWAN Interface 1101.1-1101.M. A plurality of WTs 1109.1-1109.M may share at least one WLAN 1105. In one embodiment of the invention, individual WTs 1109.1-1109.M may share the same WWAN service. This enables the WLAN group 110 to perform either or both transmit beam-forming and receive beam-forming (i.e., combining) operations.

In another embodiment of the invention, WTs 1109.1-1109.M may have connections to different WWANs and/or WWAN services. This enables the WLAN group 110 to achieve WWAN-service diversity. One or more WTs 1109.1-1109.M may optionally be capable of accessing multiple WWAN services. For example, many cellular handsets are provided with multi-mode capabilities, which give them the ability to access multiple WWANs. Some of the WTs 1109.1-1109.M may have no WWAN service. For example, one or more WTs 1109.1-1109.M may be out of range, in a WWAN dead spot, in an inactive WWAN state, or configured only to communicate via the WLAN 1105. WTs 1109.1-1109.M include, but are not limited to, cell phones, radio handsets, pagers, PDAs, wireless sensors, RFID devices, vehicle radio communication devices, laptop computers with wireless modems, wireless network access points, wireless routers, wireless switches, radio repeaters, transponders, and devices adapted to include satellite modems.

A WLAN group 110 may be adapted to perform any of various types and combinations of diversity and MIMO beam-forming. Three commonly used linear diversity-combining techniques include switched (or selection) combining, maximal ration combining (MRC), and equal gain combining (EGC). Other combining techniques may be employed. The impact of using diversity may be expressed by a probability distribution $p(\gamma)$ of the SNR γ at the output of a combining network. For switched diversity, wherein the combiner switches to the diversity branches (e.g., WTs) having the strongest signal, $p(\gamma)$ is given by:

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$$p(\gamma) = \frac{L}{\Gamma} e^{-\gamma/\Gamma} \left[1 - e^{-\gamma/\Gamma}\right]^{L-1}$$

where Γ is the average SNR for each diversity branch and L is the number of diversity branches. MRC weights branches (e.g., WT signals received from the WWAN) having better SNR more heavily (i.e., with greater-magnitude weights) than branches having poorer SNR. The $p(\gamma)$ for MRC is given by:

$$p(\gamma) = \frac{\gamma^{l-1} e^{-\gamma/\Gamma}}{\Gamma^{L}(l-1)!}$$

For EGC, $p(\gamma)$ is given by:

$$p(\gamma) = \frac{L}{a\Gamma} e^{-\gamma/a\Gamma} \left[1 - e^{-\gamma/a\Gamma}\right]^{L-1}$$

where $a = \sqrt{L/1.25}$ for $L \geq 2$, and 1 otherwise.

These diversity techniques provide the greatest improvements when the branches are uncorrelated.

Adaptive arrays (or smart antennas) may include antenna systems that automatically adjust to achieve some predetermined performance criterion, such as maximizing the signal to interference (S/I) ratio, SINR, or link margin. Adaptive antenna techniques include switched beam, beam steering, and optimum combining (e.g., a linear spatial filtering approach that employs adaptation to closely match an output signal with a reference signal). A filtering process typically suppresses any artifacts that are not part of the desired incoming signal, including noise and interference.

In an optimum combining system, signals from each WT are down converted to baseband and converted to digital signals in an ADC. Noise associated with the front end of the down converter and other sources is naturally added to the signal. The resulting signal $x_m(k)$ is multiplied by a complex weighting function $w_m(k)$ and summed with similar signals from other WT antenna elements. The resulting sum signal $\Sigma\, w_m(k)x_m(k)$ is compared with a previously derived (and updated) reference signal (e.g., a training sequence). An error signal $e(k)$ is generated and used to adjust the weight values in order to minimize $e(k)$. The objective is to derive the weighting function $w_m(k)$ that enables the best match between an estimated received signal and the actual transmitted signal.

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Alternatively, an adaptive WT array may be configured as an analog array wherein amplitude and phase adjustments (i.e., weighting functions) are performed at RF or IF.

In a MIMO communication system, signals transmitted from M_T transmit sources interfere with each other at a receiver comprising the WTs 1109.1-1109.M. Thus, interference cancellation (such as matrix inversion, channel transfer function inversion, and adaptive filtering) may be employed by one or more MIMO combiners 1103.1-1103.M to separate the signals. The received signal is expressed by:

$$y = Hx + n$$

where the received signal, y, is a vector with M_R terms $\{y_i, i = 1,...,N_R\}$ corresponding to signals received by M_R (where M_R may have a value of 2 to M) receiver elements (i.e., WTs); x represents the transmitted signal, which is a vector having M_T terms $\{x_i, i = 1,...,M_T\}$ corresponding to signals transmitted by M_T transmitter elements; H is an $M_R \times M_T$ channel-response matrix that characterizes the complex gains (i.e., transfer function, or spatial gain distribution) from the M_T transmission elements to the M_R receive elements; and n represents AWGN having zero mean and zero variance.

In the case where the channel is characterized by flat fading, such as when a narrowband signal is employed (e.g., a sub-carrier of a multi-carrier signal), the elements in matrix H are scalars. The channel-response matrix H may be diagonalized by performing an eigenvalue decomposition of the $M_T \times M_T$ correlation matrix R, where $R = H^H H$. Eigenvalue decomposition is expressed by:

$$R = EDE^H$$

where E is an $M_T \times M_T$ unitary matrix with columns corresponding to the eigenvectors e_i of R, and D is an $M_T \times M_T$ diagonal matrix wherein the diagonal elements are eigenvalues λ_i of R. The diagonal elements of D indicate the channel gain for each of the independent MIMO channels. Alternatively, other eigenvalue-decomposition approaches, such as singular value decomposition, may be employed.

The process for diagonalizing the MIMO channel response is initiated by multiplying a data vector d with the unitary matrix E to produce the transmitted vector x: $x = Es$. This requires the transmitter to have some information corresponding to the channel-response matrix H, or related information thereof. The received vector y is then multiplied with $E^H H^H$ to provide an estimate of data vector s, which is expressed by:

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$$\hat{s} = E^H H^H y = E^H H^H HEs + E^H H^H n = Ds + \hat{n}$$

where $\hat{n}$ is AWGN having a mean vector of 0 and a covariance matrix of $\Lambda_n=\sigma^2 D$.

The data vector s is transformed by an effective channel response represented by the diagonal matrix D. Thus, there are N_s non-interfering subchannels wherein each subchannel i has a power gain of λ_i^2 and a noise power of $\sigma^2\lambda_i$.

In the case where MIMO processing is performed on a multicarrier signal, or some other wideband signal that is spectrally decomposed into narrowband components, eigenmode decomposition may be performed for each frequency bin f_n.

If multicarrier spreading codes are employed (e.g., orthogonal DFT, or CI, codes), the channel-response matrix H can cause inter-symbol interference between spread data symbols, even in a SISO arrangement. Accordingly, the eigenmode decomposition technique described previously is applicable to multicarrier spreading and despreading. In one embodiment of the invention, eigenmode decomposition may be applied across two or more dimensions (e.g., both spatial and frequency dimensions). In another embodiment of the invention, eigenmode decomposition may be applied across a single dimension (e.g., spatial or frequency dimensions). For example, multicarrier spreading codes (for example, orthogonal codes for data multiplexing in a given multiple-access channel) may be generated and processed via eigenmode decomposition.

Any of various water-filling or water-pouring schemes may be employed to optimally distribute the total transmission power over the available transmission channels, such as to maximize spectral efficiency. For example, water-filling can be used to adapt individual WT transmission powers such that channels with higher SNRs are provided with correspondingly greater portions of the total transmit power. A transmission channel, as defined herein, may include a spatial (e.g., a sub-space) channel, a space-frequency channel, or some other channel defined by a set of orthogonalizing properties. Similarly, water filling may be used at a physically connected (i.e., wired) antenna array. The transmit power allocated to a particular transmission channel is typically determined by some predetermined channel-quality measurement, such as SNR, SINR, BER, packet error rate, frame error rate, probability of error, etc. However, different or additional criteria may be employed with respect to power allocation,

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including, but not limited to, WT battery life, load balancing, spatial reuse, power-control instructions, and near-far interference.

In conventional water filling, power allocation is performed such that the total transmission power P_T is some predetermined constant:

$$P_T = \sum_{j \in K} \sum_{k \in L} P_j(k)$$

where $L = \{1,...,N_S\}$ signifies the available subspaces and $K = \{1,...,N_f\}$ represents the available sub-carrier frequencies f_n. The received SNR (expressed by $\psi_j(k)$) for each transmission channel is expressed by:

$$\psi_j(k) = \frac{P_j(k)\lambda_j(k)}{\sigma^2}, \text{ for } j = \{1,..., N_S\} \text{ and } k = \{1,...,N_f\}$$

The aggregate spectral efficiency for the $N_S N_f$ transmission channels is expressed by:

$$C = \sum_{j=1}^{N_S} \sum_{k=1}^{N_f} \log_2\left(1 + \psi_j(k)\right)$$

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

An embodiment of the invention may employ reliability assessment for determining required processing and virtual-array size (i.e., the number of active WTs functioning as WWAN receiver elements). Received bits or symbols that have low reliability need more processing. Bits or symbols with high reliability may be processed with fewer elements (WTs) or provided with lower processing requirements. More information typically needs to be combined for data streams having less reliability and

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less information may need to be combined for data streams having more reliability. Also, nodes (WTs) with good channel quality may share more information via the WLAN than nodes having poor channel quality. Optimization algorithms, such as water-filling algorithms may be employed in the reliability domain.

Figure 3A illustrates an embodiment of the invention in which a WLAN controller for a WLAN group of WTs first identifies received data streams that have the least reliability (e.g., reliability that is below a predetermined threshold) 301. Then the WLAN controller increases allocated processing (e.g., increases the number of receiver nodes, increases the number of processing nodes, employs a processing approach having higher computational complexity, etc.) 302 to those data streams. Data symbols may be combined from the smallest number of nodes such that the reliability of the sum is maximized, or at least exceeds a predetermined threshold reliability. The processes 301 and 302 may be repeated 303 until a predetermined result is achieved or until there is no more data left for processing.

Figure 3B illustrates an embodiment of the invention in which a WLAN controller identifies received data streams that have the most reliability, or data streams having reliability that exceeds a predetermined reliability threshold 311. The WLAN controller may decrease allocated processing (e.g., decrease the number of receiver nodes, decrease the number of processing nodes, employ a processing approach having lower computational complexity, etc.) 312 to those data streams. The processes 301 and 302 may be repeated 303 until a predetermined result is achieved or until there is no more data left for processing. Embodiments of the invention may provide for encoding information across channels having a wide range of reliability.

Embodiments of the invention may be configured to perform blind signal separation (BSS), such as independent component analysis. For example, A. Jourjine, S. Rickard, and O. Yilmaz, "Blind Separation of Disjoint Orthogonal Signals: Demixing N Sources from 2 Mixtures," in *Proceedings of the 2000 IEEE International Conference on Acoustics, Speech, and Signal Processing*, Istanbul, Turkey, June 2000, vol. 5, pp. 2985–88, which is included herein by reference, describes a blind source separation technique that allows the separation of an arbitrary number of sources from just two mixtures, provided the time-frequency representations of the sources do not overlap. The key

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observation in the technique is that for mixtures of such sources, each time-frequency point depends on at most one source and its associated mixing parameters.

In multi-user wireless communication systems that employ multiple transmit and receive antennas, the transmission of user information through a dispersive channel produces an instantaneous mixture between user transmissions. BSS may be used in such instances to separate received transmissions, particularly when training sequences and channel estimation are absent. In an exemplary embodiment of the invention, an OFDM-MIMO protocol may be provided across multiple independent WTs. Multiple transmissions are provided on at least one frequency channel, and frequency-domain techniques of BSS may be employed to recover received signals.

In one embodiment of the invention, at least one data transmission source may be adapted to convey its data across the WLAN to a plurality of WTs for transmission into the WWAN. In another embodiment of the invention, a plurality of WTs are adapted to receive data transmissions from a WWAN and couple said received data transmissions into a WLAN (with or without baseband processing) wherein centralized or distributed signal-processing means are provided for separating the data transmissions. Said signal-processing means includes any MIMO-processing techniques, including multi-user detection, space-time processing, space-frequency processing, phased-array processing, optimal combining, and blind source separation, as well as others.

