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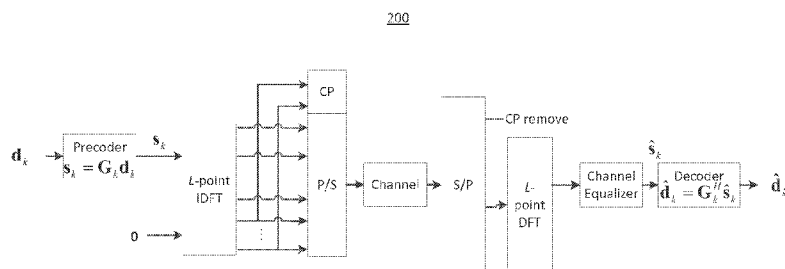
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(54) **Title:** PRECODING FOR MULTICARRIER MODULATION SYSTEMS

FIG. 2

(57) **Abstract:** Systems, methods, and instrumentalities are disclosed for selecting a precoding matrix for orthogonal frequency division multiplexing (OFDM) transmission. A wireless transmit/receive unit (WTRU) may determine a preceding matrix. The precoding matrix may be determined for a frequency band associated with a plurality of devices. A portion of the frequency band allocated to a device of the plurality of devices may be determined. A portion of the precoding matrix associated with the portion of the frequency band may be determined. Data may be sent using the portion of the precoding matrix. For example, the portion of the frequency band allocated to the given transmitter may be a plurality of OFDM subcarriers. The precoding matrix may be determined as a function of a number of devices and/or an available bandwidth of the frequency band. Spectral precoding applies to a set of K synchronized users and each spectrally precoded user spans the whole set of N subcarriers available to the K users. Since the users are synchronized, orthogonality between the N subcarriers and the users is maintained.

PRECODING FOR MULTICARRIER MODULATION SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of United States Provisional Patent Application No. 61/754,164, filed January 18, 2013 and United States Provisional Patent Application No. 61/754,282, filed January 18, 2013.

BACKGROUND

[0002] Multicarrier modulation (MCM) techniques may enable transmission of a set of data over multiple narrow band subcarriers simultaneously. With an advanced wideband modulation and coding scheme, a system with MCM may achieve higher spectral efficiency in frequency selective channels compared to those using single carrier modulation techniques. Orthogonal frequency division multiplexing (OFDM) technology, which divides the total bandwidth into several orthogonal sub-bands overlapping in frequency, is an example of MCM.

[0003] OFDM has several favorable properties, such as high spectral efficiency, robustness to channel fading, multipath delay spread tolerance, efficient digital signal processor (DSP) implementation, granular resource allocation, *etc.* OFDM may have shortcomings, which may include, for example, high peak-to-average power ratio (PAPR) and high sensitivity to carrier frequency offset. OFDM signals may have high sidelobes in their subcarriers and may create relatively large Out-of-Band Emissions (OOBE). As a result, OFDM may not be ideal for certain wireless communication systems and applications, *e.g.*, Cognitive Radio (CR). A CR system may operate in the bands assigned to licensed users (LUs) by utilizing vacant parts of LU bands and may reduce or minimize its interference to LUs. OFDM has been considered as a candidate for CR in the first cognitive radio based standard, IEEE 802.22. OFDM-based CR systems may suffer from large OOB radiation that may interfere with other bands occupied by LUs.

SUMMARY

[0004] Systems, methods, and instrumentalities are disclosed for selecting a precoding matrix for orthogonal frequency division multiplexing (OFDM) transmission. A wireless transmit/receive unit (WTRU) may determine a precoding matrix. The precoding matrix may be determined for a frequency band associated with a plurality of devices. A portion of the frequency band allocated to a device of the plurality of devices may be determined. A portion of the precoding matrix associated with the portion of the frequency band may be determined. Data may be sent using the portion of the precoding matrix. For example, the portion of the frequency band allocated to the given transmitter may be a plurality of OFDM subcarriers. The precoding matrix may be determined as a function of a number of devices and/or an available bandwidth of the frequency band.

[0005] Determining the portion of the precoding matrix that is sent based on the identity of the frequency band allocated to the given transmitter and the first precoding matrix may include selecting one or more columns of the precoding matrix based on the given plurality of OFDM subcarriers. The WTRU may be configured to determine the precoding matrix based on a singular value decomposition of a matrix that indicates or represents the spectral leakage across a frequency range such as the chosen notched frequencies. For example, the singular value decomposition of the matrix representing the spectral leakage across the notched frequencies may yield a plurality of precoding vectors that when applied to transmit data removes at least a portion and/or most of the spectral leakage across the notched frequencies. To ensure proper aggregation of the signals transmitted by each of the plurality of transmitters each of the plurality of transmitters may be synchronized with each other.

[0006] The precoding matrix may be derived for a virtual user of the entire frequency band. Each of the plurality of transmitters may independently determine the precoding matrix and may select a respective portion of the precoding matrix based on a respective allocation and the precoding matrix. Each of the plurality of transmitters may determine the precoding matrix and the respective portion of the precoding matrix without receiving signaling indicating values of the precoding matrix or the respective portion of the precoding matrix. The portion of the precoding matrix may be utilized in addition to filtering and/or windowing approaches.

[0007] Precoding techniques may be combined in a multicarrier modulation system. A precoder may be used to precode a symbol stream using a first precoding technique to generate a first precoded symbol stream. The precoder may then be used to precode the first precoded symbol stream using a second precoding technique to generate a second precoded symbol stream.

[0008] The first precoding technique may be associated with a first precoding matrix. The second precoding technique may be associated with a second precoding matrix. A third precoding matrix may be defined as a matrix product of the first precoding matrix and the second precoding matrix.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. 1A is a system diagram of an example communications system in which one or more disclosed embodiments may be implemented.

[0010] FIG. 1B is a system diagram of an example wireless transmit/receive unit (WTRU) that may be used within the communications system illustrated in FIG. 1A.

[0011] FIG. 1C is a system diagram of an example radio access network and an example core network that may be used within the communications system illustrated in FIG. 1A.

[0012] FIG. 1D is a system diagram of another example radio access network and another example core network that may be used within the communications system illustrated in FIG. 1A.

[0013] FIG. 1E is a system diagram of another example radio access network and another example core network that may be used within the communications system illustrated in FIG. 1A.

[0014] FIG. 2 is a block diagram illustrating an example transceiver of a precoded OFDM-based CR user.

[0015] FIG. 3 is a diagram illustrating example power spectral density (PSD) performance with precoding.

[0016] FIG. 4 is a block diagram illustrating an example Precoded-OFDM transceiver with filtering or windowing.

[0017] FIG. 5 is a diagram illustrating example PSD performance with multiuser precoding.

[0018] FIG. 6 is a diagram illustrating example bit error rate (BER) performance of precoded OFDM.

[0019] FIG. 7 is a diagram illustrating example peak-to-average power ratio (PAPR) performance of precoded OFDM.

[0020] FIG. 8 is a block diagram illustrating a combined precoder.

- [0021] FIG. 9 is a block diagram illustrating an example transmitter of an Orthogonal Frequency Division Multiplexing (OFDM) system.
- [0022] FIG. 10 is a block diagram illustrating an example receiver of an OFDM system.
- [0023] FIG. 11 is a block diagram illustrating an example OFDM system.
- [0024] FIG. 12 is a graph that illustrates an example PSD after applying Chung's Spectral precoding to a 64-subcarrier OFDM system.
- [0025] FIG. 13 is a graph that illustrates an example PSD of an SVD-based system with closed-notched frequencies.
- [0026] FIGS. 14 and 15 are graphs that illustrate an example comparison of PSD in SVD-based and combined NG-OFDM for close-notched and distant-notched frequencies.
- [0027] FIGS. 16 and 17 are graphs that illustrate an example comparison of PSD in SVD-based and combined ZP-OFDM for close-notched and distant-notched frequencies.
- [0028] FIGS. 18 and 19 are graphs that illustrate an example comparison of PSD in SVD-based and combined CP-OFDM for close-notched and distant-notched frequencies.
- [0029] FIG. 20 is a graph that illustrates an example bit error rate (BER) of IFFT outputs in an example NG-OFDM system using QPSK modulation.

DETAILED DESCRIPTION

[0030] A detailed description of illustrative embodiments will now be described with reference to the various Figures. Although this description provides a detailed example of possible implementations, it should be noted that the details are intended to be exemplary and in no way limit the scope of the application.

[0031] FIG. 1A is a diagram of an example communications system 100 in which one or more disclosed embodiments may be implemented. The communications system 100 may be a multiple access system that provides content, such as voice, data, video, messaging, broadcast, *etc.*, to multiple wireless users. The communications system 100 may enable multiple wireless users to access such content through the sharing of system resources, including wireless bandwidth. For example, the communications system 100 may employ one or more channel access methods, such as code division multiple access (CDMA), time division multiple access (TDMA), frequency division multiple access (FDMA), orthogonal FDMA (OFDMA), single-carrier FDMA (SC-FDMA), and the like.

[0032] As shown in FIG. 1A, the communications system 100 may include wireless transmit/receive units (WTRUs) 102a, 102b, 102c, and/or 102d (which generally or collectively may be referred to as WTRU 102), a radio access network (RAN) 103/104/105, a core network 106/107/109, a public switched telephone network (PSTN) 108, the Internet 110, and other networks 112, though it will be appreciated that the disclosed embodiments contemplate any number of WTRUs, base stations, networks, and/or network elements. Each of the WTRUs 102a, 102b, 102c, 102d may be any type of device configured to operate and/or communicate in a wireless environment. By way of example, the WTRUs 102a, 102b, 102c, 102d may be configured to transmit and/or receive wireless signals and may include user equipment (UE), a mobile station, a fixed or mobile subscriber unit, a pager, a cellular telephone, a personal digital assistant (PDA), a smartphone, a laptop, a netbook, a personal computer, a wireless sensor, consumer electronics, and the like.

[0033] The communications system 100 may also include a base station 114a and a base station 114b. Each of the base stations 114a, 114b may be any type of device configured to wirelessly interface with at least one of the WTRUs 102a, 102b, 102c, 102d to facilitate access to one or more communication networks, such as the core network 106/107/109, the Internet 110, and/or the networks 112. By way of example, the base stations 114a, 114b may be a base transceiver station (BTS), a Node-B, an eNode B, a Home Node B, a Home eNode B, a site controller, an access point (AP), a wireless router, and the like. While the base stations 114a, 114b are each depicted as a single element, it will be appreciated that the base stations 114a, 114b may include any number of interconnected base stations and/or network elements.

[0034] The base station 114a may be part of the RAN 103/104/105, which may also include other base stations and/or network elements (not shown), such as a base station controller (BSC), a radio network controller (RNC), relay nodes, *etc.* The base station 114a and/or the base station 114b may be configured to transmit and/or receive wireless signals within a particular geographic region, which may be referred to as a cell (not shown). The cell may further be divided into cell sectors. For example, the cell associated with the base station 114a may be divided into three sectors. Thus, in one embodiment, the base station 114a may include three transceivers, *e.g.*, one for each sector of the cell. In another embodiment, the base station 114a may employ multiple-input multiple output (MIMO) technology and, therefore, may utilize multiple transceivers for each sector of the cell.

[0035] The base stations 114a, 114b may communicate with one or more of the WTRUs 102a, 102b, 102c, 102d over an air interface 115/116/117, which may be any suitable wireless

communication link (*e.g.*, radio frequency (RF), microwave, infrared (IR), ultraviolet (UV), visible light, *etc.*). The air interface 115/116/117 may be established using any suitable radio access technology (RAT).