In one embodiment of the invention, a vector of binary data symbols $b_i(n)$ are encoded with a convolutional encoder to produce a coded signal:

$$s_i(n) = b_i(n) * c(n)$$

where $c(n)$ represents a convolutional code of length L'. A cluster of N coded symbols corresponding to an ith user, data source, or data stream is represented by:

$$s_{n,i} = [s_i(n), \ldots, s_i(n+N-1)]^T$$

The transmit signal is generated by performing an N-point IDFT to $s_{n,i}$ to produce:

$$S_{n,i} = [S_i(n,0), \ldots, S_i(n,N-1)]^T$$

where

$$S_i(n,k) = \sum_{m=0}^{N-1} s_i(n+m) e^{i 2\pi k m / N}$$

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The values $S_i(n,k)$ are transmitted via at least one of N_t transmit antennas.

On the receive side, N_r receive antennas (typically, $N_r \geq N_t$) are employed. The signal received by a jth antenna is expressed by:

$$R_j(n) = \sum_{i=1}^{N_t} S_i(n) * h_{ij} + n_j(n)$$

where $n_j(n)$ represents the zero-mean AWGN introduced by the channel, and h_{ij} is the channel impulse-response of the ith transmit antenna to the jth receive antenna. The received signal can be interpreted as a convolutive mixture of the coded signals, where the channel matrix h represents the mixing system. An N-point DFT is applied to the received signals $R_j(n)$ to produce:

$$r_j = [r_j(n),..., r_j(n + N - 1)]^T$$

where

$$r_j(n) = \sum_{m=0}^{N-1} R_j(n+m) e^{-i2\pi km/N}$$

Typically, a sufficient guard interval or cyclic prefix is employed to eliminate inter-symbol interference.

The signals from the N_r receiver antennas are grouped with respect to frequency bin. An observation at a kth frequency bin are expressed by:

$$r_n(k) = \left[r_1(n+k), r_2(n+k),..., r_{N_r}(n+k))\right]^T$$

$$= H(k)s(k) + n(k)$$

Thus, the observations $r_n(k)$ $\{k = 0,..., N\text{-}1\}$ can be interpreted as an instantaneous mixture of the transmitted signals $s(k)$, where $H(k)$ represents the mixing system.

There are many approaches for estimating the transmitted signals $s(k)$ from the received signals $r_n(k)$ that may be employed by the current invention. An exemplary embodiment of the invention employs BSS techniques. One class of BSS produces an output vector having the following form:

$$y(k) = W^H(k) r_n(k)$$

where $W(k)$ is an $N_r \times N_t$ matrix that groups the coefficients of the separating system. The output $y(k)$ can also be expressed by:

$$y(k) = G(k)s(k) + W^H(k)n(k)$$

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where $G(k) = W^H(k)H(k)$ represents the mixing/separating system. The goal of the separation process is to calculate the matrices $W(k)$ so that the $G(k)$ matrices are diagonal and the effects of noise $W^H(k)n(k)$ are minimized. Many different approaches are applicable for achieving these goals.

A BSS algorithm (such as the one described in J. F. Cardoso, A. Souloumiac, "Blind Beamforming for non-Gaussian Signals," *IEEE-Proceedings-F*, vol. 140, no. 6, pp. 362-370, December 1993, which is incorporated by reference herein) may be employed to separate the instantaneous mixture in each frequency bin. Each output at frequency bin k' can be regarded as corresponding to a single source at bin k' multiplied by a particular gain introduce by the algorithm. The outputs $y(k')$ are then used as reference signals in order to recover the sources at frequencies $k' \pm 1$. For example, the separation matrices $W(k)$ are determined by minimizing the mean-square error between the outputs $y(k) = W^H(k)r_n(k)$ and reference signals $y(k')$. For a given frequency bin k:

$$W_o(k) = \arg\min_{W(k)} E\left[\left|y(k) - \alpha y(k')\right|^2\right]$$

where α is a real constant, which is selected with respect to the convolutional code:

$$\alpha = \frac{\sum_{p=0}^{L-1} c^2(p)}{\sum_{p=0}^{L-2} c(p)c(p+1)}$$

This is done to ensure $G(k) = G(k')$. The solution to the optimization problem is given by:

$$W_o(k) = \alpha R_{r_n}^{-1}(k) R_{r_n y}(k,k')$$

where

$$R_{r_n}(k) = E\left[r_n(k)x^H(k)\right] \text{ and}$$

$$R_{r_n y}(k,k') = E\left[r_n(k)y^H(k')\right]$$

Figure 4A illustrates an embodiment of the invention wherein a plurality M of WTs 1109.1-1109.M is coupled to a MIMO processor 1103 via a WLAN 1105. In this particular embodiment, a computer-processing terminal 1119 may include the MIMO processor 1103. The computer processing terminal 1119 may be provided with WLAN-interface functionality, and may optionally include WWAN-interface functionality.

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The computer-processing terminal 1119 may include any of a plurality WLAN-connected devices with signal-processing capability. For example, the computer-processing terminal 1119 may include one of the WTs 1109.1-1109.M. In one aspect of the invention, the computer-processing terminal 1119 comprises a WLAN controller. In another aspect of the invention, the computer processing terminal 1119 comprises a network gateway, router, or access point including a CPU adapted to process signals received from the plurality of WTs 1109.1-1109.M. Applications of embodiments of the invention include (but are not limited to) sensor networks, micro-networks, RFID systems, cellular networks, and satellite networks.

Each WT 1109.1-1109.M may include a baseband processor 1102.1-1102.M adapted to provide WWAN baseband (or IF) signals to the MIMO processor 1103 via the WLAN 1105. The MIMO processor 1103 may be configured to separate interfering WWAN data symbols in the WWAN baseband signals. The separated WWAN data symbols are then coupled back to data processors 1104.1-1104.M in the WTs 1109.1-1109.M.

Figure 4B illustrates a functional embodiment of the invention in which MIMO processing operations (represented by MIMO processors 1103.1-1103.M) may be distributed over two or more WTs 1109.1-1109.M. Baseband processors 1102.1-1102.M provide WWAN baseband signals to a WLAN controller 1106, which may distribute the signals (and signal-processing instructions) to the MIMO processors 1103.1-1103.M. The separated WWAN data symbols are then coupled back to data processors 1104.1-1104.M.

Figure 4C represents a functional embodiment of the invention. At least one WT may provide WWAN access information 1140 to a WLAN controller. The WWAN access information typically includes necessary information (such as at least one WWAN channel assignment, authentication codes, etc.) to access at least one particular WWAN channel. The WWAN access information may optionally include performance information, such as WWAN channel estimates, link-bandwidth demand, link priority, and/or WWAN channel-quality measurements (e.g., SNR, SINR, BER, PER, latency etc.). This information is typically provided to the WLAN controller by one or more WTs.

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The WLAN controller determines which WTs to activate 1141 for a particular WWAN communication link. This may be performed for either or both transmission and reception. The determination of which WTs will be active 1141 in a given WWAN link typically depends on a combination of factors, including (but not limited to) the number *M* of WTs required to achieve predetermined channel characteristics or access parameters, which WTs have the best WWAN channel quality, load balancing, power-consumption balancing, computational overhead, latency, and WLAN-access capabilities. Accordingly, the WLAN controller may send control information via the WLAN to the WTs that includes state information (e.g., operating-mode assignments, such as active, standby, sleep, and awake).

The WLAN controller may convey WWAN information to the active WTs 1142. The WWAN information may be derived from the WWAN access information and provided to the WTs to establish and/or maintain at least one WWAN link. Accordingly, the WWAN information may include WWAN channel assignments. The WWAN information may include beam-forming weights and/or space-time codes. Accordingly, the step of conveying WWAN information to the WTs 1142 may optionally include a preliminary signal-processing step (not shown), such as blind adaptive or deterministic weight calculation. This preliminary signal-processing step (not shown) may be distributed among a plurality of the WTs, or it may be performed in a centralized mode, such as by a single computing terminal. A distributed-computing mode may take various forms. In one mode, each of a plurality of WTs takes its turn functioning as a computing terminal. In another mode, multiple WTs function as computing terminals simultaneously.

Communications in the WWAN link are coordinated between the WTs in order to synchronize the transmitted and/or received WWAN signals 1143. A receiver embodiment of the invention may provide for synchronizing the received WWAN signals, such as to provide for coherent combining. A transmitter embodiment of the invention may provide for synchronizing the transmitted WWAN signals from the WTs such as to enable coherent combining at some predetermined WWAN terminal.

An optional transmitter embodiment of the invention may employ synchronization to deliberately time-offset signals arriving at one or more WWAN

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terminals in order to provide for transmit diversity by the WTs. In such embodiments, one or more of the WT transmissions may be provided with time-varying complex weights (e.g., amplitudes and/or phases), such as described in S. A. Zekavat, C. R. Nassar and S. Shattil, "Combined Directionality and Transmit Diversity via Smart Antenna Spatial Sweeping, " proceedings of *38th Annual Allerton Conference on Communication, Control, and Computing, University of Illinois in Urbana-Champaign,* pp. 203-211, Urbana-Champaign, IL, USA, Oct. 2000, S. A. Zekavat, C. R. Nassar and S. Shattil, "Smart antenna spatial sweeping for combined directionality and transmit diversity," *Journal of Communications and Networks (JCN), Special Issue on Adaptive Antennas for Wireless Communications,* Vol. 2, No. 4, pp. 325-330, Dec. 2000, and S. A. Zekavat, C. R. Nassar and S. Shattil, "Merging multi-carrier CDMA and oscillating-beam smart antenna arrays: Exploiting directionality, transmit diversity and frequency diversity, " *IEEE Transactions on Communications*, Vol. 52, No. 1, pp. 110 – 119, Jan. 2004, which are incorporated by reference herein.

In an alternative embodiment of the invention, providing WWAN access information 1140 may include providing WWAN channel-performance information from the WTs to at least one WWAN terminal. Thus, conveying WWAN information to the WTs 1142 may be performed by at least one WWAN terminal. An optional embodiment of the invention may provide for at least one WWAN terminal determining which WTs in a WLAN group will operate in a given WWAN link and conveying that WWAN information 1142 to the WLAN group. Embodiments of the invention may provide capabilities to WWAN terminals to set up and adapt the formation of WLAN groups and determine which WTs are assigned to which WLAN groups. Such control capabilities may employ GPS positions of WTs to assist in assigning WTs to a WLAN group. Some embodiments of the invention may provide for collaboration between a WWAN and a WLAN group for activating WTs and/or assigning WTs to the WLAN group.

In one embodiment of the invention, step 1142 may include a preliminary signal-processing step (not shown) in which at least one WWAN terminal calculates cooperative-beamforming weights for the WTs based on channel-performance information provided by the WTs. Accordingly, the WWAN information may include cooperative-beamforming weights derived by at least one WWAN terminal and conveyed

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to at least one WT. Synchronization 1143 of the transmitted and/or received WWAN signals by the WTs may optionally be performed by at least one WWAN terminal. Similarly, embodiments of the invention may provide for applying time-varying weights to WWAN-terminal transmissions (such as described previously).

Figure 4D illustrates a functional embodiment of the invention adapted to perform cooperative beamforming. WWAN channel information is provided 1144 for assigning subchannels 1145 and calculating cooperative beamforming (i.e., WT) weights 1146. The beamforming weights are then distributed to the appropriate WTs 1147.

Sub-channel assignments 1145 are typically performed with respect to a predetermined subchannel-quality threshold, such as SNR, SINR, or BER. Subchannels having the required minimum performance may be assigned for transmission and/or reception. Sub-channel assignments 1145 may also provide for bit loading. Alternatively, sub-channel assignments 1145 may be performed without regard to sub-channel quality. In such cases, spreading or channel coding may be performed to mitigate the effects of lost and compromised subchannels.

Weight calculations 1146 may be achieved by either deterministic or blind adaptive techniques. The calculations may be performed by one or more WTs, or alternatively, by at least one WWAN terminal. Cooperative beamforming weights may be provided to achieve at least one form of array processing benefit, including diversity combining, interference cancellation, and spatial reuse.