[0036] More specifically, as noted above, the communications system 100 may be a multiple access system and may employ one or more channel access schemes, such as CDMA, TDMA, FDMA, OFDMA, SC-FDMA, and the like. For example, the base station 114a in the RAN 103/104/105 and the WTRUs 102a, 102b, 102c may implement a radio technology such as Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access (UTRA), which may establish the air interface 115/116/117 using wideband CDMA (WCDMA). WCDMA may include communication protocols such as High-Speed Packet Access (HSPA) and/or Evolved HSPA (HSPA+). HSPA may include High-Speed Downlink Packet Access (HSDPA) and/or High-Speed Uplink Packet Access (HSUPA).

[0037] In another embodiment, the base station 114a and the WTRUs 102a, 102b, 102c may implement a radio technology such as Evolved UMTS Terrestrial Radio Access (E-UTRA), which may establish the air interface 115/116/117 using Long Term Evolution (LTE) and/or LTE-Advanced (LTE-A).

[0038] In other embodiments, the base station 114a and the WTRUs 102a, 102b, 102c may implement radio technologies such as IEEE 802.16 (*e.g.*, Worldwide Interoperability for Microwave Access (WiMAX)), CDMA2000, CDMA2000 1X, CDMA2000 EV-DO, Interim Standard 2000 (IS-2000), Interim Standard 95 (IS-95), Interim Standard 856 (IS-856), Global System for Mobile communications (GSM), Enhanced Data rates for GSM Evolution (EDGE), GSM EDGE (GERAN), and the like.

[0039] The base station 114b in FIG. 1A may be a wireless router, Home Node B, Home eNode B, or access point, for example, and may utilize any suitable RAT for facilitating wireless connectivity in a localized area, such as a place of business, a home, a vehicle, a campus, and the like. In one embodiment, the base station 114b and the WTRUs 102c, 102d may implement a radio technology such as IEEE 802.11 to establish a wireless local area network (WLAN). In another embodiment, the base station 114b and the WTRUs 102c, 102d may implement a radio technology such as IEEE 802.15 to establish a wireless personal area network (WPAN). In yet another embodiment, the base station 114b and the WTRUs 102c, 102d may utilize a cellular-based RAT (*e.g.*, WCDMA, CDMA2000, GSM, LTE, LTE-A, *etc.*) to establish a picocell or femtocell. As shown in FIG. 1A, the base station 114b may have a direct connection to the

Internet 110. Thus, the base station 114b may not be required to access the Internet 110 via the core network 106/107/109.

[0040] The RAN 103/104/105 may be in communication with the core network 106/107/109, which may be any type of network configured to provide voice, data, applications, and/or voice over internet protocol (VoIP) services to one or more of the WTRUs 102a, 102b, 102c, 102d. For example, the core network 106/107/109 may provide call control, billing services, mobile location-based services, pre-paid calling, Internet connectivity, video distribution, *etc.*, and/or perform high-level security functions, such as user authentication. Although not shown in FIG. 1A, it will be appreciated that the RAN 103/104/105 and/or the core network 106/107/109 may be in direct or indirect communication with other RANs that employ the same RAT as the RAN 103/104/105 or a different RAT. For example, in addition to being connected to the RAN 103/104/105, which may be utilizing an E-UTRA radio technology, the core network 106/107/109 may also be in communication with another RAN (not shown) employing a GSM radio technology.

[0041] The core network 106/107/109 may also serve as a gateway for the WTRUs 102a, 102b, 102c, 102d to access the PSTN 108, the Internet 110, and/or other networks 112. The PSTN 108 may include circuit-switched telephone networks that provide plain old telephone service (POTS). The Internet 110 may include a global system of interconnected computer networks and devices that use common communication protocols, such as the transmission control protocol (TCP), user datagram protocol (UDP) and the internet protocol (IP) in the TCP/IP internet protocol suite. The networks 112 may include wired or wireless communications networks owned and/or operated by other service providers. For example, the networks 112 may include another core network connected to one or more RANs, which may employ the same RAT as the RAN 103/104/105 or a different RAT.

[0042] Some or all of the WTRUs 102a, 102b, 102c, 102d in the communications system 100 may include multi-mode capabilities, *e.g.*, the WTRUs 102a, 102b, 102c, 102d may include multiple transceivers for communicating with different wireless networks over different wireless links. For example, the WTRU 102c shown in FIG. 1A may be configured to communicate with the base station 114a, which may employ a cellular-based radio technology, and with the base station 114b, which may employ an IEEE 802 radio technology.

[0043] FIG. 1B is a system diagram of an example WTRU 102. As shown in FIG. 1B, the WTRU 102 may include a processor 118, a transceiver 120, a transmit/receive element 122, a speaker/microphone 124, a keypad 126, a display/touchpad 128, non-removable memory 130,

removable memory 132, a power source 134, a global positioning system (GPS) chipset 136, and other peripherals 138. It will be appreciated that the WTRU 102 may include any sub-combination of the foregoing elements while remaining consistent with an embodiment. Also, embodiments contemplate that the base stations 114a and 114b, and/or the nodes that base stations 114a and 114b may represent, such as but not limited to transceiver station (BTS), a Node-B, a site controller, an access point (AP), a home node-B, an evolved home node-B (eNodeB), a home evolved node-B (HeNB or HeNodeB), a home evolved node-B gateway, and proxy nodes, among others, may include some or all of the elements depicted in FIG. 1B and described herein.

[0044] The processor 118 may be a general purpose processor, a special purpose processor, a conventional processor, a digital signal processor (DSP), a plurality of microprocessors, one or more microprocessors in association with a DSP core, a controller, a microcontroller, Application Specific Integrated Circuits (ASICs), Field Programmable Gate Array (FPGAs) circuits, any other type of integrated circuit (IC), a state machine, and the like. The processor 118 may perform signal coding, data processing, power control, input/output processing, and/or any other functionality that enables the WTRU 102 to operate in a wireless environment. The processor 118 may be coupled to the transceiver 120, which may be coupled to the transmit/receive element 122. While FIG. 1B depicts the processor 118 and the transceiver 120 as separate components, it will be appreciated that the processor 118 and the transceiver 120 may be integrated together in an electronic package or chip.

[0045] The transmit/receive element 122 may be configured to transmit signals to, or receive signals from, a base station (*e.g.*, the base station 114a) over the air interface 115/116/117. For example, in one embodiment, the transmit/receive element 122 may be an antenna configured to transmit and/or receive RF signals. In another embodiment, the transmit/receive element 122 may be an emitter/detector configured to transmit and/or receive IR, UV, or visible light signals, for example. In yet another embodiment, the transmit/receive element 122 may be configured to transmit and receive both RF and light signals. It will be appreciated that the transmit/receive element 122 may be configured to transmit and/or receive any combination of wireless signals.

[0046] In addition, although the transmit/receive element 122 is depicted in FIG. 1B as a single element, the WTRU 102 may include any number of transmit/receive elements 122. More specifically, the WTRU 102 may employ MIMO technology. Thus, in one embodiment, the WTRU 102 may include two or more transmit/receive elements 122 (*e.g.*, multiple antennas) for transmitting and receiving wireless signals over the air interface 115/116/117.

[0047] The transceiver 120 may be configured to modulate the signals that are to be transmitted by the transmit/receive element 122 and to demodulate the signals that are received by the transmit/receive element 122. As noted above, the WTRU 102 may have multi-mode capabilities. Thus, the transceiver 120 may include multiple transceivers for enabling the WTRU 102 to communicate via multiple RATs, such as UTRA and IEEE 802.11, for example.

[0048] The processor 118 of the WTRU 102 may be coupled to, and may receive user input data from, the speaker/microphone 124, the keypad 126, and/or the display/touchpad 128 (*e.g.*, a liquid crystal display (LCD) display unit or organic light-emitting diode (OLED) display unit). The processor 118 may also output user data to the speaker/microphone 124, the keypad 126, and/or the display/touchpad 128. In addition, the processor 118 may access information from, and store data in, any type of suitable memory, such as the non-removable memory 130 and/or the removable memory 132. The non-removable memory 130 may include random-access memory (RAM), read-only memory (ROM), a hard disk, or any other type of memory storage device. The removable memory 132 may include a subscriber identity module (SIM) card, a memory stick, a secure digital (SD) memory card, and the like. In other embodiments, the processor 118 may access information from, and store data in, memory that is not physically located on the WTRU 102, such as on a server or a home computer (not shown).

[0049] The processor 118 may receive power from the power source 134, and may be configured to distribute and/or control the power to the other components in the WTRU 102. The power source 134 may be any suitable device for powering the WTRU 102. For example, the power source 134 may include one or more dry cell batteries (*e.g.*, nickel-cadmium (NiCd), nickel-zinc (NiZn), nickel metal hydride (NiMH), lithium-ion (Li-ion), *etc.*), solar cells, fuel cells, and the like.

[0050] The processor 118 may also be coupled to the GPS chipset 136, which may be configured to provide location information (*e.g.*, longitude and latitude) regarding the current location of the WTRU 102. In addition to, or in lieu of, the information from the GPS chipset 136, the WTRU 102 may receive location information over the air interface 115/116/117 from a base station (*e.g.*, base stations 114a, 114b) and/or determine its location based on the timing of the signals being received from two or more nearby base stations. It will be appreciated that the WTRU 102 may acquire location information by way of any suitable location-determination implementation while remaining consistent with an embodiment.

[0051] The processor 118 may further be coupled to other peripherals 138, which may include one or more software and/or hardware modules that provide additional features,

functionality and/or wired or wireless connectivity. For example, the peripherals 138 may include an accelerometer, an e-compass, a satellite transceiver, a digital camera (for photographs or video), a universal serial bus (USB) port, a vibration device, a television transceiver, a hands free headset, a Bluetooth® module, a frequency modulated (FM) radio unit, a digital music player, a media player, a video game player module, an Internet browser, and the like.

[0052] FIG. 1C is a system diagram of the RAN 103 and the core network 106 according to an embodiment. As noted above, the RAN 103 may employ a UTRA radio technology to communicate with the WTRUs 102a, 102b, 102c over the air interface 115. The RAN 103 may also be in communication with the core network 106. As shown in FIG. 1C, the RAN 103 may include Node-Bs 140a, 140b, 140c, which may each include one or more transceivers for communicating with the WTRUs 102a, 102b, 102c over the air interface 115. The Node-Bs 140a, 140b, 140c may each be associated with a particular cell (not shown) within the RAN 103. The RAN 103 may also include RNCs 142a, 142b. It will be appreciated that the RAN 103 may include any number of Node-Bs and RNCs while remaining consistent with an embodiment.

[0053] As shown in FIG. 1C, the Node-Bs 140a, 140b may be in communication with the RNC 142a. Additionally, the Node-B 140c may be in communication with the RNC 142b. The Node-Bs 140a, 140b, 140c may communicate with the respective RNCs 142a, 142b via an Iub interface. The RNCs 142a, 142b may be in communication with one another via an Iur interface. Each of the RNCs 142a, 142b may be configured to control the respective Node-Bs 140a, 140b, 140c to which it is connected. In addition, each of the RNCs 142a, 142b may be configured to carry out or support other functionality, such as outer loop power control, load control, admission control, packet scheduling, handover control, macrodiversity, security functions, data encryption, and the like.

[0054] The core network 106 shown in FIG. 1C may include a media gateway (MGW) 144, a mobile switching center (MSC) 146, a serving GPRS support node (SGSN) 148, and/or a gateway GPRS support node (GGSN) 150. While each of the foregoing elements are depicted as part of the core network 106, it will be appreciated that any one of these elements may be owned and/or operated by an entity other than the core network operator.

[0055] The RNC 142a in the RAN 103 may be connected to the MSC 146 in the core network 106 via an IuCS interface. The MSC 146 may be connected to the MGW 144. The MSC 146 and the MGW 144 may provide the WTRUs 102a, 102b, 102c with access to circuit-switched networks, such as the PSTN 108, to facilitate communications between the WTRUs 102a, 102b, 102c and traditional land-line communications devices.

[0056] The RNC 142a in the RAN 103 may also be connected to the SGSN 148 in the core network 106 via an IuPS interface. The SGSN 148 may be connected to the GGSN 150. The SGSN 148 and the GGSN 150 may provide the WTRUs 102a, 102b, 102c with access to packet-switched networks, such as the Internet 110, to facilitate communications between and the WTRUs 102a, 102b, 102c and IP-enabled devices.

[0057] As noted above, the core network 106 may also be connected to the networks 112, which may include other wired or wireless networks that are owned and/or operated by other service providers.

[0058] FIG. 1D is a system diagram of the RAN 104 and the core network 107 according to an embodiment. As noted above, the RAN 104 may employ an E-UTRA radio technology to communicate with the WTRUs 102a, 102b, 102c over the air interface 116. The RAN 104 may also be in communication with the core network 107.

[0059] The RAN 104 may include eNode-Bs 160a, 160b, 160c, though it will be appreciated that the RAN 104 may include any number of eNode-Bs while remaining consistent with an embodiment. The eNode-Bs 160a, 160b, 160c may each include one or more transceivers for communicating with the WTRUs 102a, 102b, 102c over the air interface 116. In one embodiment, the eNode-Bs 160a, 160b, 160c may implement MIMO technology. Thus, the eNode-B 160a, for example, may use multiple antennas to transmit wireless signals to, and receive wireless signals from, the WTRU 102a.

[0060] Each of the eNode-Bs 160a, 160b, 160c may be associated with a particular cell (not shown) and may be configured to handle radio resource management decisions, handover decisions, scheduling of users in the uplink and/or downlink, and the like. As shown in FIG. 1D, the eNode-Bs 160a, 160b, 160c may communicate with one another over an X2 interface.

[0061] The core network 107 shown in FIG. 1D may include a mobility management gateway (MME) 162, a serving gateway 164, and a packet data network (PDN) gateway 166. While each of the foregoing elements are depicted as part of the core network 107, it will be appreciated that any one of these elements may be owned and/or operated by an entity other than the core network operator.

[0062] The MME 162 may be connected to each of the eNode-Bs 160a, 160b, 160c in the RAN 104 via an S1 interface and may serve as a control node. For example, the MME 162 may be responsible for authenticating users of the WTRUs 102a, 102b, 102c, bearer activation/deactivation, selecting a particular serving gateway during an initial attach of the WTRUs 102a, 102b, 102c, and the like. The MME 162 may also provide a control plane function

for switching between the RAN 104 and other RANs (not shown) that employ other radio technologies, such as GSM or WCDMA.

[0063] The serving gateway 164 may be connected to each of the eNode-Bs 160a, 160b, 160c in the RAN 104 via the S1 interface. The serving gateway 164 may generally route and forward user data packets to/from the WTRUs 102a, 102b, 102c. The serving gateway 164 may also perform other functions, such as anchoring user planes during inter-eNode B handovers, triggering paging when downlink data is available for the WTRUs 102a, 102b, 102c, managing and storing contexts of the WTRUs 102a, 102b, 102c, and the like.

[0064] The serving gateway 164 may also be connected to the PDN gateway 166, which may provide the WTRUs 102a, 102b, 102c with access to packet-switched networks, such as the Internet 110, to facilitate communications between the WTRUs 102a, 102b, 102c and IP-enabled devices.

[0065] The core network 107 may facilitate communications with other networks. For example, the core network 107 may provide the WTRUs 102a, 102b, 102c with access to circuit-switched networks, such as the PSTN 108, to facilitate communications between the WTRUs 102a, 102b, 102c and traditional land-line communications devices. For example, the core network 107 may include, or may communicate with, an IP gateway (*e.g.*, an IP multimedia subsystem (IMS) server) that serves as an interface between the core network 107 and the PSTN 108. In addition, the core network 107 may provide the WTRUs 102a, 102b, 102c with access to the networks 112, which may include other wired or wireless networks that are owned and/or operated by other service providers.

[0066] FIG. 1E is a system diagram of the RAN 105 and the core network 109 according to an embodiment. The RAN 105 may be an access service network (ASN) that employs IEEE 802.16 radio technology to communicate with the WTRUs 102a, 102b, 102c over the air interface 117. As will be further discussed below, the communication links between the different functional entities of the WTRUs 102a, 102b, 102c, the RAN 105, and the core network 109 may be defined as reference points.

[0067] As shown in FIG. 1E, the RAN 105 may include base stations 180a, 180b, 180c, and an ASN gateway 182, though it will be appreciated that the RAN 105 may include any number of base stations and ASN gateways while remaining consistent with an embodiment. The base stations 180a, 180b, 180c may each be associated with a particular cell (not shown) in the RAN 105 and may each include one or more transceivers for communicating with the WTRUs 102a, 102b, 102c over the air interface 117. In one embodiment, the base stations 180a, 180b, 180c

may implement MIMO technology. Thus, the base station 180a, for example, may use multiple antennas to transmit wireless signals to, and receive wireless signals from, the WTRU 102a. The base stations 180a, 180b, 180c may also provide mobility management functions, such as handoff triggering, tunnel establishment, radio resource management, traffic classification, quality of service (QoS) policy enforcement, and the like. The ASN gateway 182 may serve as a traffic aggregation point and may be responsible for paging, caching of subscriber profiles, routing to the core network 109, and the like.

[0068] The air interface 117 between the WTRUs 102a, 102b, 102c and the RAN 105 may be defined as an R1 reference point that implements the IEEE 802.16 specification. In addition, each of the WTRUs 102a, 102b, 102c may establish a logical interface (not shown) with the core network 109. The logical interface between the WTRUs 102a, 102b, 102c and the core network 109 may be defined as an R2 reference point, which may be used for authentication, authorization, IP host configuration management, and/or mobility management.

[0069] The communication link between each of the base stations 180a, 180b, 180c may be defined as an R8 reference point that includes protocols for facilitating WTRU handovers and the transfer of data between base stations. The communication link between the base stations 180a, 180b, 180c and the ASN gateway 182 may be defined as an R6 reference point. The R6 reference point may include protocols for facilitating mobility management based on mobility events associated with each of the WTRUs 102a, 102b, 102c.

[0070] As shown in FIG. 1E, the RAN 105 may be connected to the core network 109. The communication link between the RAN 105 and the core network 109 may be defined as an R3 reference point that includes protocols for facilitating data transfer and mobility management capabilities, for example. The core network 109 may include a mobile IP home agent (MIP-HA) 184, an authentication, authorization, accounting (AAA) server 186, and a gateway 188. While each of the foregoing elements are depicted as part of the core network 109, it will be appreciated that any one of these elements may be owned and/or operated by an entity other than the core network operator.

[0071] The MIP-HA may be responsible for IP address management, and may enable the WTRUs 102a, 102b, 102c to roam between different ASNs and/or different core networks. The MIP-HA 184 may provide the WTRUs 102a, 102b, 102c with access to packet-switched networks, such as the Internet 110, to facilitate communications between the WTRUs 102a, 102b, 102c and IP-enabled devices. The AAA server 186 may be responsible for user authentication and for supporting user services. The gateway 188 may facilitate interworking

with other networks. For example, the gateway 188 may provide the WTRUs 102a, 102b, 102c with access to circuit-switched networks, such as the PSTN 108, to facilitate communications between the WTRUs 102a, 102b, 102c and traditional land-line communications devices. In addition, the gateway 188 may provide the WTRUs 102a, 102b, 102c with access to the networks 112, which may include other wired or wireless networks that are owned and/or operated by other service providers.

[0072] Although not shown in FIG. 1E, it will be appreciated that the RAN 105 may be connected to other ASNs and the core network 109 may be connected to other core networks. The communication link between the RAN 105 and the other ASNs may be defined as an R4 reference point, which may include protocols for coordinating the mobility of the WTRUs 102a, 102b, 102c between the RAN 105 and the other ASNs. The communication link between the core network 109 and the other core networks may be defined as an R5 reference, which may include protocols for facilitating interworking between home core networks and visited core networks.

[0073] Several schemes may reduce the OOB radiation of Orthogonal Frequency Division Multiplexing (OFDM) based Cognitive Radio (CR) systems. One or more of the following may apply. Filtering or windowing may be used. This may introduce long delays and degradation of bit error rate (BER). Some of the CR subcarriers may be disabled to create some guard bands between CR bands and LU bands. This may not be enough to reduce the interference to a practically acceptable level even though the spectral efficiency may be lost. Cancellation Carriers (CC) may be used. Instead of just disabling subcarriers, the inputs of these subcarriers may be designed so that the radiation at certain frequencies, which are usually assigned to LUs, is minimized. The design of the inputs depends on the inputs of the remaining data subcarriers, which may be computationally complex. Subcarrier Weighting (SW) may be used. SW may be viewed as a precoding method with a real diagonal matrix that does not decrease the spectral efficiency. Subcarrier Weighting may involve designing inputs of subcarriers to minimize the radiation at certain frequencies, and may be computationally complex. Beek's singular value decomposition (SVD) precoding may be used, which may decrease the spectral efficiency. In Beek's singular value decomposition (SVD) precoding a precoding matrix of a less-than-one code rate may be designed to reduce the OOB radiation. In other words, unlike Subcarrier Weighting, the matrix used in this precoding may not be a square matrix. This matrix design may not depend on the input data, and, complexity may be decreased. Chung's Spectral precoding may be used. Chung's Spectral precoding may be independent of the input data. Instead of SVD precoding that may minimize the system's energy at certain frequencies, Chung's Spectral

precoding may use new orthogonal basis sets to replace the rectangular pulse for each conventional OFDM symbol so that the new sidelobes fall off faster than those of the sinc functions. The spectral efficiency may be reduced due to the limited number of available basis sets when the in-band range is fixed. A significant OOB power suppression improvement may happen when the spectral efficiency is reduced from 1 to $(N-1)/N$ and from $(N-1)/N$ to $(N-2)/N$, where N is the number of subcarriers. As the spectral efficiency continues to decrease, the improvement may become not as significant as it was. If part of the total spectral efficiency loss is redistributed from Spectral precoding to some other precoding such as SVD precoding, the resulting combined schemes may be better than either of the precoding used separately.

[0074] Orthogonal Frequency Division Multiplexing (OFDM) may have a high peak-to-average power ratio (PAPR) that may lead to low power efficiency of the system. Many MCM systems may suffer from the high PAPR problem. PAPR reduction methods can be broadly categorized into two groups. The first group involves signal scrambling techniques, including various techniques to scramble codes to decrease the PAPR, such as Selective Level Mapping (SLM) and Partial Transmit Sequences (PTS). Side information may be used for signal scrambling techniques, by which redundancy may be introduced and the effective throughput may be reduced. The precoding technique may also be an efficient way of reducing PAPR while maintaining decent error performance by introducing some redundancy. The second group of PAPR reduction techniques may involve signal distortion, which may reduce high peaks by directly distorting the signal. Companding techniques and clipping and filtering techniques may be in this category. Though such techniques may be efficient in reducing PAPR, they may degrade error performance significantly.