Figure 5A illustrates a functional embodiment of the invention that may be implemented by hardware and/or software. A plurality of transmitted WWAN signals are received 1150 by a plurality of WTs. Baseband (or IF) WWAN information is derived 1151 from the received WWAN signals. For example, in an OFDM system, a baseband WWAN signal s_k received by a kth WT can be represented by a linear superposition of up to M transmitted data symbols d_i $\{i = 1,...,M\}$ weighted by complex channel weights α_{ik}:

$$s_k = \sum_{i=1}^{M} \alpha_{ik} d_i + \eta_k$$

Baseband WWAN signals (which typically include the complex channel weights α_{ik}), are optionally transmitted 1158 into a WLAN for distribution to one or more other WTs. Accordingly, data (including baseband WWAN signals s_k, complex channel weights α_{ik},

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and/or MIMO weights β_{il}) from the one or more other WTs is received 1152 from the WLAN. MIMO processing 1153 may be performed to produce at least one set of MIMO weights β_{il} and/or estimated transmitted data symbols d_i, which may optionally be transmitted 1159 to at least one other WT via the WLAN. Baseband information recovery 1154 may optionally be performed on the estimated transmitted data symbols d_i. For example, baseband operations may include despreading, demodulation, error correction (e.g., channel decoding), demultiplexing, de-interleaving, data formatting, etc.

Figure 5B illustrates an alternative functional embodiment of the invention that may be implemented by hardware and/or software. In this case, WWAN baseband information that does not include MIMO weights may be received 1155 from at least one other WT via the WLAN. Thus, MIMO processing 1153 includes generating MIMO weights, which may be transmitted 1159 to one or more WTs via the WLAN. The functional embodiment illustrated in Figure 5B is particularly applicable to a WT functioning as a computer-processing terminal in a WLAN group. In the case where the subject WT functions as the only MIMO-processing terminal in a given WLAN group, the functional embodiment may be characterized solely by steps 1155, 1153, 1154, and optional step 1159. Furthermore, the functional embodiments described herein may be adapted to perform other array-processing operations in addition to, or instead of, MIMO.

Figure 6A illustrates functional and apparatus embodiments of the present invention pertaining to one or more WTs, such as WT 1109. In particular, a WWAN interface 1161 may be coupled to a beam-forming system 1162, which is coupled to a WLAN interface 1163. The beam-forming system 1162 may employ data received from the WLAN interface 1163 (and optionally, from data received from the WWAN interface 1161) to perform beam-forming operations. The WLAN interface 1163 is adapted to provide WLAN data communications with at least one other WT (not shown). The beam-forming system 1162 may be adapted to provide either or both WWAN transmission beam-forming and reception beam-forming operations.

Figure 6B illustrates a preferred embodiment of the invention that may be employed as either or both apparatus and functional embodiments. A WWAN interface 1161 includes an RF front-end 1611, a DAC/ADC module 1612, a pulse-shaping filter 1613, a modulator/demodulator module 1614, an equalizer modulator 1615 that

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optionally employs pre-equalization means, a multiplexer/ demultiplexer module 1616, and a baseband-processing module 1617. The WWAN interface may also include a network-control module 1618 that may be responsive to both WWAN control signaling and WLAN-control signals configured to convey WWAN control information to the WWAN interface 1161.

A WLAN interface 1163 includes an RF front-end 1631, a DAC/ADC module 1632, a pulse-shaping filter 1633, a modulator/demodulator module 1634, an equalizer modulator 1635 that optionally employs pre-equalization means, a multiplexer/ demultiplexer module 1636, and a baseband-processing module 1637. A beam-forming module 1162 is adapted to process signals from either or both baseband modules 1617 and 1637. The beam-forming module 1162 may be adapted to process local data symbols generated by a local data source 1160.

As described previously, the beam-forming module 1162 may be adapted to perform beam-forming operations on baseband WWAN signals received from either or both the WWAN interface 1161 and the WLAN interface 1163. Specifically, the beam-forming module 1162 may be adapted to perform beam forming by utilizing baseband WWAN signals, channel weights (or other channel-characterization information), beam-forming weights (such as MIMO weights), and/or baseband data symbols. Baseband data symbols may be received from the local data source 1160, from local data sources on other WTs, and/or from estimated data generated by one or more external beam-forming modules (e.g., beam-forming modules on other WTs). Optionally, the beam-forming module 1162 may be configured to adjust equalization and/or pre-equalization 1615.

In an exemplary embodiment of the invention, the beam-forming module 1162 is configured to process baseband WWAN signals received from the baseband-processing module 1617 and the WLAN interface 1163. Information output from the beam-forming module 1162 is conveyed to at least one of the WLAN interface 1163 and a local data sink 1169. Estimated WWAN data symbols output by the beam-forming module 1162 may optionally be processed by the baseband-processing module 1617 or the local data sink 1169. For example, the baseband-processing module 1617 may be configured to perform various types of signal processing, including error correction (such as Viterbi decoding), constellation mapping, and data formatting on data output by the beam-

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forming module 1162. The resulting processed data may then be coupled to the local data sink 1169 and/or the WLAN interface 1163. Alternatively, the local data sink 1169 may perform the previously described signal-processing types.

Beam forming is performed cooperatively with other WTs to provide predetermined WWAN spatial processing for transmitted and/or received WWAN signals. Thus, a network-function adapter 1165 may be employed to provide WWAN channel-access information to one or more WTs. For example, some embodiments of the invention require multiple WTs to function as a single WT. In this case, each WT is provided with WWAN-access information corresponding to the single WT it is configured to spoof. The network function adapter 1165 may be configured to generate WWAN-access information to be distributed to at least one other WT and/or it may be configured to receive WWAN-access information from the WLAN interface 1163 and convey it to the network-control module 1618 in the WWAN interface 1161.

WWAN-access information typically includes channelization (or some other form of multiple access) information used to transmit and/or receive data from the WWAN. For example, WWAN-access information may take the form of user identification sequences, assigned time slots, frequency band assignments, and/or multiple-access code assignment.

In some embodiments of the invention, a particular WT may be required to function as multiple WTs. In this case, WWAN-access information is conveyed to the network-control module 1618 and data is configured to be appropriately multiplexed and/or demultiplexed relative to a plurality of multiple-access channels.

The network-function adapter 1165 may be used to convey other WWAN control information to WTs, including (but not limited to) power-control commands, timing and synchronization information, key-exchange messages, WWAN routing tables, acknowledgements, requests for retransmission, probing signals, and paging messages. The network-function adapted 1165 may be configured to alter or adapt the WWAN-control information that it receives from either or both the WWAN interface 1161 and the WLAN interface 1163. For example, WWAN power-control commands received by one or more WTs may be adapted by the network-function adapter 1165 prior to being conveyed to network-control modules (such as network-control module 1618) on

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multiple WTs. Power control may be adapted by one or more network-function adapters 1165 for particular WTs depending on their WWAN channel quality and power. Alternatively, the network-function adapter 1165 may adapt the number M of WTs servicing a given link in response to WWAN control information.

In some embodiments of the invention, it may be advantageous to employ a single decision system for network-function adaptation 1165. In one mode of operation, the network-function adapter 1165 of only one of a plurality of WTs assigned to a particular WWAN channel is adapted to convey WWAN control information to the other WTs. In each of the other WTs, the associated network-function adapter 1165 identifies the WWAN control information received from the WLAN and couples it to the network-control module 1618. Thus, the network-function adapter 1165 may instruct the network-control module 1618 to disregard one or more types of WWAN control information received from the WWAN interface 1161. One or more network-function adapters (such as network-function adapter 1165) may synchronize WT responses to WWAN control information.

In another embodiment of the invention, each WT may be responsive to WWAN control information that it receives. In yet another embodiment, each of a plurality of WWAN multiple-access channels is preferably controlled by a separate network-function adapter 1165. These and other adaptations and permutations of network function may be embodied by functional aspects of the network-function adapter 1165.

One embodiment of the invention employs the functionality of a group of WTs corresponding to Figure 1C with respect to the transceiver embodiment shown in Figure 6B. In a transmission configuration, a serial data stream $s(n)$ from the local data source 1160 of a particular WT is channel coded to produce coded data stream $u(n)$, which is grouped in blocks of size N: $\boldsymbol{u}(i) = [u(iN), u(iN+1),\ldots, u(iN+N-1)]^{T}$. In this case, N is chosen to equal the number M of WTs employed as antenna elements. The N-1 coded data symbols $u(n)$ are distributed to the other N-1 WTs via the WLAN interface 1163.

At each WT's Mux/DeMux block 1615, a particular data symbol $u(n)$ is mapped into a frequency bin vector. In one aspect of the invention, each data symbol $u(n)$ is provided with both a unique frequency bin and a unique WT, such as to achieve optimal diversity benefits. This takes the form of a frequency-bin vector having all zeros except

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for one bin corresponding to $u(n)$. This scheme can be used to achieve low transmitted PAPR, as well as other benefits. In other embodiments, alternative WT/frequency-bin combinations may be employed. For example, multiple serial data streams $s(n)$ may be provided to the frequency-bin vector. Redundant symbols may be provided. Alternatively, the data $s(n)$ may be spread across frequencies and/or WTs.

At each Mod/DeMod block 1614, an IFFT is applied to each data block to produce:

$$\tilde{u}(i) = F^H u(i)$$

where F is the $N \times N$ FFT matrix with $F_{nm} = N^{-1/2}\exp(-j2\pi nm/N)$. A cyclic prefix of length N_{CP} may be inserted in $\tilde{u}(i)$ to produce $\tilde{u}_{CP}(i) = \beta T_{CP}\tilde{u}(i)$, which has length $N_T = N+N_{CP}$. The term $\boldsymbol{T}_{CP} = [\boldsymbol{I}_{CP}{}^T \boldsymbol{I}_N{}^T]^T$ represents the cyclic prefix insertion in which the last N_{CP} rows of the $N \times N$ identity matrix $\boldsymbol{I}_N$ (denoted by $\boldsymbol{I}_{CP}$) are concatenated with identity matrix $\boldsymbol{I}_N$. The term β is the power loss factor, $\beta = \sqrt{N/N_T}$.

The block $\tilde{u}_{CP}(i)$ is serialized to yield $\tilde{u}_{CP}(n)$, which is then pulse shaped 1613, carrier modulated 1612, amplified, and transmitted 1611 via multiple antenna elements through a channel. The channel impulse response $h(n)$ includes the effects of pulse shaping, channel effects, receiver filtering, and sampling.

In a receiver configuration of the invention, each of a plurality of WTs is adapted to receive a different transmitted symbol on a different orthogonal carrier frequency. For a WT employing a square-root Nyquist receive filter, the received samples are expressed by:

$$x(n) = \tilde{u}_{CP}(n) * h(n) + v(n)$$

where $v(n)$ is additive white Gaussian noise (AWGN). The received samples are grouped into blocks of size N_T: $x_{CP}(i) = [x(iN_T), x(iN_T+1),\ldots, x(iN_T+N_T-1)]^T$. The first N_{CP} values of $x_{CP}(i)$ corresponding to the cyclic prefix are discarded, which leaves N-length blocks expressed by: $x(i) = [x(iN_T+N_{CP}), x(iN_T+ N_{CP}+1),\ldots, x(iN_T+N_T-1)]^T$. H is defined as an $N \times N$ circulant matrix with $\tilde{H}_{n,m} = h((n-m)_{\mathrm{mod}\,N})$. The block input-output relationship is expressed as: $\tilde{x}(i) = \beta\tilde{H}\tilde{u}(i) + \tilde{\eta}(i)$, where $\tilde{\eta}(i) = [v(iN_T+N_{CP}), v(iN_T+ N_{CP}+1),\ldots, v(iN_T+N_T-1)]^T$ is the AWGN block. Applying the FFT to $\tilde{x}(i)$ yields:

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$$x(i) = F\tilde{x}(i) = \beta F\tilde{H}F^H u(i) + \tilde{\eta}(i)$$
$$= \beta D_H u(i) + \eta(i)$$

where

$$D_H = diag\left[H\left(e^{j0}\right), H\left(e^{j(2\pi/N)}\right), \ldots H\left(e^{j(2\pi(N-1)/N)}\right)\right] = F\tilde{H}F^H$$

and $H(e^{j2\pi f})$ is the frequency response of the ISI channel; $H\left(e^{j2\pi f}\right) = \sum_{n=0}^{N_{CP}} h(n)e^{-j2\pi fn}$. An equalizer followed by a decoder uses $x(i)$ to estimate the data symbols encoded on $u(i)$.

Preferred embodiment of the invention may employ Spread-OFDM, which involves multiplying each data block $s(n)$ by a spreading matrix A:

$$u(n) = As(n)$$

In the case where CI spreading codes are employed, $A_{nm} = \exp(-j2\pi nm/N)$. This maps the data symbols to pulse waveforms positioned orthogonally in time. This choice of spreading codes also gives the appearance of reversing the IFFT. However, the resulting set of pulse waveforms is a block, rather than a sequence, wherein each waveform represents a cyclic shift within the block duration T_s, such as described in U.S. Pat. Appl. Pubs. 20030147655 and 20040086027, which are both incorporated by reference.

Figure 7A illustrates a functional embodiment of the invention related to calculating MIMO weights in a cooperative-beamforming network. A plurality of WTs provide received baseband information from a WWAN channel 1701 that includes a training sequence and/or a data sequence having a predetermined constellation of values. WWAN MIMO processing is performed 1702 on the received baseband information to derive a plurality of array-processing weights β_i, which are then distributed 1703 via the WLAN to a predetermined plurality of WTs.

Figure 7B illustrates a functional embodiment of the invention adapted to calculate transmitted data symbols received by a cooperative-beamforming network. A plurality of WTs provide received baseband information from a WWAN channel 1701 that includes a data sequence having a predetermined constellation of values. WWAN MIMO processing may be performed 1704 on the received baseband information to derive a plurality of estimated data symbols d_i, which are then conveyed 1705 via the WLAN to at least one destination WT. The WWAN MIMO processing 1704 may

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optionally include providing for any of a set of signal-processing operations, including filtering, demodulation, demultiplexing, error correction, and data formatting.

Figure 8A illustrates a functional embodiment for a method and apparatus of the invention. Specifically, a data source 1800 is adapted to distribute a plurality of data symbols via a WLAN channel 199 to a plurality N_t of WTs 1806.1-1806.N_t, which are adapted to transmit the data symbols into at least one WWAN channel 99. Although the functional embodiment shown in Figure 8A is illustrated with respect to uplink WWAN functionality, the functional blocks may alternatively be inverted to provide for downlink WWAN functionality.

The data source and the WTs 1806.1-1806.N_t include appropriate WLAN-interface equipment to support distribution of the data symbols to the WTs 1806.1-1806.N_t. For example, the WTs 1806.1-1806.N_t are shown including WLAN-interface modules 1801.1-1801.N_t. The WLAN channel 199 may optionally include additional network devices that are not shown, such as routers, access points, bridges, switches, relays, gateways, and the like. Similarly, the data source 1800 and/or the WTs 1806.1-1806.N_t may include one or more said additional network devices. The data source 1800 may include at least one of the WTs 1806.1-1806.N_t.

A coder 1803.1-1803.N_t in each of the WTs 1806.1-1806.N_t is adapted to receive a baseband data sequence from the associated WLAN-interface module 1801.1-1801.N_t and provide coding, such as channel coding, spreading, and/or multiple-access coding. A coded data sequence output from each coder 1803.1-1803.N_t is mapped into frequency bins of multicarrier generators, such as IDFTs 1804.1-1804N_t. This embodiment may be employed to produce multicarrier signals or to synthesis single-carrier signals from a plurality of spectral components. Alternatively, other types of multicarrier generators may be employed, such as quadrature-mirror filters or DSPs configured to perform other transform operations, including Hadamard transforms. The resulting multicarrier signals are coupled into the WWAN channel 99 by associated WWAN-interface modules 1805.1-1805.N_t.

For each flat-fading subcarrier frequency channel, the WWAN channel may be characterized by channel responses 1890.1-1890-N_t and 1899.1-1899-N_t of a mixing system. The channel responses 1890.1-1890-N_t and 1899.1-1899-N_t represent elements of

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H, an $N_r \times N_t$ channel-response matrix that characterizes the complex gains (i.e., transfer function, or spatial gain distribution) from the N_t transmission elements to the N_r receive elements; and n_i(n) represents an AWGN contribution having zero mean and zero variance.

There are N_r receiver elements comprising WWAN-interface modules 1815.1-1815.N_r and filter banks, such as DFTs 1814.1-1814.N_r, coupled to at least one MIMO combiner 1810. The MIMO combiner 1810 is adapted to perform any number of signal-processing operations, including decoding received data symbols. In one embodiment of the invention, the MIMO combiner 1810 is adapted to perform diversity combining. In another embodiment of the invention, the MIMO combiner 1810 is adapted to perform spatial (e.g., sub-space) processing. Furthermore, many other applications and embodiments of the invention may be achieved using the functional description (or minor variations thereof) depicted in Figure 8A.

Figure 8B illustrates a functional embodiment of the invention that may be incorporated into specific apparatus and method embodiments. In particular, WWAN signals received from a WWAN channel 99 by a plurality N_r of WTs 1836.1-1836.N_r are conveyed via a WLAN channel 199 to a MIMO combiner 1830.

In this case, WWAN data symbols are encoded by one or more coders (such as coders 1821.1-1821.N_t), impressed on a plurality of subcarriers by IDFTs 1822.1-1822.N_t, and coupled into the WWAN channel 99 by a plurality of WWAN-interface modules 1825.1-1825.N_t. Received WWAN signals may be coupled from the WWAN channel 99 by a plurality N_r of WTs 1836.1-1836.N_r. Each WT 1836.1-1836.N_r includes at least one WWAN-interface module (such as WWAN-interface modules 1831.1-1831.N_r), a filter bank (such as DFTs 1834.1-1834.N_r), and a WLAN-interface module (such as 1835.1-1835.N_r).

WWAN signals received by each WT 1836.1-1836.N_r are converted to a baseband data sequence, separated into frequency components (by the DFTs 1834.1-1834.N_r), and then adapted for transmission into the WLAN channel 99. A MIMO combiner 1830 may be configured to receive WLAN transmissions, recover the frequency components, and perform MIMO processing to generate estimates of the transmitted WWAN data symbols. The MIMO combiner 1830 and/or the WTs 1836.1-

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1836.N_r may be adapted to perform decoding. In one embodiment of the invention, the MIMO combiner 1830 may include one or more of the WTs 1836.1-1836.N_r.

Figure 8C illustrates an embodiment of the invention in which WTs 1836.1-1836.N_r are adapted to perform time-domain (e.g., Rake) processing. Specifically, each WT 1836.1-1836.N_r includes a Rake receiver 1854.1-1854.N_r. The embodiment illustrated in Figure 8C is particularly suited to performing MIMO operations on received direct-sequence signals, such as direct sequence CDMA (DS-CDMA) signals.

Particular embodiments of the invention may be directed toward transmitting and/or receiving any of the well-known types of spread signals. Spread signals include spread-spectrum signals in which a transmitted signal is spread over a frequency band much wider than the minimum bandwidth needed to transmit the information being sent. Spread spectrum includes direct-sequence modulation commonly used in CDMA systems (e.g., cdmaOne, cdma2000, 1xRTT, cdma 1xEV-DO, cdma 1xEV-DV, cdma2000 3x, W-CDMA, Broadband CDMA, and GPS), as well as frequency-domain spreading techniques, such as spread-OFDM, multi-carrier CDMA, and multi-tone CDMA.

In a DS-CDMA system, a kth WWAN transmission signal $s^k(t)$ that includes N code bits $\{b^k[n]\}_{n=1}^{N}$ is given by:

$$s^k(t) = \sum_{n=0}^{N-1} b^k[n] g_{T_b}(t - nT_b) g_\tau(t) a^k(t - iT_b) \cos(2\pi f_c t)$$

where $a^k(t) = \sum_{i=0}^{G-1} C_i^k g_{T_c}(t - iT_c)$, $C_i^k \in \{-1,1\}$ is the DS spreading signal, G represents processing gain, T_c is the chip duration, T_b is the bit duration, and $g_{T_c}(t)$, $g_{T_b}(t)$, and $g_\tau(t)$ represent the chip, bit, and transmitted pulse shapes, respectively.

A plurality M of WTs linked together by a WLAN comprises elements of an M-element antenna array capable of receiving $K \le M$ transmission channels. In a frequency-selective channel, the received signal at the array is:

$$r(t) = \sum_{k=1}^{K} \sum_{l=0}^{L^k-1} \sum_{n=0}^{N-1} \alpha_l^k \vec{V}(\vartheta_l^k) b_k[n] g(t - \tau_l^k - nT_b) \cos(2\pi f_c t + \varphi_l^k) + \upsilon(t)$$

where $\vec{V}(\vartheta)$ is an array-response vector, K is the number of received transmission channels, L^k is the number of distinct fading paths corresponding to the kth user, α_l^k is the

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fade amplitude associated with path l and user k, $\varphi_l^k = U[0,2\pi]$ represents the associated fade phase, τ_l^k is the path time-delay (which occurs below a predetermined duration threshold T_{max}), and ϑ_l^k denotes angle of arrival. The array response vector $\vec{V}(\vartheta)$ is expressed by:

$$\vec{V}(\vartheta) = \begin{bmatrix} 1 & e^{-2\pi d_1 \cos\theta/\lambda} & \dots & e^{-2\pi d_{M-1}\cos\theta/\lambda} \end{bmatrix}$$

where d_m is the antenna separation, and λ is the wavelength corresponding to carrier frequency f_c. For a jth user's l^{th} path, the nth bit at the beamformer output is given by:

$$z_l^j[n] = W^H(\vartheta_l^k)\int_{+(n-1)T_b}^{+nT_b} r(t)\cos(2\pi f_c t + \varphi_l^j)a^j(t-\tau_l^j-(n-1)T_b)dt$$

where $W(\vartheta_l^k)$ is the weighting vector of the beamforming system. $z_l^k[n]$ can be expressed by four components:

$$z_l^k[n] = S_i^j[n] + ISI_i^j[n] + IXI_i^j[n] + \upsilon_i^j[n]$$

where S is the desired signal, ISI is inter-symbol interference, IXI is cross interference (i.e., multiple-access interference), and ν is the AWGN contribution. These components can be expressed as follows:

$$S_l^j[n] = \alpha_l^j W^H(\vartheta_l^j)\vec{V}(\vartheta_l^j)b^j[n]G$$

$$ISI_i^j[n] = \sum_{\substack{h=0\\h\neq l}}^{L^k-1}\sum_{n=0}^{N-1}\alpha_l^k W^H(\vartheta_h^j)\vec{V}(\vartheta_l^k)b^j[n]\cos(\varphi_h^j-\varphi_l^j)R_{jj}(\tau_h^j-\tau_l^j-nT_b)$$

$$IXI_i^j[n] = \sum_{\substack{k=1\\k\neq j}}^{K}\sum_{\substack{h=0\\h\neq l}}^{L^k-1}\sum_{n=0}^{N-1}\alpha_l^k W^H(\vartheta_h^k)\vec{V}(\vartheta_l^j)b^j[n]\cos(\varphi_h^k-\varphi_l^j)R_{kj}(\tau_l^j-\tau_h^k-nT_b)$$

$$\upsilon_l^j[n] = \int_{+(n-1)T_b}^{+nT_b} W^H(\vartheta_l^j)n(t)a^j(t-\tau_l^j)\cos(2\pi f_c t+\varphi_l^j)dt$$

where $W^H(\vartheta_l^j)\vec{V}(\vartheta_l^j)$ represents the spatial correlation, φ_l^j and τ_l^j are the random phase and time delay for the jth user's l^{th} path, G is the processing gain, and R_{jj} and R_{kj} are the partial auto-correlation and cross-correlation of the direct sequence code(s):

$$R_{kj}(\tau) = \int_\tau^T a^k(t)a^j(t-\tau)dt$$

Maximal ratio combining produces an output:

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$$z^j[n] = \sum_{l=0}^{L-1} \alpha_l^j z_l^j[n]$$

which can be processed by a decision processor. In this case, the BER is given by:

$$P_e = \int_0^\infty Q(2r_o) f(r_o \mid \bar{r}_o) dr_o$$

where $\bar{r}_o$ is the mean value of the instantaneous SINR, r_o, and $Q(\ )$ represents the complementary error function.