[0075] Precoding techniques may provide remedies to the drawbacks of MCM systems, such as OFDM systems. There are different precoding techniques to achieve different goals in MCM waveform design. Combining precoding techniques may realize advantages of some of the different aforementioned precoding techniques to achieve one or multiple design goals in MCM waveform design. These design goals may include, but are not limited to, minimizing OOB power leakage, reducing PAPR, minimizing BER, *etc.*

[0076] Some approaches to suppress the OOB of OFDM signals may include time-domain approaches and frequency-domain approaches. Example time-domain approaches may include windowing and filtering in order to reduce the OOB via time domain processing (*e.g.*, after the inverse discrete Fourier transform (IDFT) operation). Example frequency-domain approaches may include subcarrier weighting, carrier cancellation, precoding, *etc.* For the frequency domain

approaches, OOB reduction may be carried out in the frequency domain by performing processing before the IDFT operation.

[0077] To suppress OOB using time-domain approaches and/or frequency domain approaches, tradeoffs may be made relative to other OFDM transmission properties. For example, some OOB reduction approaches can result in a spectral efficiency loss. Other tradeoffs may include a degradation in system performances (*e.g.*, such as increases in block error rate (BER) and/or PAPR), increases in system complexity (*e.g.*, such as increases in the amount of computation efforts during processing and/or increases in signaling overhead), *etc.* To achieve sufficient OOB suppression, some approaches may result in a loss of spectral efficiency and/or some significant performance degradations.

[0078] Precoding may be able to achieve satisfactory spectral containment with a relatively small spectral efficiency loss. Precoding may avoid the addition of significant signaling overhead, and may achieve the OOB suppression with little to no BER performance loss and negligible PAPR degradation. Additionally, precoding may not depend on the contents of the input data.

[0079] Multiuser precoding approaches may suppress OOB of OFDM transmissions without resulting in significant negative tradeoffs that may be applicable to other OOB suppression techniques. For example, a contiguous spectrum may be shared by K OFDM-based cognitive radio (CR) users. The spectral leakages by CR users outside this shared spectrum may be under a certain threshold in order to protect the licensed users. In addition, when the CR users cannot be synchronized, the spectral leakage from each CR user to other CR users may be kept under a threshold. The spectral loss due to OOB suppression may scale by the number of CR users, K . However, when the CR users can be synchronized (*e.g.*, ideally perfectly synchronized), there may be little or no inter-carrier interference among the CR users and the spectral leakage from the CR users within the spectrum may no longer be a concern. Based on this property applicable of synchronized CR users, an efficient multiuser precoding approach may be implemented to reduce the spectral efficiency loss. For example, by choosing different notched frequencies for different CR users, the spectral efficiency loss may not be scaled by or be linearly proportional to K , but it may still increase as K increases.

[0080] In many-to-one and many-to-many communication scenarios, when transmitting the frequency band that is shared by the multiple transmitting users, out-of-passband leakage among different users may be reduced by using a precoding method individually in each user. Since individual precoding may lead to a lower spectral efficiency due to the redundancy for certain

subcarriers, in multiple user cases, the loss in spectral efficiency may be scaled by the number of users. If the number of users is large, the loss in spectral efficiency may be large.

[0081] K cognitive radio (CR) users may be synchronized and may be considered a virtual single user that utilizes the entire detected spectrum. A multiuser precoding approach may further reduce the spectral efficiency loss due to OOB suppression. As an example, each CR user may determine or may be configured with a virtual precoder as if it were the virtual single user. The CR user may determine its own precoder by selecting the columns of the virtual precoder according to its allocated subcarriers. In this way, the spectral efficiency loss may be further reduced and may be independent of the number K of CR users. In addition, the CR users may use non-contiguous spectrum without additional loss of spectral efficiency. By allowing the CR users to use non-contiguous spectrum without additional loss of spectral efficiency, granular resource allocations may be facilitated. Simulations and numerical results demonstrate that the proposed synchronized multi-user precoding approach may achieve lower OOB and higher spectral efficiency than individual precoding approaches. In addition, compared with the uncoded-OFDM, the proposed synchronized multi-user precoding approach may result in little or no degradation in BER performance and little or negligible increase in PAPR.

[0082] As an example, a set of N contiguous subcarriers may be utilized by K synchronized OFDM-based CR users. For the k^{th} user, the time-domain OFDM transmit symbol, ϕ_k , may be expressed as

$$\phi_k(t) = \sum_n \sum_{i=1}^{N_k} d_{k,i}[n] \delta(t - nT) * p_{k,i}(t) \quad (1)$$

where $T = T_s + T_{cp}$ and T may be the symbol duration, T_s may be the effective symbol duration, and T_{cp} may be the cyclic prefix duration. N_k may be the number of subcarriers used by the k^{th} user. For the i^{th} subcarrier, $d_{k,i}$ may be the data and $p_{k,i}$ may be the windowed subcarrier waveform. $p_{k,i}$ may be expressed as:

$$p_{k,i}(t) = e^{j2\pi \frac{N_{k,i}}{T_s} t} g_c(t) \quad (2)$$

where $g_c(t)$ may be a pulse shape function that may be expressed as:

$$g_c(t) = \begin{cases} 1, & -T_{CP} \leq t < T_s \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

The value $N_{k,i}$ of Equation (2) may be the subcarrier index and may be expressed as:

$$N_{k,i} = N_{k,1} + i - 1, i = 1, 2, \dots, N_k \quad (4)$$

[0083] To increase or maximize the spectral efficiency, the last carrier of the k^{th} user may be set to be adjacent to the first carrier of the $(k+1)^{\text{th}}$ user. Such a relationship may be expressed as:

$$N_{k+1,1} = N_{k,N_k} + 1, \text{ if } N_{k,N_k} \neq -1 \quad (5)$$

$$\mathcal{N}_{k+1,1} = \mathcal{N}_{k,N_k} + 2, \text{ if } \mathcal{N}_{k,N_k} = -1 \quad (6)$$

with $k = 1, 2, \dots, K-1$. Equation (6) may be designed to skip the zero frequency. Thus, the total number of subcarriers under use may be the same as the number of subcarriers available, excluding the DC subcarrier. Such a relationship may be expressed as:

$$N = \sum_{k=1}^K N_k \quad (7)$$

[0084] Spectral precoding may be used to suppress the transmit signal at certain frequencies, for example, at the expense of spectral efficiency loss. For example, the frequency domain signal representation of the transmit signal described in Equation (1) may be expressed as:

$$X_k(f) = \sum_{i=1}^{N_k} d_{k,i} P_{k,i}(f) \quad (8)$$

with:

$$P_{k,i}(f) = \frac{1}{T} \int_{-\infty}^{+\infty} p_{k,i}(t) e^{-j2\pi ft} dt \quad (9)$$

$$P_{k,i}(f) = \frac{e^{jn\left(\frac{N_{k,i}}{T_s} - f\right)(T_s - T_{CP})}}{\pi\left(\frac{N_{k,i}}{T_s} - f\right)T} \sin\left(\pi\left(\frac{N_{k,i}}{T_s} - f\right)T\right) \quad (10)$$

where $T = T_{CP} + T_s$ may be the OFDM symbol duration. To suppress $X_k(f_l)$, $l = 1, \dots, L_k$ for the k^{th} user, a precoding process $\{G_{k,im}\}$ may be imposed on the data and $X_k(f_l)$ may then be expressed as:

$$X_k(f_l) = \sum_{i=1}^{N_k} \left(\sum_{m=1}^{M_k} G_{k,im} d_{k,m} \right) P_{k,i}(f_l) \quad (11)$$

where the number of data transmitted may be reduced from N_k to M_k where $N_k \geq M_k$. In matrix form, Equation (8) may then be expressed as:

$$\mathbf{x}_k = \mathbf{P}_k \mathbf{s}_k, \mathbf{s}_k = \mathbf{G}_k \mathbf{d}_k \quad (12)$$

with:

$$\mathbf{x}_k = \begin{bmatrix} X_k(f_1) \\ X_k(f_2) \\ \vdots \\ X_k(f_{L_k}) \end{bmatrix}, \mathbf{d}_k = \begin{bmatrix} d_{k,1} \\ d_{k,2} \\ \vdots \\ d_{k,M_k} \end{bmatrix}, \mathbf{P}_k = \begin{bmatrix} P_{k,1}(f_1) & \cdots & P_{k,N_k}(f_1) \\ \vdots & \ddots & \vdots \\ P_{k,1}(f_{L_k}) & \cdots & P_{k,N_k}(f_{L_k}) \end{bmatrix}, \mathbf{G}_k = [G_{k,im}]$$

where $\mathbf{s}_k$ may be the precoded data, $\mathbf{G}_k$ may be the precoding matrix, $\mathbf{d}_k$ may be the user data signal, $\mathbf{P}_k$ may be a matrix indicating spectral leakage or signal leakage (e.g., over frequencies $\{f_1, f_2, \dots, f_{L_k}\}$), and $\mathbf{x}_k$ may be the signal leakage over frequencies $\{f_1, f_2, \dots, f_{L_k}\}$.

[0085] To reduce or minimize $\|\mathbf{x}_k\|$, a singular value decomposition of $\mathbf{P}_k$ may be performed. The singular value decomposition of $\mathbf{P}_k$ may result in:

$$\mathbf{P}_k = \mathbf{U}_k \mathbf{\Sigma}_k \mathbf{V}_k^H \quad (13)$$

where $\mathbf{U}_k$ may be a $L_k \times L_k$ unitary matrix, $\mathbf{\Sigma}_k$ may be a diagonal $L_k \times N_k$ matrix containing the singular values of $\mathbf{P}_k$ in non-increasing order on its diagonal, and $\mathbf{V}_k$ may be a $N_k \times N_k$ unitary

matrix whose columns may be $\mathbf{v}_{k,1}, \mathbf{v}_{k,2} \dots \mathbf{v}_{k,N_k}$. In an example, the precoding matrix may then be selected as:

$$\mathbf{G}_k = [\mathbf{v}_{k,N_k-M_k+1} \dots \mathbf{v}_{k,N_k-1} \quad \mathbf{v}_{k,N_k}] \quad (14)$$

[0086] The coding rate λ_k may be defined as $\lambda_k = \frac{M_k}{N_k}$, and the coding redundancy R_k may be defined as $R_k = N_k - M_k$. If $R_k \geq L_k$, $\|\mathbf{x}_k\| = 0$ for any arbitrary data vector $\mathbf{d}_k$ because $\mathbf{s}_k$ may be in the null space of $\mathbf{P}_k$. Values may be selected such that $R_k = L_k$. Thus, $\{f_l\}$ with $l = 1, \dots, L_k$ may be notched frequencies.

[0087] If each of the CR users are precoded individually by this method, the overall coding rate of all K users may be expressed as:

$$\lambda = 1 - \frac{\sum_{k=0}^{K-1} R_k}{N} \quad (15)$$

From the above equation(s), it may be noted that the system spectral efficiency may be reduced as the number of CR users and/or the coding redundancy (e.g., the number of notched frequencies in this paper) increases. FIG. 2 is a block diagram illustrating an example transceiver 200 of the k^{th} precoded OFDM-based CR user.

[0088] For a given pass band, the subcarriers far away from the two edges of the pass band may be associated with less OOB as compared to the subcarriers near the edges. Thus, the CR users using the subcarriers far away from the edges may be precoded in a different way than the CR users near the edges. Based on this observation, a reduced number of notched frequencies for each CR user may be used based on selecting the notched frequencies appropriately to improve the spectrum efficiency.