It should be appreciated that the WTs may be adapted to perform either or both time-domain (e.g., Rake) or frequency-domain processing as part of a receiver operation. Signals received by a plurality of WTs may be combined with respect to any combining technique, including EGC, MRC, Minimum Mean Squared Error Combining, other types of optimal combining, Successive Interference Cancellation, and other matrix-reduction/matrix diagonalization techniques. Array-processing operations may include combinations of local and global processing. For example, diversity combining may be performed at each multi-element WT. Then signals from each WT may be combined (e.g., in a central processor) to perform sub-space (e.g., directional) processing. Other combinations of local and global processing may be employed. Similarly, combinations of sub-space processing (i.e., capacity enhancement) and diversity combining (i.e., signal-quality enhancement) may be performed. It should also be appreciated that the WTs may be adapted to perform either or both time-domain and frequency-domain processing for transmission. Thus, appropriate delays or complex weights may be provided to WT transmissions to produce a coherent phase front that converges at a predetermined WWAN destination node.

Figure 9A illustrates an optional transmission embodiment of the present invention. That is, method and apparatus configurations can be inferred from the following descriptions. A data source 1900 is adapted to provide data for processing by an array processor, such as MIMO processor 1902. Optionally, other types of array processors may be provided. A physical (e.g., wired) connection 1902 and/or a wireless connection 1901 couple the data between the data source 1900 and the MIMO processor 1902. The wireless connection 1901 is enabled by a WLAN 1999. The MIMO processor

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1902 is adapted to provide MIMO processing to the data, such as providing complex channel weights, providing spreading weights, and/or providing channel coding.

In one exemplary embodiment of the invention, MIMO processor 1902 provides convolutional or block channel coding to the data, which effectively spreads each data bit over multiple coded data bits. The resulting coded data bits are then grouped in serial blocks by the MIMO processor 1902. Signal-block outputs from the MIMO processor 1902 are provided with serial-to-parallel conversion by the WLAN 1999 (which is denoted by S/P 1914) and distributed to a plurality of WTs 1906.1-1906.M.

Each WT 1906.1-1906.M has a WLAN interface 1907.1-1907.M adapted to receive and demodulate the data received from the MIMO processor 1902. The MIMO processor 1902 is accordingly equipped with a WLAN interface that is not shown. The MIMO processor 1902 is typically comprised of one or more WTs 1906.1-1906.M. In some embodiments of the invention, MIMO processor 1902 may include at least one computer-processing terminal that does have a WWAN interface.

Data received from the MIMO processor 1902 is then modulated 1908.1-1908.M by each WT 1906.1-1906.M for transmission into a WWAN channel by a corresponding WWAN interface 1909.1-1909.M. Modulation 1908.1-1908.M typically includes mapping blocks of data bits to data symbols, which are then mapped to a modulation constellation. Modulation 1908.1-1908.M may also include channel coding and/or data interleaving. In an exemplary embodiment of the invention, modulation 1908.1-1908.M includes the application of complex WWAN channel weights. Such channel weights may optionally be provided by the MIMO processor 1902. In alternative embodiment of the invention, modulators 1908.1-1908.M provide a predetermined delay profile (provided by the MIMO processor 1902) to the data to be transmitted into the WWAN channel.

Figure 9B illustrates a functional flow chart that pertains to transmitter apparatus and method embodiments of the invention. One or more data sources 1920.1-1920.K are coupled via a WLAN 1999 to a plurality M of WTs 1926.1-1926.M. Each WT 1926.1-1926.M includes a WLAN interface 1927.1-1927.M, an array processor (such as a MIMO processor 1926.1-1926.M), and a WWAN interface 1929.1-1929.M.

The data sources 1920.1-1920.K optionally include baseband-processing capabilities, such as channel coding, interleaving, spreading, multiplexing, multiple-

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access processing, etc. The data sources 1920.1-1920.K include WLAN interfaces (not shown). The data sources 1920.1-1920.K may include one or more WTs 1926.1-1926.M.

The WLAN interfaces 1927.1-1927.M include apparatus and means for converting received signals that were formatted for transmission in the WLAN 1999 into baseband data signals. The MIMO processors 1926.1-1926.M are adapted to provide for frequency-domain and/or time-domain MIMO operations on the baseband data signals received from the WLAN interfaces 1927.1-1927.M. Alternatively, the MIMO processors 1926.1-1926.M may be adapted to perform phase operations at WWAN carrier frequencies transmitted by the WWAN interfaces 1929.1-1929.M. The WWAN interfaces 1929.1-1929.M provide any necessary baseband, IF, and RF operations necessary for transmitting data in a WWAN channel.

Figure 10A illustrates software components of a transmission embodiment of the invention residing on a computer-readable memory 1950. An array-processing weighting source-code segment 1951 is adapted to generate a plurality of array-element weights for an antenna array comprised of a plurality of WTs coupled to at least one WWAN. The array-element weights may include at least one of frequency-domain weights (e.g., complex sub-carrier weights) and time-domain weights (e.g., weighted Rake taps). The array-processing weighting source-code segment 1951 is adapted to accept as input at least one of a set of information inputs, including data signals for transmission into the WWAN, training signals (e.g., known transmission symbols) received from the WWAN, data signals (e.g., unknown transmission symbols) received from the WWAN, WWAN channel estimates, and WWAN-control information.

The array-processing weighting source-code segment 1951 is adapted to provide as output at least one of a set of information signals, including WWAN weights and weighted data for transmission into the WWAN (i.e., weighted WWAN data). A WLAN distribution source code segment 1952 is provided for distributing either or both WWAN weights and weighted WWAN data received from source-code segment 1951 to a plurality of WTs via at least one WLAN. The WLAN distribution source code segment 1952 may optionally function to couple at least one of a set of information inputs to the source-code segment 1951, including data signals for transmission into the WWAN (such

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as generated by other WTs), training signals received from the WWAN, data signals received from the WWAN, WWAN channel estimates, and WWAN-control information.

Figure 10B illustrates software components of a receiver embodiment of the invention residing on a computer-readable memory 1960. An array-processing weighting source-code segment 1961 is adapted to generate a plurality of array-element weights for an antenna array comprised of a plurality of WTs coupled to at least one WWAN. The array-element weights may include at least one of frequency-domain weights (e.g., complex sub-carrier weights) and time-domain weights (e.g., weighted Rake taps). The array-processing weighting source-code segment 1961 is adapted to accept as input at least one of a set of information inputs, including training signals (e.g., known transmission symbols) received from the WWAN, data signals (e.g., unknown transmission symbols) received from the WWAN, WWAN channel estimates, and WWAN-control information.

The array-processing weighting source-code segment 1961 is adapted to provide as output at least one of a set of information signals, including WWAN weights, weighted received WWAN data for transmission into the WLAN (i.e., weighted received WWAN data), weighted WWAN data received from a plurality of WTs connected by the WLAN and then combined (i.e., combined weighted WWAN data), and estimates of said combined weighted WWAN data. A WLAN distribution source code segment 1962 is provided for distributing at least one of a set of signals (including the WWAN weights, the weighted received WWAN data, the combined weighted WWAN data, and the estimates said combined weighted WWAN data) to a plurality of WTs via at least one WLAN. The WLAN distribution source code segment 1962 may optionally function to couple at least one of a set of information inputs to the source-code segment 1961, including WWAN data signals received by other WTs, training signals received from the WWAN by other WTs, WWAN channel estimates (either of both locally generated and received from other WTs), WWAN-control information, weights received from at least one other WT, and weighted WWAN data received from at least one other WT.

Since software embodiments of the invention may reside on one or more computer-readable memories, the term computer-readable memory is meant to include more than one memory residing on more than one WT. Thus, embodiments of the

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invention may employ one or more distributed-computing methods. In one embodiment of the invention, the computer-readable memory 1950 and/or 1960 further includes a distributed-computing source-code segment (not shown). It will be appreciated that many different types of distributed computing, which are well known in the art, may be performed. The WLAN distribution source code segment 1952 and/or 1962 may be adapted to provide for synchronizing transmitted and/or received WWAN signals.

Embodiments of the invention described herein disclose array-processing methods (including software implementations) and apparatus embodiments employed in a WWAN and coordinated between a plurality of WTs connected via at least one WWAN. WTs in a WLAN group typically share the same WWAN access. However, some embodiments of the invention provide for WTs with access to different WWANs. Furthermore, one or more WTs may have access to a plurality of WWANs and WWAN services. In some cases, one or more WTs may not be configured to access any WWAN.

In some embodiments of the invention, the computer-readable memory 1950 and/or 1960 further includes a WLAN setup source-code segment (not shown) capable of establishing and/or dynamically reconfiguring at least one WLAN group. For example, WTs may convey location information (e.g., GPS) and/or signal-strength information (e.g., in response to a WLAN probing signal) to the WLAN setup source-code segment (not shown). The WLAN setup source-code segment (not shown) may reside on one or more of the WTs and/or at least one WWAN terminal, such as a cellular base station.

The WLAN setup source-code segment (not shown) may provide one or more WLAN group configuration functions, including determining the number of WWAN-enabled WTs, the total number of WTs in the WLAN group, which WTs are active (and inactive), which WTs are in the WLAN group, and selecting which WT(s) has (have) network-control functionality. The WLAN setup source-code segment (not shown) may be adapted to perform WWAN channel quality analysis functions, including determining WWAN link performance (relative to one or more WTs) from training sequences or pilot signals, performing WWAN-channel estimation, receiving link performance or channel estimates from the WWAN, and performing channel-quality calculations (e.g., SNR, BER, PER, etc.).

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The WLAN setup source-code segment (not shown) may select which WTs are WWAN-enabled based on one or more criteria points, including WWAN link performance, WLAN link performance, required transmission and/or reception needs (e.g., the number of WLAN-group WTs requesting WWAN services, the types of WWAN services required, individual and total throughput, required signal-quality threshold, and WWAN bandwidth available to the WLAN group), computational load, WLAN capacity, power-consumption load, diversity gain, and interference mitigation.

The WLAN distribution source code segments 1952 and 1962 may be adapted to route WWAN channel-access information to the WTs. For example, WWAN channel-access information can include multiple-access information (e.g., multiple-access codes, frequency bands, time slots, spatial (or sub-space) channels, etc.), power control commands, timing and synchronization information, channel coding, modulation, channel pre-coding, and/or spread-spectrum coding.

Figure 11 shows a WWAN comprising a WWAN access point (e.g., a base station) 2120 and a local group 2100 comprising a plurality of wireless terminals (WTs) 2101-2104 communicatively coupled together via a WLAN 2105. A network-management operator 2106 is configured to handle WWAN-control operations within the local group 2100. In an exemplary embodiment, the network-management operator 2106 is coupled to at least one of the WTs 2101-2104 (e.g., WT 2103). One or more of the WTs 2101-2104 may be configured to transmit and/or receive WWAN communication signals, such as WWAN traffic channels 2110 and WWAN control messages 2111. Signals in the WWAN traffic channels 2110 may be processed by one or more of the WTs 2101-2104, which may include at least one local area network controller (e.g., 2103). The WWAN control messages 2111 are processed by the network-management operator 2106.

In an exemplary embodiment of the invention, a target WT (e.g., WT 2104) communicates with one or more WTs in the local group 2100 via the WLAN 2105, and the local group 2100 is configured to communicate with the base station 2120 via the WWAN. More specifically, one or more of the WTs 2101-2104 may be configured to participate in WWAN communications at any particular time. The target WT 2104 may communicate with the network controller (e.g., WT 2103), which is configured to

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communicate with other WTs in the local group 2100. The network controller 2103 typically oversees network control functions in the local area network. Alternatively, the target WT 2104 may function as a local area network controller. A particular WT may determine which WTs to use for transmitting and/or receiving signals in the WWAN based on local area network criteria, as well as WWAN-related criteria. Local area network control and/or WWAN control functionality may be distributed between one or more WTs in the local group.

In Figure 12, a communication system comprises a plurality *M* of WTs 2209.1 – 2209.M communicatively coupled together in a WLAN, which comprises a WLAN controller 2206. A WWAN network-management operator 2210 is communicatively coupled to the WLAN controller 2206. WWAN network-management operator 2210 is configured for cooperatively processing WWAN-control messages for the WTs 2209.1 – 2209.M, each of which comprises at least one WWAN interface 2201.1 – 2201.M, respectively.

According to one aspect of the invention, the WWAN interfaces 2201.1 – 2201.M receive WWAN control messages from the WLAN that were processed by the WWAN network-management operator 2210 and transmit those messages into the WWAN. According to another aspect of the invention, the WWAN interfaces 2201.1 – 2201.M receive WWAN control messages from the WWAN and couple those messages through the WLAN to the WWAN network-management operator 2210. According to yet another aspect of the invention, one or more WTs functions as the WWAN network-management operator 2210. Thus, the WWAN network-management operator 2210 may comprise one or more WWAN interfaces and be configured to transmit WWAN control messages into the WWAN.