[0089] Specifically, user 1 (e.g., $k=1$) may use subcarriers $\mathcal{N}_{1,1}$ to $\mathcal{N}_{1,N_1}$ where $\mathcal{N}_{1,1}$ may be the lowest subcarrier index within the band. Thus, user 1 may be adjacent to the lower edge of the available pass band. To design a precoder for this user, the transceiver may be designed such that notched frequencies are located in the left (e.g., low frequency) stop band but not in the right (e.g., high frequency) stop band.

[0090] Similarly, user K (e.g., $k=K$) may use subcarriers $\mathcal{N}_{K,1}$ to $\mathcal{N}_{K,N_K}$, where $\mathcal{N}_{K,N_K}$ may be the highest subcarrier index. Thus, user K may be adjacent to the right/higher edge of the available pass band. To design the precoder for user K , the transceiver may be designed such that notched frequencies are located in the right (e.g., high frequency) stop band but not in the left (e.g., low frequency) stop band. For user(s) k with $K > k > 1$, since these middle band users may use the inner part of the frequency band, the numbers of notched frequencies on both sides may be reduced, for example, by an amount or amounts that may be determined according to the distances

between the two edges of its own frequency band and the two edges of the entire available pass band. Therefore, the coding rate for the k^{th} subcarrier may be reduced to:

$$\lambda_k' = 1 - \frac{R_k'}{N_k} \quad (16)$$

where $R_k' \leq R_k$, and the overall coding rate may be expressed as:

$$\lambda' = 1 - \frac{\sum_{k=0}^{K-1} R_k'}{N} \quad (17)$$

$\lambda' \geq \lambda$ as $R_k' \leq R_k$ for $k = 0, 1, \dots, K-1$.

[0091] Among synchronized CR users, there may be little or no inter-cell interference. If each CR user determines or designs its own precoder, the designs may not take advantage of the synchronization between the CR users and the ability to jointly design precoders for different CR users. Aspectral precoding approach may consider multiple users that be assigned with a contiguous frequency band as a virtual single user. For example, for a user (*e.g.*, each user), the CR transceiver may determine a virtual precoding matrix $\mathbf{G}$ for the entire allocated pass band. A user may select the appropriate columns of $\mathbf{G}$ corresponding to its allocated subcarriers in order to precode its data during transmission. If the this approach is used by each of the users allocated subcarriers within the band corresponding to the virtual user, the same $\mathbf{G}$ may be derived by each user, which may reduce complexity since it may be implemented without additional signaling. The multi-user system may operate as a virtual single user system. This spectral precoding approach may improve overall spectral efficiency.

[0092] For example, $[f_1, f_2, \dots, f_L]$ may represent the notched frequencies of the virtual single user. As described herein, the frequency domain representation of the transmit signal of leakage of the virtual signal user may be expressed as:

$$X(f_l) = \sum_{i=1}^N (\sum_{m=1}^M G_{im} d_m) P_i(f_l) \quad (18)$$

with $N \leq M$ and

$$P_i(f_l) = \frac{e^{j\pi \left(\frac{l+N_{1,1}-1}{T_s} f_l \right) (T_s - T_{CP})}}{\pi \left(\frac{l+N_{1,1}-1}{T_s} - f \right) T} \cdot \sin \left(\pi \left(\frac{l+N_{1,1}-1}{T_s} - f_l \right) T \right) \quad (19)$$

In matrix form, Equation (18) may be expressed as:

$$\mathbf{x} = \mathbf{P}\mathbf{s}, \mathbf{s} = \mathbf{G}\mathbf{d} \quad (20)$$

where:

$$\mathbf{x} = \begin{bmatrix} X(f_1) \\ X(f_2) \\ \vdots \\ X(f_L) \end{bmatrix}, \mathbf{d} = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_M \end{bmatrix}, \mathbf{P} = \begin{bmatrix} P_1(f_1) & \cdots & P_N(f_1) \\ \vdots & \ddots & \vdots \\ P_N(f_L) & \cdots & P_N(f_L) \end{bmatrix}, \mathbf{G} = [G_{im}]$$

To reduce or minimize $\|\mathbf{x}\|$, a singular value decomposition of $\mathbf{P}$ may be performed. The singular value decomposition may factorize $\mathbf{P}$ as

$$\mathbf{P} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H \quad (21)$$

where $\mathbf{U}$ may be an $L \times L$ unitary matrix, $\mathbf{\Sigma}$ may be a diagonal $L \times N$ matrix that may include the singular values of $\mathbf{P}$ in non-increasing order on its diagonal, and $\mathbf{V}$ may be a $N \times N$ unitary matrix whose columns may be $\mathbf{v}_1, \mathbf{v}_2 \dots \mathbf{v}_N$. The precoding matrix may be expressed as:

$$\mathbf{G} = [\mathbf{v}_{N-M+1} \dots \mathbf{v}_{N-1} \quad \mathbf{v}_N] \quad (22)$$

where the last M columns of $\mathbf{V}$ may be selected as the vectors to use in order to cancel the spectral leakage. These columns may represent the right-singular vectors that correspond to the M smallest singular values of $\mathbf{P}$. For example, these values may be orthonormal to the other columns in $\mathbf{V}$ (e.g., the right-singular vectors that may correspond to the $N - M$ largest singular values of $\mathbf{P}$). The precoding matrix $\mathbf{G}$ may null out or remove at least a portion of the signal leakage to the notched frequencies.

[0093] The CR user devices may divide the data vector $\mathbf{d}$ into K data sub-blocks according to the data lengths for the K users. The CR user devices may divide the precoding matrix $\mathbf{G}$ into K precoding sub-matrices corresponding to the K data sub-blocks. For example, the sub-matrices corresponding to the K data sub-blocks may be expressed as:

$$\mathbf{s} = \mathbf{G}\mathbf{d} = [\mathbf{G}_1 \quad \mathbf{G}_2 \quad \dots \quad \mathbf{G}_K] \begin{bmatrix} \mathbf{d}_1 \\ \mathbf{d}_2 \\ \vdots \\ \mathbf{d}_K \end{bmatrix} = \sum_{k=1}^K \mathbf{s}_k \quad (23)$$

where $\mathbf{G}_k$ may be the precoder and $\mathbf{d}_k$ may be the data vector for the k^{th} user.

[0094] In Equation (23), the precoded data $\mathbf{s}_k = \mathbf{G}_k \mathbf{d}_k$ for the k^{th} user may be modulated by the available N subcarriers. For example, in other approaches, the precoded data $\mathbf{s}_k$ for the k^{th} user may be modulated by N_k subcarriers (e.g., only N_k subcarriers), rather than across each of the subcarriers associated with the virtual user. The construction of $\mathbf{G}_k$ may be applied to non-contiguous spectra. For example, the notations described herein for the contiguous approach may be similar to those for a non-contiguous frequency band, the parameters the $\mathbf{s}_k$, $\mathbf{G}_k$, $\mathbf{d}_k$ in Equation (23) and $\mathbf{s}_k$, $\mathbf{G}_k$, $\mathbf{d}_k$ in Equation (12), respectively, may have different dimensions.

[0095] At the receiver, after the discrete Fourier transform (DFT) and frequency domain equalization, the received precoded data, denoted by $\tilde{\mathbf{s}}_k$, for the k^{th} user, may be decoded by the decoder $\mathbf{G}_k^H$ because $\mathbf{G}_k^H \mathbf{G}_k = \mathbf{I}_{M_k}$. The estimated data vector may be represented as:

$$\tilde{\mathbf{d}}_k = \mathbf{G}_k^H \tilde{\mathbf{s}}_k \quad (24)$$

[0096] Although the K users may use the same virtual single user precoder $\mathbf{G}$, the precoding processes (and/or the decoding processes) for the K users may be performed independently and the methods and systems may be implemented without the introduction of additional signaling loading among the K users.

[0097] Multiuser precoding as disclosed herein may take advantage of synchronization between the users; otherwise, the interference between users may be significant. As shown in FIG. 3, which may be an example of power spectral density (PSD) performance using the “single virtual precoder” described herein, the power within the band may be quite high. To possibly mitigate this situation, a user (*e.g.*, each individual user) may use filtering and windowing to remove the interference. If the spectrum occupied by a user is continuous, both filtering and windowing may be effective interference reduction techniques. If the spectrum is noncontiguous, windowing may be effective, but filtering may be less effective.

[0098] FIG. 4 depicts an example Precoded-OFDM transceiver 400 with filtering and/or windowing. A long filter may be used, and/or a long guard interval may be used for windowing, which may achieve low OOB leakage. If the precoding can lower the OOB leakage to certain level, for example, near the pass band, the length of the filter or the guard interval of the window may be reduced to a level that may be implemented in most practical scenarios.

[0099] Simulation results may demonstrate the effectiveness of a precoding approach where the CR users may determine their individual precoding matrices based on the overall, single-user virtual precoding matrix and their respective resource allocation within the single user band. To illustrate the performance of the proposed multiuser precoding approach, simulations were performed in which $T_s = \frac{1}{15}$ ms, $T_g = \frac{1}{16} T_s$, $T = T_s + T_g$, the number of samples per symbol duration was 1024, and the pass band for the CR users was between -3600kHz and 3600kHz. The pass band may include 480 subcarriers (*e.g.*, skipping the zero frequency). The modulation type used for the simulation was Quadrature Phase Shift Keying (QPSK).

[0100] FIG. 5 illustrates OOBE performance of a multiuser precoding approach where each user is precoded individually (*e.g.*, a multiuser precoder approach may be used, but the individual precoding matrices of the CR users are not selected based on the virtual single user across the entire band). As an example, in the example simulations there may be four users (*e.g.*, user 1, user 2, user 3, and user 4), and each user may be assigned an equally divided portion of the pass band (*e.g.*, one-fourth of the bandwidth). For example, user 1 may transmit in the frequency band between -3600kHz and -1800kHz. Since its transmission band is far from the right/upper edge (*e.g.*, 3600kHz) of the entire pass band, the precoder may be selected such that notch frequencies are located in the left/lower stop band (*e.g.*, lower than -3600kHz), while the right/lower stop band may not be considered. Thus, the CR for user 1 may select four notched frequencies, for example at [-6101, -6099, -4101, -4099] kHz for user 1.

[0101] Similarly, user 4 may transmit in the frequency band between 1800kHz and 3600kHz, which may be far away from the left/lower edge (*e.g.*, -3600kHz) of the entire pass band. For

user 4, since the notched frequencies may be included on the right/upper side, but not on the left/lower side, the device may select notch frequencies located in the right/upper stop band (*e.g.*, greater than 3600kHz), for example [4099, 4101, 6099, 6101] kHz.

[0102] For user 2, the allocated portion of the frequency band may be between -1800kHz and 0 Hz, which may be relatively close to both edges of the entire pass band. For user 3, the frequency band may be between 0Hz and 1800kHz, which may also be relatively close to both edges of the entire pass band. Thus, both user 2 and user 3 may select notched frequencies on both sides of the entire pass band. Hence, user 2 and user 3 may select notch frequencies on both sides of the entire band pass. For example [-4101, -4099, 4099, 4101] kHz may be selected as the four notched frequencies for both user 2 and user 3. In FIG. 5, the PSD curves of the individual precoded-OFDM signals of the four users and the PSD curve of the total precoded-OFDM signal (*e.g.*, the sum of the four signals) are illustrated.

[0103] FIG. 3 illustrates example PSD curves of the precoded-OFDM signals of the four users when the individual precoding matrices are selected based on the precoding matrix of the single virtual user and the identity of the individual allocations within the band. For example, using the proposed efficient multiuser precoding approach based on a single virtual user precoder, [-6101, -6099, -4101, -4099, 4099, 4101, 6099, 6101] kHz may be selected to be the 8 notched frequencies of the virtual single user. FIG. 3 illustrates the PSD curves of the four precoded-OFDM signals of the four users and the PSD curve of the total precoded-OFDM signal. As illustrated by FIG. 3, each of the four PSD curves of the four users spreads to the frequency bands of other users, but the PSD curves and the PSD of the total signal (*e.g.*, the sum of four signals) may show good OOB suppression on both sides of the entire pass band.

[0104] When comparing the performance of the technique where the individual precoders are selected from the single virtual user precoder and the knowledge of the individual allocation within the band (*e.g.*, illustrated by FIG. 3) with an approach where multiuser precoding is utilized but the individual precoders are determined and selected by the individual users (*e.g.*, illustrated by FIG. 5), the OOB suppression in the example of FIG. 3 may be better than that in the example of FIG. 5. Additionally, there may be sixteen notched frequencies used by the precoding approach associated with FIG. 5, but eight notched frequencies may be used for the virtual single user approach illustrated in FIG. 3. The virtual single user approach may achieve a higher spectral efficiency of 59/60 (*e.g.*, derived from $1 - 8/480$) and a better (*e.g.*, larger) OOB suppression than the multiuser precoding approach where the precoders are individually determined. For example, the spectral efficiency in the simulation illustrated in FIG. 5 may be 29/30 (*e.g.*, derived from $1 - 16/480$).

[0105] FIG. 6 illustrates an example comparison of the bit error rate (BER) performance of precoding approaches disclosed herein. The BER performance of the two precoding approaches may be relatively consistent with the BER performance of the uncoded OFDM. FIG. 7 illustrates an example comparison of the peak-to-average power ratio (PAPR) performance of the precoding approaches illustrated in FIG. 3 and FIG. 5. The PAPR performance degradation may be related to the coding rate. Lower coding rates may be related to worse PAPR performance. In FIG. 7, since the coding rates of these two approaches are large (*e.g.*, close to 1), the PAPR performances for the two precoding approaches may be similar to that of the uncoded OFDM. As a result, precoder selection based on the virtual precoder determined for the entire band and the knowledge of the individual allocations within the entire band may achieve increased spectral efficiency while not sacrificing BER or PAPR performance.

[0106] A combined precoding technique may be used to combine multiple individual precoding techniques as illustrated in FIG. 8, *e.g.*,

$$G = G_N G_{N-1} \cdots G_2 G_1 \quad (25)$$

where G_i is the i^{th} component precoder (*e.g.*, the i^{th} precoder the data streams essentially go through) and represents the precoding matrix of one precoding technique. FIG. 8 conceptually illustrates each component precoder of a combined precoder 800 as a precoder block 802. Each individual component precoder may contribute to one or multiple design goals, such as minimizing OOB power leakage, reducing PAPR, and/or minimizing BER. The i^{th} precoding matrix G_i of dimension $N_i \times K_i$ may satisfy the matched coding rate (*e.g.*, dimension) constraint such that

$$K_i = N_{i-1} \quad (26)$$

The combination of precoding techniques may not disable the functionality of each of the component precoding techniques.

[0107] FIG. 9 illustrates an exemplary transmitter 900 of an Orthogonal Frequency Division Multiplexing (OFDM) system. FIG. 10 illustrates an exemplary receiver 1000 of the OFDM system. FIGS. 9 and 10 illustrate the general case of a precoded OFDM (P-OFDM) system with arbitrary contiguous or non-contiguous available spectrum.

[0108] When the available spectrum is non-contiguous, in order to reduce out-of-band (OOB) power leakage, one of the component precoding matrices may be designed to notch down the out-of-band frequencies.

[0109] As an example of a combined precoding technique, component precoders may be used to reduce OOB power leakage in an OFDM system. For example, Beek's SVD precoding notches down the power at certain frequencies located outside the passband to reduce out-of-

band power emission. Chung's Spectral precoding replaces the rectangular pulse shaping in OFDM with spectral precoding across subcarriers to achieve faster roll off in power spectral density located outside the passband. These precodings may be used as component precoders in a combined precoder, *e.g.*, as shown generally in FIG. 8. By adjusting the precoding matrices' dimensions, *e.g.*, by properly assigning the matched code rates, the combined precoder may have a better OOB power suppression effect than either of the two component precoders individually.

[0110] FIG. 11 illustrates an example OFDM system 1100 that may use precoding. As shown in FIG. 11, a source bit stream may be mapped into a symbol stream by a PSK/QAM modulation block 1102. The symbol stream may go through a serial-to-parallel (S/P) conversion block 1104. If $\mathbf{d}_l = [d_{1,l} \ d_{2,l} \ \dots \ d_{K,l}]^T$ denotes the l^{th} data vector, where l is the index in the time domain and K is the length of each vector, then each vector may be left-multiplied by an $N \times K$ precoding matrix $\mathbf{G}$, *e.g.*, $\mathbf{b}_l = \mathbf{G}\mathbf{d}_l$, where $\mathbf{b}_l = [b_{1,l} \ b_{2,l} \ \dots \ b_{N,l}]^T$ may denote the l^{th} precoded vector, at a precoding block 1106. The code rate may be defined as K/N , which may be no larger than 1. $\mathbf{x}_l$ may be the Inverse Fast Fourier Transform (IFFT) output of $\mathbf{b}_l$ at an IFFT block 1108. Cyclic Prefix (CP) or Zero Padding (ZP) may be added to $\mathbf{x}_l$ at a block 1110 to counteract the channel effects. The symbol stream may be transmitted via a channel at a block 1112. At the receiver, CP or ZP may be removed from the received vector $\mathbf{r}_l'$ at a block 1114. The symbol stream may go through an FFT block 1116 and may be decoded by being left-multiplied by a $K \times N$ decoding matrix $\hat{\mathbf{G}}$, *i.e.*, $\hat{\mathbf{d}}_l = \hat{\mathbf{G}}\mathbf{b}_l$, at a decoding block 1118. If the channel is ideal, then the data may be correctly decoded if $\hat{\mathbf{G}}\mathbf{G} = \mathbf{I}$. The decoded symbol stream may be processed by a parallel-to-serial (P/S) conversion block 1120 and may be mapped to a bit stream by a PSK/QAM demodulation block 1122.

[0111] In Beck's SVD precoding, the continuous time-domain transmit signal $x_l(t)$ for a given $\mathbf{b}_l$ may be expressed as $x_l(t) = \sum_{i=1}^N b_{i,l} p_i(t)$, where $p_i(t)$ is the windowed subcarrier waveform $p_i(t) = e^{j2\pi \frac{i}{T_d} t} g_c(t)$ with the pulse shape function $g_c(t) = \begin{cases} 1, & -T_{CP} \leq t < T_d \\ 0, & \text{otherwise} \end{cases}$. In this pulse shape function, T_d is the effective symbol duration and T_{CP} is the cyclic prefix duration. The frequency domain of $x_l(t)$ is $X_l(f) = \sum_{i=1}^N b_{i,l} P_i(f)$, where

$$P_i(f) = \frac{e^{j\pi(\frac{i}{T_d} - f)(T_d - T_{CP})}}{\pi(\frac{i}{T_d} - f)T} \sin\left(\pi\left(\frac{i}{T_d} - f\right)T\right), \text{ where } T = T_{CP} + T_d \text{ is the entire symbol duration.}$$

To minimize the radiation power at the frequencies $f_1, f_2, \dots, f_M$ by designing a precoding matrix $\mathbf{G}^S$, if a matrix $\mathbf{X}_l = [X_l(f_1) \ X_l(f_2) \ \dots \ X_l(f_M)]^T$, then

$\mathbf{X}_l = \mathbf{P}\mathbf{G}^S \mathbf{d}_l$, $\mathbf{P} = \begin{bmatrix} P_1(f_1) & \cdots & P_N(f_1) \\ \vdots & \ddots & \vdots \\ P_1(f_M) & \cdots & P_N(f_M) \end{bmatrix}$. To reduce or minimize $\|\mathbf{X}_l\|$ regardless of $\mathbf{d}_l$, an

SVD of $\mathbf{P}$ may be performed that factorizes $\mathbf{P}$ as $\mathbf{P} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$, where $\mathbf{U}$ is an $M \times M$ unitary matrix, $\mathbf{\Sigma}$ is a diagonal $M \times N$ matrix containing the singular values of $\mathbf{P}$ in non-increasing order, and $\mathbf{V}$ is an $N \times N$ unitary matrix whose columns are $\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_N$. The precoding matrix may be chosen as $\mathbf{G}^S = [\mathbf{v}_{N-K+1} \ \mathbf{v}_{N-K+2} \ \cdots \ \mathbf{v}_N]$. $R = N - K$ may be defined as the coding redundancy. If $R \geq M$, then $\|\mathbf{X}_l\| = 0$ for any arbitrary $\mathbf{d}_l$ because $\mathbf{b}_l$ may be in the null space of $\mathbf{P}$.

[0112] Rectangularly pulsed OFDM may possess discontinuous pulse edges and may exhibit relatively large power spectral sidelobes that may fall off as f^{-2} . By contrast, in Chung's Spectral precoding, continuous-phase OFDM signals may exhibit relatively small power spectral sidelobes that may fall off as f^{-4} , and may provide higher spectral efficiency than a rectangularly pulsed OFDM signal. In Chung's Spectral precoding, two families of new basis sets that satisfy the continuous-phase requirement may be introduced, named as family W and family V , respectively.

[0113] A corresponding precoded OFDM structure may be used to construct OFDM signals using the basis sets along with the arbitrary input data. The entries of the family W_L -based precoding matrix $\mathbf{G}^{W_L}$ may be defined as

$$g_{N(1-2^{1-u})+n, n2^u+v}^{W_L} = 2^{-\frac{u}{2}}(-1)^{1+\psi_{u,v}}, \quad (27)$$

$$n \in \left[0, \frac{N}{2^u} - 1\right] \text{ and } v \in [0, 2^u - 1],$$

for $u = 1, 2, \dots, L$. In this formula, $\psi_{u,v}$ may be the sum of the most and least significant bits in the binary representation (in bits) of the modulo- 2^u value of v when $u \geq 2$ and $\psi_{1,v} = 1$ by default. All entries may equal 0.

[0114] The entries of the family V_L -based precoding matrix $\mathbf{G}^{V_L}$ may be defined as

$$g_{N(1-2^{1-u})+n, n+\frac{N}{2^u}v}^{V_L} = 2^{-\frac{u}{2}}\phi_{u,v}, \quad (28)$$

$$n \in \left[0, \frac{N}{2^u} - 1\right] \text{ and } v \in [0, 2^u - 1],$$

for $u = 1, 2, \dots, L$. In this formula, $\phi_{u,v} = 1$ if $u = \log_2 N$ and $\phi_{u,v} = (-1)^{\zeta_v}$ otherwise, where ζ_v may represent the least significant bit in the binary representation of v . All other entries may equal 0.

[0115] In Chung's Spectral precoding method, L may be a parameter that may determine the code rate, which may equal $1 - 2^{-L}$, $L \in [1, \log_2 N]$. Since $\mathbf{G}^S$, $\mathbf{G}^{W_L}$ and $\mathbf{G}^{V_L}$ may be left unitary

matrices containing orthonormal columns, the decoding matrices may be their conjugate transposes.