For the purpose of the present disclosure, a WWAN comprising a plurality of wireless terminals communicatively coupled together via a WLAN may be defined as one or more of the following system configurations:

- A plurality of WTs in a local group configured to receive from a base station a signal intended for at least one WT.

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- A plurality of WTs in a local group configured to receive from a base station a plurality of signals modulated on interfering (e.g., common) channels and intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a base station a plurality of signals modulated on different non-interfering channels and intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a plurality of base stations a signal modulated on a common channel intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a plurality of base stations a signal redundantly modulated on a plurality of different channels intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a plurality of base stations a plurality of signals modulated on interfering channels and intended for at least one WT.
- A plurality of WTs in a local group configured to receive from a plurality of base stations a plurality of signals modulated on different non-interfering channels and intended for at least one WT.
- A plurality of WTs in a local group configured to transmit to a base station a signal originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a base station a plurality of signals modulated on interfering (e.g., common) channels originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a base station a plurality of signals modulated on different non-interfering channels originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a plurality of base stations a signal modulated on a common channel originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a plurality of base stations a signal redundantly modulated on a plurality of different channels originating from at least one WT.

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- A plurality of WTs in a local group configured to transmit to a plurality of base stations a plurality of signals modulated on interfering channels originating from at least one WT.
- A plurality of WTs in a local group configured to transmit to a plurality of base stations a plurality of signals modulated on different non-interfering channels and originating from at least one WT.
- A plurality of WTs in a first local group configured to receive from a second local group a signal intended for at least one WT in the first local group.
- A plurality of WTs in a first local group configured to receive from a second local group a plurality of signals modulated on interfering channels and intended for at least one WT in the first local group.
- A plurality of WTs in a first local group configured to receive from second local group a plurality of signals modulated on different non-interfering channels and intended for at least one WT in the first local group.
- A plurality of WTs in a first local group configured to transmit to a second local group a signal originating from at least one WT in the first local group.
- A plurality of WTs in a first local group configured to transmit to a second local group a plurality of signals modulated on interfering channels and originating from at least one WT in the first local group.
- A plurality of WTs in a first local group configured to transmit to a second local group a plurality of signals modulated on different non-interfering channels and originating from at least one WT in the first local group.
- A base station comprising a plurality of WTs in a base station local group configured to transmit a signal intended for at least one subscriber WT not in the base station local group.
- A base station comprising a plurality of WTs in a base station local group configured to transmit a plurality of signals modulated on interfering (e.g., common) channels and intended for at least one subscriber WT not in the base station local group.
- A base station comprising a plurality of WTs in a base station local group configured to transmit a plurality of signals modulated on different non-interfering channels and intended for at least one subscriber WT not in the base station local group.

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- Multiple base stations comprising at least one base station local group configured to transmit a signal modulated on a common channel intended for at least one WT.
- Multiple base stations comprising at least one base station local group configured to transmit to a plurality of WTs a signal redundantly modulated on a plurality of different channels intended for at least one WT.
- Multiple base stations comprising at least one base station local group configured to transmit to a plurality of WTs a plurality of signals modulated on interfering channels and intended for at least one WT.
- Multiple base stations comprising at least one base station local group configured to transmit to a plurality of WTs a plurality of signals modulated on different non-interfering channels and intended for at least one WT.
- A base station comprising a plurality of WTs in a base station local group configured to receive a signal originating from at least one WT.
- A base station comprising a plurality of WTs in a base station local group configured to receive a plurality of signals originating from at least one WT and modulated on interfering channels.
- A base station comprising a plurality of WTs in a base station local group configured to receive a plurality of signals modulated on different non-interfering channels and originating from at least one WT.
- Multiple base stations comprising at least one base station local group configured to receive a signal modulated on a common channel originating from at least one WT.
- Multiple base stations comprising at least one base station local group configured to receive a signal redundantly modulated on a plurality of different channels originating from at least one WT.
- Multiple base stations comprising at least one base station local group configured to receive a plurality of signals modulated on interfering channels and originating from at least one WT.
- Multiple base stations comprising at least one base station local group configured to receive a plurality of signals modulated on different non-interfering channels and originating from at least one WT.

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A WWAN network-management operator may include a single WT or a plurality of WTs. In one embodiment, the WWAN network-management operator includes a single WT communicatively coupled to the WWAN and configured to perform WWAN-control operations for one or more WTs in the local group. For example, a block diagram of a WT 2300 shown in Figure 13 comprises a WWAN network-management operator module 2302 communicatively coupled to a WWAN interface 2301 and a WLAN interface 2303. In another embodiment, the WWAN network-management operator may comprise WWAN network-management operator modules residing in a plurality of WTs. Thus, the WWAN network-management operator may be configured to transmit and/or receive WWAN-control parameters in the WWAN on behalf of one or more WTs in the local group. A local area network controller may also include a WWAN network-management operator module and may perform WWAN network management for one or more WTs in the group.

Each WT may function as its own network-management operator. For example, a WT functioning as its own network-management operator may be communicatively coupled to the WWAN and configured to transmit and receive WWAN control information directly with the WWAN, whereas traffic-channel processing may be performed in cooperation with one or more other WTs in the local group. In another exemplary configuration, WWAN control information may be coupled from a target WT (e.g., a source or destination WT relative to the subject information, i.e., the WWAN control information) to a relay WT communicatively coupled to the WWAN and configured to transmit and receive the target WT's WWAN control information. While the target WT functions as its own network-management operator, it may employ other WTs in the local group to transmit and receive WWAN control messages. Thus, the relay WT may merely function as a pass through having optional added physical-layer adjustments for the WWAN control information. The physical-layer adjustments may be used to condition the WWAN control messages for the WWAN channel and/or the WLAN channel. Similarly, a WT functioning as a network-management operator for itself and/or at least one other WT may employ one or more WTs in the local group for transmitting and receiving WWAN control messages in the WWAN.

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In another embodiment, a WT may function as a network-management operator for one or more other WTs. For example, a network controller may function as a network-management operator for at least one other WT. In another embodiment, at least one WT that is neither a network controller nor a target WT may function as the network-management operator. For example, a WT having the best WWAN channel (such as may be determined by any of a variety of signal quality criteria that are well known in the art) may be selected as the network-management operator. Various criteria for selecting WTs for network-management operator responsibilities may be implemented, including load balancing.

In another embodiment of the invention, a plurality of WTs in a local group may simultaneously function as a network-management operator. The network-management operator may comprise multiple WTs including a target WT, multiple WTs including a network controller, multiple WTs not including a network controller, or multiple WTs not including a target WT. A plurality of WTs may redundantly process WWAN control messages. Alternatively, each of a plurality of WTs configured to perform WWAN-control operations may be configured to perform a predetermined subset of the WWAN-control operations.

A network-management operator may participate in any combination of various WWAN-control operations, including power control, data-rate control, session control, authentication, key exchange, paging, control-channel monitoring, traffic channel request, channel assignment, error detection, acknowledgement, request for retransmission, identification, reconnects, synchronization, flow control, request for service from a particular sector or access point, hand-off.

Figure 14 is a flow diagram of a communication method configured in accordance with an aspect of the invention. A WLAN is employed for sharing WWAN control information between a group of WTs 2401. WWAN control information is coordinated between the group of WTs and the WWAN 2402, and WWAN control information is cooperatively processed by the group 2403.

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The Open Systems Interconnection Reference Model (OSI Reference Model) may be used to describe the function of a WWAN comprising a local group of a plurality of WTs communicatively coupled together via a WLAN.

In the Application Layer, each WT typically employs its own user applications for accessing network services (e.g., login, data upload, data download, multi-media processing). Thus, each WT handles its own application-layer network access, flow control, and error processing. Each WT controls its own user interface for access to services that support user applications. These applications typically are not subject to cooperative access (e.g., sharing). However, certain network resources (e.g., printers, faxes) may be shared. Some applications, such as computational processing applications, may provide for distributed computing processes between WTs in a network. However, such distributed-computing applications have not been employed in the prior art for receiving and decoding wireless communications.

In the Presentation Layer, each WT may translate data from an application format to a network format and vice-versa. Different data formats from different applications are processed to produce a common data format. Each WT may manage its own protocol conversion, character conversion, data encryption/decryption, and data compression/expansion. Alternatively, a network controller that serves multiple WT may perform one or more presentation-layer functions. For example, data-processing intelligence may be handled by a network controller, and individual WTs may function as dumb terminals. In some multimedia applications, a network controller may function essentially as a media server configured to deliver predetermined data formats to each WT functioning as a media device. Furthermore, there are various degrees of how presentation-layer processing may be shared between WTs and a network controller.

In the Session Layer, each WT may be responsible for identification so only designated parties can participate in a session. Session setup, reconnects, and synchronization processes may be managed by the target WT (e.g., a subscriber, an access point, or a base station), which functions as its own network-management operator for session-layer processing. Alternatively, a network controller may manage session-layer activities for each of one or more WTs in the local group. The network controller

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may store identities for each WT and manage sessions and the flow of information for each WT.

In another embodiment, multiple WTs may participate in session management. Some centralized decision-processing (such as by the target WT or a network controller) may be employed to direct one or more WTs to perform specific session-layer activities. Multiple responsibilities may be divided among the WTs. For example, one WT may conduct synchronization processes and another WT may perform session setup. The WTs assigned to perform particular functions may change with respect to signal quality with the WWAN, load balancing criteria, and/or other considerations.

In the Transport Layer, each WT may convert data streams into packets or predetermined segments. Each WT may also process received packets to reassemble messages. Thus, each WT may perform its own error handling, flow control, acknowledgement, and request for retransmission.

Alternatively, a network controller may manage transport-layer operations for each of one or more WTs in a local group. The network controller may be configured to convert data streams received from the WTs into packets. Similarly, the WT may convert data packets received from the WWAN into data streams that are routed to the appropriate WTs. The network controller may perform common network-management operator functions, including error handling, flow control, acknowledgement, and request for retransmission for each of the WTs.

In yet another embodiment, multiple WTs may be used to convert data streams into packets and/or process received packets to reassemble messages for a particular target WT. Each of a plurality of WTs may process only a portion of the received data stream and perform error handling, flow control, acknowledgement, and request for retransmission for the data it processes. Alternatively, multiple WTs may handle the same data. For example, redundant transport-layer processing may be performed by different WTs having uncorrelated WWAN channels in order to reduce errors, and thus, requests for retransmission. In another embodiment, only one WT may handle transport-layer processing at any given time. For example, a particular WT may be assigned to handle transport-layer processing if it has favorable WWAN-channel conditions. Other criteria,

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such as load balancing, may be used to select and transfer transport-layer processing responsibilities between WTs.

In the Network Layer, WTs may perform their own network-layer processing, such as addressing and routing. A WT, such as a router, a base station, a switch, or a relay may perform network-layer processes, including managing data congestion, adjusting data frames, packet switching, and routing. In addition to managing network-layer control within its local group, a network controller may perform network-layer processes for the WWAN.

The Data Link layer includes a Media Access Control (MAC) sub-layer and the Logical Link Control (LLC) sub-layer. Each WT may perform Data-link processing, such as converting received raw data bits into packets and managing error detection for other WTs. Similarly, each WT may convert data packets into raw data bits for one or more other WTs. In one embodiment, a target WT may perform its own data-link processing. Alternatively, a network controller may perform data-link processing for one or more WTs.

A Physical layer embodiment may provide for performing all physical-layer processes by a target WT. For example, a target WT distributes spread, scrambled baseband data to the other WTs, which then up convert and transmit the target's transmission signal as specified by the target WT. Similarly, each WT may receive and down convert WWAN transmissions and direct the down-converted signal via the WLAN for processing (e.g., descrambling and despreading) by a target WT.

In one embodiment, physical-layer processes may be divided between a target WT and other WTs in a local group. For example, the target WT may convey baseband data and control parameters to other WTs, which then spread and scramble the baseband data with respect to the control parameters. Additional control parameters, such as power control, and data rate control may be specified. Similarly, WTs in a local group may descramble and despread received data for further processing by a target WT. WTs may monitor control channels for signals addressed to any of a plurality of WTs in a local group.

In yet another embodiment, a network controller may perform some or all physical-layer processes corresponding to a target WT. A network controller may

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perform all physical-layer processes for a target WT (and other WTs in the corresponding local group if it performs higher-layer processes for the target WT). Alternatively, some of the higher-layer processes may be performed by the network controller and/or other WTs as part of a distributed computing procedure regardless of how the physical-layer processes are performed.

Several aspects of physical-layer processing include WWAN-control operations. Other WWAN-control operations may fall within any of a plurality of the OSI reference model layers. Embodiments and interpretations of the invention should not be constrained to the limitations of the OSI reference model. The OSI reference model is a generalization that may not be suitable for expressing the implementation of all WWAN-control operations.

In one aspect of the invention, a cellular base station may transmit a probe signal (e.g., a predetermined signal that is ramped in signal power) to a plurality of subscriber WTs. A network-management operator in a local group of WTs may be responsive to the probe signal for indicating a signal power level capable of being received from the base station. Similarly, the signal power level may be used as an indicator for transmit power and/or data rate.

Functions of the network-management operator may be distributed over a plurality of WTs in the local group, and network-management responsibilities may be shared by more than one WT and/or dynamically assigned to particular WTs. For example, a WT that first detects the probe signal may be assigned subsequent network-management responsibilities, such as predicting forward-link SINR and an associated achievable data rate, sending an acknowledgement to the base station, or requesting a particular data rate (e.g., sending a dynamic rate control signal to the base station). In another embodiment of the invention, WWAN signals received by a group of WTs may be combined before being processed by a network-management operator.

In one embodiment of the invention, a network-management operator in a local group performs open loop estimation to adjust reverse link (i.e., local group) transmit power. Alternatively, closed-loop power corrections may involve both the network-management operator and the base station. The network-management operator may send

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an access probe sequence and wait for an acknowledgement from a base station. Initial probe power is typically determined via power control.

A WT in the local group is typically denoted as being in an inactive state relative to the WWAN when it is not assigned a forward traffic channel. However, the network-management operator may assign one or more WWAN traffic channels to WTs that the WWAN considers inactive. In such cases, inactive WTs may help transmit and/or receive WWAN communications intended for active WTs in the local group. Similarly, active WTs may be assigned additional traffic channels by the network-management operator for transmitting and/or receiving WWAN communications intended for other active WTs in the group. Such assignments may be invisible to the WWAN, since so-called inactive WTs are used for connecting active WTs to the WWAN. In other embodiments of the invention, complex assignments, including sharing traffic channels between WTs, may be implemented.

A network-management operator may service one or more WTs in a variable-rate state. For example, a forward traffic channel is transmitted at a variable rate determined by the network-management operator's data rate control value. The network-management operator may determine the maximum data rate using any of a variety of well-known techniques. The network-management operator uses a data rate control channel to instruct the WWAN what data rate to serve to a particular WT in the local group. In response, the base station selects modulation, channel coding, power and/or number of multiple-access slots.

The network-management operator may direct its instructions to the best base station (i.e., the base station having the best channel relative to the local group) in its active set via addressing (e.g., a covering code). Alternatively, the network-management operator may instruct multiple base stations to serve the local group. This may occur when WTs can access more than one WWAN. This may also occur when some WTs are better served by one base station or sector while other WTs in the same local group are better served by a different base station or sector.

A WT enters a fixed-rate state when its network-management operator signals a request for a specific fixed rate from a base station or sector. The WT may transition to a variable rate if it cannot receive packets at the previously requested fixed rate. A

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network-management operator may select a fixed rate if there is an imbalance (e.g., different channel conditions) between the forward and reverse links.

In one aspect of the invention, a network-management operator is configured to perform connection-layer protocols that are typically conducted between a target WT and the base station. For example, the network-management operator may participate in acquisition and initialization state protocols, air link management protocols, connection state protocols, route updates, and/or idle state protocols.

A WT in an inactive state typically awakes from a sleep state periodically to monitor a control channel to receive overhead parameter messages and paging messages. In one aspect of the invention, a network-management operator may wait for an activate command from a default air link management protocol. A network-management operator may monitor a WWAN control channel for multiple WTs in a local group. In an alternative embodiment, WTs in the local group may take turns monitoring the WWAN control channel. In this case, responsibilities of the network-management operator are transferred betweens WTs in the local group. In another embodiment, a plurality of WTs may monitor the WWAN control channel, wherein each WT is configured to monitor the channel for only a subset of WTs in the local group.

In a network determination state, the network-management operator selects a channel on which to acquire a base station for a WT in the local group. After selecting a channel, the network-management operator enters a pilot acquisition state in which the network-management operator tunes to a particular channel and searches for the strongest pilot signal. Upon acquiring a pilot, the network-management operator enters a synchronization state. At this point, the network-management operator may transfer synchronization responsibilities to the target WT. If the network-management operator (or the target WT) is unable to obtain a pilot, it reverts back to the network determination state.

In the synchronization state, the network-management operator or the target WT looks for a sync message on the control channel and sets its clock to the time specified in the sync message. Failure to receive the sync message or similar failures may result in returning to the network determination state.

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The base station undergoes various state transitions in the process of serving the WTs. In an initialization state, the base station activates an initialization state protocol, overhead message protocol, and a control channel MAC protocol. A network-management operator may selectively route certain messages through WTs in a local group comprising the base station while reserving other messages for WWAN transmission only by the base station.

An idle state occurs after the network is acquired, but before an open connection is established. The base station initiates an idle state protocol, overhead messages protocol, route update protocol, control channel MAC protocol, access channel MAC protocol, and forward and reverse channel MAC protocols. In the connected state, base station and the target WT have an open connection until the connection is closed (i.e., goes to the idle state) or network redirection (goes to the initialization state). The base station activates a connected state protocol, overhead messages protocol, route update, control channel MAC protocol, and forward and reverse channel MAC protocols.

A network-management operator may be configured to direct hand offs between WWAN sectors, base stations, and/or networks. In one embodiment, a network-management operator in a local group may measure the SINR on each pilot in an active set (e.g., a set of base stations that actively serve the local group) and request data from the sector having the highest SINR. The network-management operator predicts the SINR for the next packet and request a higher data rate if it can decode it at that SINR. The rate request (which may include data rate, format, and modulation type) is sent by the network-management operator to the appropriate sector using a data rate control channel.

Generally, the network-management operator requests data from only one sector at a time. However, different WTs in a local group serving a particular target WT may request WWAN channels from multiple sectors at a time on identical or different WWAN channels. The network-management operator may coordinate requests for channels from different sectors. Multiple sectors (or base stations) may be configured to serve the same WWAN channel simultaneously. Alternatively, multiple WWAN channels may be used to serve one WT in the group. Although the target WT may have a better connection with a particular base station, the local group as a whole may have a better connection with a different base station. Thus, the network-management operator

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may dictate that the link be established and maintained relative to the group's connection rather than the target WT's connection.

A base-station scheduler may allocate physical channels for WTs. However, a network-management operator in a local group may provide logical channel assignments to the WTs that are invisible to the physical channel operation of the WWAN. Multiple WTs in a local group may utilize a single WT channel, such as for packet switched data communications. Each WT may utilize multiple physical channels, such as when higher data rates are required. The network-management operator may assign logical channels to various physical WWAN channels, and thus, effectively hand off those data channels to other sectors, base stations, or WWAN networks serving those physical WWAN channels.

Data rates requested by WTs may follow a channel fading process, wherein higher data requests occur when channel conditions are favorable and lower rates are requested as the channel degrades. It is well known that when a base station serves a large number of WTs, that diversity of multiple units can mitigate system-wide variations in data rate due to changing channel conditions. Multi-user diversity teaches that the opportunity for serving good channels increases with the number of users, which increases total network throughput.

One embodiment of the invention may provide for a network-management operator that dynamically selects one WT in a local group to communicate with a WWAN at a particular time, even though one or more channels may be served between the base station and the local group. The selection of which WT in the group communicates with the WWAN may change with changing channel conditions between the local group and the base station(s). Thus, the update rate for the dynamic selection may be based on the rate of change of WWAN channel conditions. This embodiment may be adapted for simultaneous communication by multiple WTs and/or the use of multiple base stations and/or WWANs. In another exemplary embodiment, the network-management operator may interleave communications (e.g., packets) across multiple WWAN channels undergoing uncorrelated channel distortions. Similarly, a WWAN specifically configured to interact with a local group may interleave messages across multiple WWAN channels transmitted to the local group. Different WWAN channels

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may be transmitted and received by one base station or a plurality of base stations. This type of interleaving (at either the local group and the base station) may be determined by a network-management operator.

In another embodiment, a network-management operator may be configured to redundantly transmit data symbols over multiple slots or physical channels to reduce transmission power or to allocate more power to data.

A network-management operator may employ an authentication protocol to authenticate traffic between a base station and a MT. For example, a network-management operator may identify a particular WT in a local group to a base station. The base station may then verify that the WT has a legitimate subscription record with a service provider that utilizes the WWAN. Upon verification, the base station allows access to the air interface and the network-management operator (whose responsibilities may be transferred to the WT) signs access channel packets to prove it is the true owner of the session. In one exemplary embodiment of the invention, the WT and/or the network-management operator may use IS-856 Air Interface Authentication.

In one embodiment of the invention, a target WT includes a network-management operator that employs other WTs in its local group to interact with a WWAN. In this case, authentication may be performed only with the target WT. In an alternative embodiment, the network-management operator resides in at least one other WT, such as a network controller. Thus, authentication may be performed with a network-management operator in a single terminal that is configured to perform authentication for more than one WT.

A network-management operator may employ a key exchange protocol (e.g., a Diffie-Hellman algorithm) for exchanging security keys between a WT and a WWAN for authentication and encryption. Typically, there is some predetermined key exchange algorithm used within a particular WWAN. Public values are exchanged and then messages are exchanged between the WT and the WWAN to indicate that the session keys have been correctly calculated. The keys may be used by the WT and the WWAN in an encryption protocol to encrypt traffic.

In one embodiment of the invention, a network-management operator resides on a target WT that accesses the WWAN via multiple WTs in a local group. The network-

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management operator may be configured to encrypt and decrypt WWAN traffic for the target WT without vital security information being made available to WTs other than the target WT. In another embodiment, the network-management operator may reside in a network controller. In this case, the network-management operator may be configured to engage in security protocols for more than one WT in the local group. Network-management operators according to various embodiments of the invention may be configured to participate in security protocols used to provide crypto sync, time stamps, and other elements used in authentication and encryption protocols.

All publications and patent applications mentioned in this specification are herein incorporated by reference to the same extent as if each individual publication or patent application was specifically and individually incorporated by reference.

Various embodiments of the invention may include variations in system configurations and the order of steps in which methods are provided. In many cases, multiple steps and/or multiple components may be consolidated.

The method and system embodiments described herein merely illustrate the principles of the invention. It should be appreciated that those skilled in the art will be able to devise various arrangements, which, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. Furthermore, all examples and conditional language recited herein are intended to be only for pedagogical purposes to aid the reader in understanding the principles of the invention. This disclosure and its associated references are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

It should be appreciated by those skilled in the art that the block diagrams herein represent conceptual views of illustrative circuitry, algorithms, and functional steps embodying the principles of the invention. Similarly, it should be appreciated that any

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flow charts, flow diagrams, signal diagrams, system diagrams, codes, and the like represent various processes which may be substantially represented in computer-readable medium and so executed by a computer or processor, whether or not such computer or processor is explicitly shown.

The functions of the various elements shown in the drawings, including functional blocks labeled as “processors” or “systems,” may be provided through the use of dedicated hardware as well as hardware capable of executing software in association with appropriate software. When provided by a processor, the functions may be provided by a single dedicated processor, by a shared processor, or by a plurality of individual processors, some of which may be shared. Moreover, explicit use of the term "processor" or "controller" should not be construed to refer exclusively to hardware capable of executing software, and may implicitly include, without limitation, digital signal processor (DSP) hardware, read-only memory (ROM) for storing software, random access memory (RAM), and non-volatile storage. Other hardware, conventional and/or custom, may also be included. Similarly, the function of any component or device described herein may be carried out through the operation of program logic, through dedicated logic, through the interaction of program control and dedicated logic, or even manually, the particular technique being selectable by the implementer as more specifically understood from the context.