[0116] The SVD precoding matrix and the Spectral precoding matrix, *e.g.*, $\mathbf{G}^{W_L}$, may be combined by defining either $\mathbf{G} = \mathbf{G}^S \mathbf{G}^{W_L}$ or $\mathbf{G} = \mathbf{G}^{W_L} \mathbf{G}^S$. The former way of defining $\mathbf{G}$ may have the disadvantage that the continuous-phase property of $\mathbf{G}^{W_L} \mathbf{b}_l$ may not be maintained after it is left-multiplied by $\mathbf{G}^S$. By choosing the latter way of defining $\mathbf{G}$, the continuous-phase property of $\mathbf{G}^{W_L} \mathbf{b}_l$ may be maintained, as may the advantage of SVD precoding.

The precoders may be combined by first designing $\mathbf{G}^{W_L}$ using the formula

$$g_{N(1-2^{1-u})+n, n2^u+v}^{W_L} = 2^{-\frac{u}{2}} (-1)^{1+\psi_{u,v}},$$

$$n \in \left[0, \frac{N}{2^u} - 1\right] \text{ and } v \in [0, 2^u - 1],$$

without considering $\mathbf{G}^S$. The SVD of $\mathbf{P} \mathbf{G}^{W_L}$ may be performed by replacing $\mathbf{P}$ in the formula

$\mathbf{P} = \mathbf{U} \mathbf{\Sigma} \mathbf{V}^H$ with $\mathbf{P} \mathbf{G}^{W_L}$ and determining $\mathbf{G}^S$ using the formula $\mathbf{G}^S =$

$[\mathbf{v}_{N-K+1} \quad \mathbf{v}_{N-K+2} \quad \dots \quad \mathbf{v}_N]$. Next, let $\mathbf{G} = \mathbf{G}^{W_L} \mathbf{G}^S$ and $\hat{\mathbf{G}} = (\mathbf{G}^{W_L} \mathbf{G}^S)^H$. The transmitted signal

$$\mathbf{x}_l \text{ for Spectral precoding in the formula } g_{N(1-2^{1-u})+n, n2^u+v}^{W_L} = 2^{-\frac{u}{2}} (-1)^{1+\psi_{u,v}},$$

$$n \in \left[0, \frac{N}{2^u} - 1\right] \text{ and } v \in [0, 2^u - 1],$$

may be the real part of the IFFT output at the IFFT block 1108 of FIG. 11, while the complex part of the IFFT output may be used for SVD precoding. In the system of FIG. 11, the complex output may be used.

[0117] The matched dimensions of $\mathbf{G}^S$ and $\mathbf{G}^{W_L}$ may be distributed to achieve a desired OOB power suppression effect. FIG. 12 is a graph 1200 that illustrates the PSD after applying Chung's Spectral precoding to a 64-subcarrier OFDM system without any CP or ZP (NG) using QPSK modulation and an FFT size of 256. Simulation results may show that the PSD of a W_L -based system may outperform that of the V_L -based system for the same L , *e.g.*, for NG, ZP, and CP. The code rate is $1 - 2^{-L}$. The five curves 1202, 1204, 1206, 1208, and 1210 in FIG. 12 show that the largest OOB power decrement may appear when the code rate drops from 1 (uncoded) to 63/64 ($L=6$). The curve 1202 illustrates the PSD for an uncoded system. The curves 1204, 1206, 1208, and 1210 illustrate the PSD for values of L of 6, 5, 4, and 3, respectively. As L further decreases linearly, the cumulative suppression impact may become less effective as the code rate drops exponentially.

[0118] FIG. 13 is a graph 1300 that illustrates the PSD after applying Beek's SVD precoding method. A curve 1302 illustrates the PSD for an uncoded system. Two groups of notched frequencies are used in this simulation, namely, group 1 comprising close-notched frequencies of $[-14.5 \text{ } -13.5 \text{ } -12.5 \text{ } -11.5 \text{ } 74.5 \text{ } 75.5 \text{ } 76.5 \text{ } 77.5]$ and group 2 comprising distant-notched

frequencies of $[-35.5 \text{ } -34.5 \text{ } -33.5 \text{ } -32.5 \text{ } 95.5 \text{ } 96.5 \text{ } 97.5 \text{ } 98.5]$. Curves 1304 and 1306 illustrate the PSD for groups 1 and 2, respectively, when $R=2$. Curves 1308 and 1310 illustrate the PSD for groups 1 and 2, respectively, when $R=4$. Curves 1312 and 1314 illustrate the PSD for groups 1 and 2, respectively, when $R=6$. Curves 1316 and 1318 illustrate the PSD for groups 1 and 2, respectively, when $R=8$.

[0119] With an active subcarrier index of 0-63 and an FFT size of 256 in this simulation, group 1 may be close to the in-band and group 2 may be distant. FIG. 13 shows that the allocation of the chosen notched frequencies may provide a tradeoff between the OOB power and the decaying rate. The power decrement per $1/64$ coding decrement may not change substantially and may be larger than that of spectral precoding when the code rate is less than $62/64$. When the overall rate is fixed as k/n , an OOB power suppression effect may be achieved by adopting the $[K/(N-1), (N-1)/N]$ code rate pair, e.g., assigning $K/(N-1)$ as the SVD precode rate and $(N-1)/N$ as the spectral precode rate.

[0120] FIGS. 14 and 15 are graphs 1400 and 1500 that show the comparison of SVD-based and combined NG-OFDM for group 1 (close-notched) and group 2 (distant-notched) notched frequencies, respectively. FIG. 14 is based on the notched frequencies in group 1 in Beek's SVD precoding and combined scheme. FIG. 15 is based on the notched frequencies in group 2 in Beek's SVD precoding and combined scheme. In FIGS. 14 and 15, curves 1402 and 1502 show the PSD for an uncoded system. Curves 1404 and 1504 show the PSD for a code rate for $R=4$. Curves 1406 and 1506 show the PSD for a code rate for $R=3$, $L=6$. Curves 1408 and 1508 show the PSD for a code rate for $R=6$. Curves 1410 and 1510 show a PSD for a code rate for $R=5$, $L=6$. Curves 1412 and 1512 show a PSD for a code rate for $R=8$. Curves 1414 and 1514 show a PSD for a code rate for $R=7$, $L=6$. FIG. 14 shows that, for the three code rates, the combined scheme gives about 15 dB lower total OOB power than Beek's SVD precoding scheme at a cost of a slightly wider transition band. The transition band difference between Beek's SVD precoding method and the combined schemes disclosed herein is larger in FIG. 15 than in FIG. 14, but a relatively significant OOB power decrement may be seen using the combined scheme.

[0121] FIGS. 16 and 17 are graphs 1600 and 1700 that show the comparison of SVD-based and combined ZP-OFDM for group 1 (close-notched) and group 2 (distant-notched) notched frequencies, respectively. FIG. 16 is based on the notched frequencies in group 1 in Beek's SVD precoding and combined scheme. FIG. 17 is based on the notched frequencies in group 2 in Beek's SVD precoding and combined scheme. In FIGS. 16 and 17, curves 1602 and 1702 show the PSD for an uncoded system. Curves 1604 and 1704 show the PSD for a code rate for $R=4$. Curves 1606 and 1706 show the PSD for a code rate for $R=3$, $L=6$. Curves 1608 and 1708 show

the PSD for a code rate for $R=6$. Curves 1610 and 1710 show a PSD for a code rate for $R=5$, $L=6$. Curves 1612 and 1712 show a PSD for a code rate for $R=8$. Curves 1614 and 1714 show a PSD for a code rate for $R=7$, $L=6$. FIGS. 16 and 17 may look similar to FIGS. 14 and 15 because the continuous-phase property of spectral precoding may be maintained because the value on both edges of each data block before ZP is also zero and because the $\mathbf{P}$ and $\mathbf{V}$ values in the formula $\mathbf{P} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$ may show little changes after ZP is added.

[0122] FIGS. 18 and 19 are graphs 1800 and 1900 that show the comparison of SVD-based and combined CP-OFDM for group 1 (close-notched) and group 2 (distant-notched) notched frequencies, respectively. FIG. 18 is based on the notched frequencies in group 1 in Beek's SVD precoding and combined scheme. FIG. 19 is based on the notched frequencies in group 2 in Beek's SVD precoding and combined scheme. In this example, the length of CP may be $T_d/16$. Since CP may be added and the starting edge of CP is usually not zero, then the spectral precoding scheme may not be able to construct a continuous signal with CP. Therefore, assigning $1/K$ of the total spectral efficiency loss to spectral precoding and the rest $(K - 1)/K$ to SVD precoding may not be better than assigning all the spectral efficiency loss to SVD precoding only.

[0123] In FIGS. 18 and 19, curves 1802 and 1902 show the PSD for an uncoded system. Curves 1804 and 1904 show the PSD for a code rate for $R=4$. Curves 1806 and 1906 show the PSD for a code rate for $R=3$, $L=6$. Curves 1808 and 1908 show the PSD for a code rate for $R=6$. Curves 1810 and 1910 show a PSD for a code rate for $R=5$, $L=6$. Curves 1812 and 1912 show a PSD for a code rate for $R=8$. Curves 1814 and 1914 show a PSD for a code rate for $R=7$, $L=6$.

[0124] The OOB power suppression effects of all three code rates for CP-OFDM may be worse than for NG-OFDM and ZP-OFDM. In NG-OFDM and ZP-OFDM, the width of the sidelobes may be equal to the frequency spacing of adjacent subcarriers. Each sidelobe of one subcarrier may overlap with some sidelobes from the other subcarriers. The singular values of $\mathbf{P}$ in the formula $\mathbf{P} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$ may drop quickly. However, when CP is added and symbol duration is increased, the width of the sidelobe may become narrower. Therefore, the singular values of $\mathbf{P}$ may drop more slowly. If P_l is the average power leakage after precoding at the chosen notched frequencies f_l , then P_l can be expressed by $P_l = P_s \sum_{i=R}^{N-1} \sigma_i^2(\mathbf{P})$, where P_s is the average power of $\mathbf{d}_l$ and $\sigma^i(\mathbf{P})$ is the i^{th} largest singular value of $\mathbf{P}$. In this sense, for the same value of R , the power leakage P_l of CP-OFDM may be larger than the P_l of NG-OFDM or ZP-OFDM.

[0125] FIG. 20 shows the bit error rate (BER) of the three schemes' IFFT outputs in an example NG-OFDM system using QPSK modulation. The number of subcarriers is 64, and the FFT size is 256. In this example, the channel is assumed as an AWGN channel, e.g., $\mathbf{r}'_l = \mathbf{x}'_l +$

$\mathbf{n}_l$, where $\mathbf{n}_l$ may denote the noise vector. SNR (dB) may be defined as $SNR = 10 \log_{10} \frac{E(|\mathbf{x}_l|^2)}{E(|\mathbf{n}_l|^2)}$.

A curve 2002 shows the BER for an uncoded system. A curve 2004 shows the BER for a code rate for R=4. A curve 2006 shows the BER for a code rate for R=3, L=6. A curve 2008 shows the BER for a code rate for R=6. A curve 2010 shows the BER for a code rate for R=5, L=6. A curve 2012 shows the BER for a code rate for R=8. A curve 2014 shows the BER for a code rate for R=7, L=6.

[0126] As shown in FIG. 20, the combined scheme, which may use distant notched frequencies, may have almost the same BER curves as Beek's SVD precoding or spectral precoding when they have the same code rates. Further, as the code rate decreases, the BER may become slightly better, *e.g.*, smaller, because the length of $\mathbf{d}_l$, which may be estimated at the receiver, may be reduced while the row size of the precoding matrix may be unchanged. Accordingly, a lower code rate may provide a slightly higher diversity gain.

[0127] The processes and instrumentalities described herein may apply in any combination, may apply to other wireless technologies, and for other services.