Any element expressed herein as a means for performing a specified function is intended to encompass any way of performing that function including, for example, a combination of circuit elements which performs that function or software in any form, including, therefore, firmware, micro-code or the like, combined with appropriate circuitry for executing that software to perform the function. The invention as defined herein resides in the fact that the functionalities provided by the various recited means are combined and brought together in the manner which the operational descriptions call for. Applicant regards any means which can provide those functionalities as equivalent as those shown herein.

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Claims

1. A method for receiving an Orthogonal Frequency Division Multiplexing (OFDM) signal transmitted by a user device in a wireless network, the method comprising:

determining a plurality of subcarrier frequencies allocated to the user device;

converting the OFDM signal to a plurality of frequency-domain values corresponding to the plurality of subcarrier frequencies; and

decoding the plurality of frequency-domain values to recover a plurality of data symbols encoded by the user device on the plurality of subcarrier frequencies;

wherein decoding employs a plurality of codes that are inverse to, complex-conjugate of, or complementary to a set of complex-valued codes that the user device employs to shape the OFDM signal into a superposition of cyclic-shifted pulse waveforms that each has one of the plurality of data symbols modulated thereon.

2. The method of claim 1, wherein each of the plurality of codes employed for decoding comprises a different vector of linear phase offsets.

3. The method of claim 1, wherein the cyclic-shifted waveforms have cyclic shifts that cause the cyclic-shifted waveforms to be orthogonal, and each of the plurality of codes employed for decoding comprises a set of linear phase offsets that corresponds to one of the cyclic shifts.

4. The method of claim 1, wherein the complex-valued codes cause the cyclic-shifted waveforms to be Sinc waveforms, and the plurality of codes is configured to decode the Sinc waveforms.

5. The method of claim 1, wherein the plurality of subcarrier frequencies has a frequency spacing f_s, and the plurality of cyclic-shifted waveforms are periodic over a symbol interval $T_s = 1/f_s$.

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6. The method of claim 1, wherein converting the OFDM signal to a plurality of frequency-domain values uses a discrete Fourier transform.

7. The method of claim 1, further comprising removing at least one of a guard interval, a cyclic prefix, and a cyclic postfix from the OFDM signal before converting the OFDM signal to the plurality of frequency-domain values.

8. The method of claim 1, wherein converting the OFDM signal to the plurality of frequency-domain values provides for orthogonal frequency division multiple access for the user device and at least one other user device.

9. The method of claim 1, wherein an mth one of the plurality of codes is expressed as a set of N code chips for a set of integers $n = \{0,\ldots, N-1\}$, wherein each code chip is expressed by $e^{i2\pi nm/N}$, wherein *i* is the square root of -1, and π is Pi.

10. An apparatus for receiving an Orthogonal Frequency Division Multiplexing (OFDM) signal transmitted by a user device in a wireless network, the apparatus comprising:

at least one processor; and

a non-transitory computer-readable memory communicatively coupled to the at least one processor, the non-transitory computer-readable memory including a set of instructions stored thereon and executable by the at least one processor for:

determining a plurality of subcarrier frequencies allocated to the user device;

converting the OFDM signal to a plurality of frequency-domain values corresponding to the plurality of subcarrier frequencies; and

decoding the plurality of frequency-domain values to recover a plurality of data symbols encoded by the user device on the plurality of subcarrier frequencies;

wherein decoding employs a plurality of codes that are inverse to, complex-conjugate of, or complementary to a set of complex-valued codes that the user device employs to shape the OFDM signal into a superposition of cyclic-shifted

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pulse waveforms that each has one of the plurality of data symbols modulated thereon.

11. The apparatus of claim 10, wherein each of the plurality of codes employed for decoding comprises a different vector of linear phase offsets.

12. The apparatus of claim 10, wherein the cyclic-shifted waveforms have cyclic shifts that cause the cyclic-shifted waveforms to be orthogonal, and each of the plurality of codes employed for decoding comprises a set of linear phase offsets that corresponds to one of the cyclic shifts.

13. The apparatus of claim 10, wherein the complex-valued codes cause the cyclic-shifted waveforms to be Sinc waveforms, and the plurality of codes is configured to decode the Sinc waveforms.

14. The apparatus of claim 10, wherein the plurality of subcarrier frequencies has a frequency spacing f_s, and the plurality of cyclic-shifted waveforms are periodic over a symbol interval $T_s = 1/f_s$.

15. The apparatus of claim 10, wherein converting the OFDM signal to a plurality of frequency-domain values uses a discrete Fourier transform.

16. The apparatus of claim 10, wherein the non-transitory computer-readable memory further includes instructions stored thereon and executable by the at least one processor for removing at least one of a guard interval, a cyclic prefix, and a cyclic postfix from the OFDM signal before converting the OFDM signal to the plurality of frequency-domain values.

17. The apparatus of claim 10, wherein converting the OFDM signal to the plurality of frequency-domain values provides for orthogonal frequency division multiple access for the user device and at least one other user device.

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18. The apparatus of claim 10, wherein an mth one of the plurality of codes is expressed as a set of N code chips for a set of integers n = {0,…, N-1}, wherein each code chip is expressed by $e^{i2\pi nm/N}$, wherein *i* is the square root of -1, and π is Pi.

19. A computer program product for receiving an Orthogonal Frequency Division Multiplexing (OFDM) signal transmitted by a user device in a wireless network, the computer program product comprising a non-transitory computer readable storage device having computer readable program code stored therein, said program code containing instructions executable by one or more processors of a computer system for:

determining a plurality of subcarrier frequencies allocated to the user device;

converting the OFDM signal to a plurality of frequency-domain values corresponding to the plurality of subcarrier frequencies; and

decoding the plurality of frequency-domain values to recover a plurality of data symbols encoded by the user device on the plurality of subcarrier frequencies;

wherein decoding employs a plurality of codes that are inverse to, complex-conjugate of, or complementary to a set of complex-valued codes that the user device employs to shape the OFDM signal into a superposition of cyclic-shifted pulse waveforms that each has one of the plurality of data symbols modulated thereon.

20. The computer program product of claim 19, wherein each of the plurality of codes employed for decoding comprises a different vector of linear phase offsets.

21. The computer program product of claim 19, wherein the cyclic-shifted waveforms have cyclic shifts that cause the cyclic-shifted waveforms to be orthogonal, and each of the plurality of codes employed for decoding comprises a set of linear phase offsets that corresponds to one of the cyclic shifts.

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22. The computer program product of claim 19, wherein the complex-valued codes cause the cyclic-shifted waveforms to be Sinc waveforms, and the plurality of codes is configured to decode the Sinc waveforms.

23. The computer program product of claim 19, wherein the plurality of subcarrier frequencies has a frequency spacing f_s, and the plurality of cyclic-shifted waveforms are periodic over a symbol interval $T_s = 1/f_s$.

24. The computer program product of claim 19, wherein converting the OFDM signal to a plurality of frequency-domain values uses a discrete Fourier transform.

25. The computer program product of claim 19, wherein the non-transitory computer-readable storage device further includes instructions stored therein and executable by the one or more processors for removing at least one of a guard interval, a cyclic prefix, and a cyclic postfix from the OFDM signal before converting the OFDM signal to the plurality of frequency-domain values.

26. The computer program product of claim 19, wherein converting the OFDM signal to the plurality of frequency-domain values provides for orthogonal frequency division multiple access for the user device and at least one other user device.

27. The computer program product of claim 19, wherein an mth one of the plurality of codes is expressed as a set of N code chips for a set of integers $n = \{0,\ldots, N-1\}$, wherein each code chip is expressed by $e^{i2\pi nm/N}$, wherein i is the square root of -1, and π is Pi.

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PTO/AIA/15 (03-13)
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UTILITY PATENT APPLICATION TRANSMITTAL

(Only for new nonprovisional applications under 37 CFR 1.53(b))

Attorney Docket No.	CBF-006.C3.2
First Named Inventor	Shattil
Title	Transmit Pre-Coding
Express Mail Label No.	

APPLICATION ELEMENTS

See MPEP chapter 600 concerning utility patent application contents.

1. [✔] **Fee Transmittal Form** (PTO/SB/17 or equivalent)
2. [✔] **Applicant asserts small entity status.** See 37 CFR 1.27
3. [ ] **Applicant certifies micro entity status.** See 37 CFR 1.29. Applicant must attach form PTO/SB/15A or B or equivalent.
4. [✔] **Specification** [*Total Pages* 77] Both the claims and abstract must start on a new page. *(See MPEP § 608.01(a) for information on the preferred arrangement)*
5. [✔] **Drawing(s)** (35 U.S.C. 113) [*Total Sheets* 17]
6. **Inventor's Oath or Declaration** [*Total Pages* 2] *(including substitute statements under 37 CFR 1.64 and assignments serving as an oath or declaration under 37 CFR 1.63(e))*
   a. [✔] Newly executed (original or copy)
   b. [ ] A copy from a prior application (37 CFR 1.63(d))
7. [✔] **Application Data Sheet** ** See note below.* See 37 CFR 1.76 (PTO/AIA/14 or equivalent)
8. **CD-ROM or CD-R** in duplicate, large table, or Computer Program (*Appendix*)
   [ ] Landscape Table on CD
9. **Nucleotide and/or Amino Acid Sequence Submission** (*if applicable, items a. – c. are required*)
   a. [ ] Computer Readable Form (CRF)
   b. [ ] Specification Sequence Listing on:
      i. [ ] CD-ROM or CD-R (2 copies); or
      ii. [ ] Paper
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ACCOMPANYING APPLICATION PAPERS

10. [ ] **Assignment Papers** (cover sheet & document(s))
    Name of Assignee _____
11. [ ] **37 CFR 3.73(c) Statement** (*when there is an assignee*) [ ] **Power of Attorney**
12. [ ] **English Translation Document** (*if applicable*)
13. [ ] **Information Disclosure Statement** (PTO/SB/08 or PTO-1449)
    [ ] Copies of citations attached
14. [ ] **Preliminary Amendment**
15. [ ] **Return Receipt Postcard** (*MPEP § 503*) (*Should be specifically itemized*)
16. [ ] **Certified Copy of Priority Document(s)** (*if foreign priority is claimed*)
17. [ ] **Nonpublication Request** Under 35 U.S.C. 122(b)(2)(B)(i). Applicant must attach form PTO/SB/35 or equivalent.
18. [ ] **Other:** _____

*Note: (1) Benefit claims under 37 CFR 1.78 and foreign priority claims under 1.55 **must** be included in an Application Data Sheet (ADS).
(2) For applications filed under 35 U.S.C. 111, the application must contain an ADS specifying the applicant if the applicant is an assignee, person to whom the inventor is under an obligation to assign, or person who otherwise shows sufficient proprietary interest in the matter. See 37 CFR 1.46(b).

19. CORRESPONDENCE ADDRESS

[✔] The address associated with Customer Number: 74284 **OR** [ ] Correspondence address below

Name					
Address					
City		State		Zip Code	
Country		Telephone		Email	

Signature	/Steven J Shattil/	Date	11/26/2020
Name (Print/Type)	Steven J Shattil	Registration No. (Attorney/Agent)	40170

This collection of information is required by 37 CFR 1.53(b). The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 12 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

If you need assistance in completing the form, call 1-800-PTO-9199 and select option 2.

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The **Privacy Act of 1974 (P.L. 93-579)** requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (*i.e.*, GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

Electronic Patent Application Fee Transmittal

Application Number:	
Filing Date:	
Title of Invention:	Transmit Pre-Coding
First Named Inventor/Applicant Name:	Steve Shattil
Filer:	Steven J Shattil
Attorney Docket Number:	CBF-006.C3.2

Filed as Small Entity

Filing Fees for Track I Prioritized Examination - Nonprovisional Application under 35 USC 111(a)

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
UTILITY FILING FEE (ELECTRONIC FILING)	4011	1	80	80
UTILITY SEARCH FEE	2111	1	350	350
UTILITY EXAMINATION FEE	2311	1	400	400
REQUEST FOR PRIORITIZED EXAMINATION	2817	1	2100	2100
Pages:				
Claims:				
CLAIMS IN EXCESS OF 20	2202	7	50	350
Miscellaneous-Filing:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
PUBL. FEE- EARLY, VOLUNTARY, OR NORMAL	1504	1	0	0
PROCESSING FEE, EXCEPT PROV. APPLS.	2830	1	70	70

Petition:	
Patent-Appeals-and-Interference:	
Post-Allowance-and-Post-Issuance:	
Extension-of-Time:	
Miscellaneous:	
Total in USD ($)	**3350**