[0128] A WTRU may refer to an identity of the physical device, or to the user's identity such as subscription related identities, *e.g.*, MSISDN, SIP URI, *etc.* WTRU may refer to application-based identities, *e.g.*, user names that may be used per application. A WTRU or device may refer to a user. A user may refer to a WTRU or device.

[0129] The processes described above may be implemented in a computer program, software, and/or firmware incorporated in a computer-readable medium for execution by a computer and/or processor. Examples of computer-readable media include, but are not limited to, electronic signals (transmitted over wired and/or wireless connections) and/or computer-readable storage media. Examples of computer-readable storage media include, but are not limited to, a read only memory (ROM), a random access memory (RAM), a register, cache memory, semiconductor memory devices, magnetic media such as, but not limited to, internal hard disks and removable disks, magneto-optical media, and/or optical media such as CD-ROM disks, and/or digital versatile disks (DVDs). A processor in association with software may be used to implement a radio frequency transceiver for use in a WTRU, UE, terminal, base station, RNC, and/or any host computer.

CLAIMS

What is Claimed:

1. A method associated with orthogonal frequency division multiplexing (OFDM) transmission, the method comprising:
 - determining a precoding matrix, wherein the precoding matrix is determined for a frequency band associated with a plurality of devices;
 - determining a portion of the frequency band allocated to a device, wherein the device is one of the plurality of devices;
 - determining a portion of the precoding matrix associated with the portion of the frequency band; and
 - sending data using the portion of the precoding matrix.
2. The method of claim 1, wherein determining the precoding matrix comprises determining the precoding matrix as a function of at least one of a number of devices or an available bandwidth of the frequency band.
3. The method of claim 1, wherein the portion of the frequency band allocated to the device comprises a plurality of OFDM subcarriers.
4. The method of claim 3, wherein determining the portion of the precoding matrix comprises selecting one or more columns of the precoding matrix based on the plurality of OFDM subcarriers.
5. The method of claim 1, wherein determining the precoding matrix comprises determining the precoding matrix based on a singular value decomposition of a matrix representing a spectral leakage across a plurality of notched frequencies.
6. The method of claim 5, wherein the singular value decomposition of the matrix representing the spectral leakage across the notched frequencies yields a plurality of precoding vectors that, when applied to transmit data, removes at least a portion of the spectral leakage across the notched frequencies.
7. The method of claim 1, wherein the plurality of devices are synchronized.

8. The method of claim 1, wherein the precoding matrix is derived for a virtual user of the frequency band.

9. The method of claim 1, wherein determining the precoding matrix comprises determining the precoding matrix as a matrix product of at least two precoding matrices.

10. The method of claim 9, wherein the precoding matrix maintains a continuous phase property.

11. A wireless transmit/receive unit (WTRU) comprising a processor configured to select a precoding matrix for orthogonal frequency division multiplexing (OFDM) transmission by:

determining a first precoding matrix, wherein the first precoding matrix is determined for a frequency band to be used for transmission by a plurality of devices;

determining a portion of the frequency band allocated to a device, wherein the device is one of the plurality of devices;

determining a portion of the precoding matrix associated with the portion of the frequency band; and

sending data using the portion of the precoding matrix.

12. The WTRU of claim 11, wherein determining the precoding matrix comprises determining the precoding matrix as a function of at least one of a number of devices or an available bandwidth of the frequency band.

13. The WTRU of claim 11, wherein the portion of the frequency band allocated to the device comprises a plurality of OFDM subcarriers.

14. The WTRU of claim 13, wherein the processor is further configured to determine the portion of the precoding matrix by selecting one or more columns of the precoding matrix based on the plurality of OFDM subcarriers.

15. The WTRU of claim 11, wherein determining the precoding matrix comprises determining the precoding matrix based on a singular value decomposition of a matrix representing a spectral leakage across a plurality of notched frequencies.

16. The WTRU of claim 15, wherein the singular value decomposition of the matrix representing the spectral leakage across the notched frequencies yields a plurality of precoding vectors that, when applied to transmit data, removes at least a portion of the spectral leakage across the notched frequencies.

17. The WTRU of claim 11, wherein the plurality of devices are synchronized.

18. The WTRU of claim 11, wherein the processor is configured to derive the precoding matrix for a virtual user of the frequency band.

19. The WTRU of claim 11, wherein determining the precoding matrix comprises determining the precoding matrix as a matrix product of at least two precoding matrices.

20. The WTRU of claim 19, wherein the precoding matrix maintains a continuous phase property.

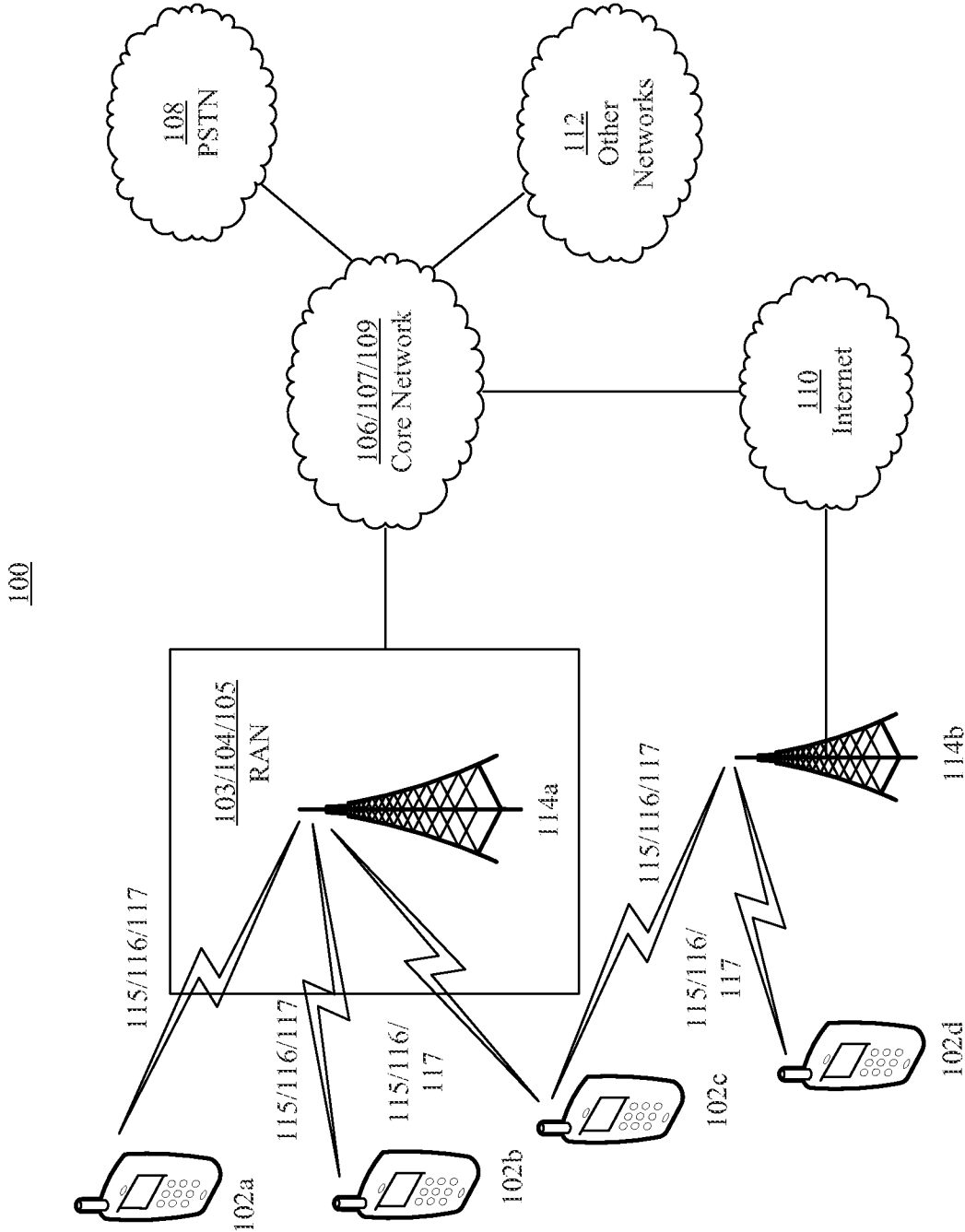
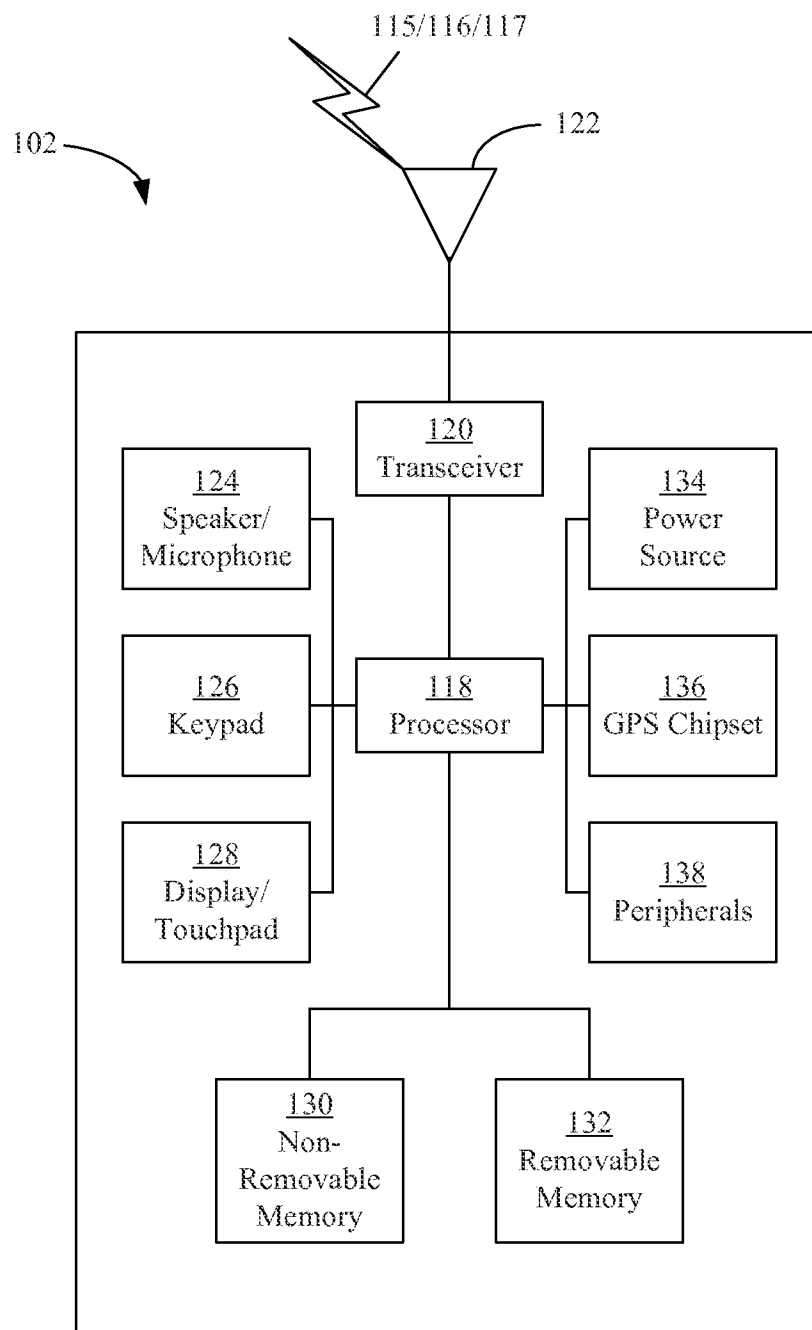


FIG. 1A

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**FIG. 1B**

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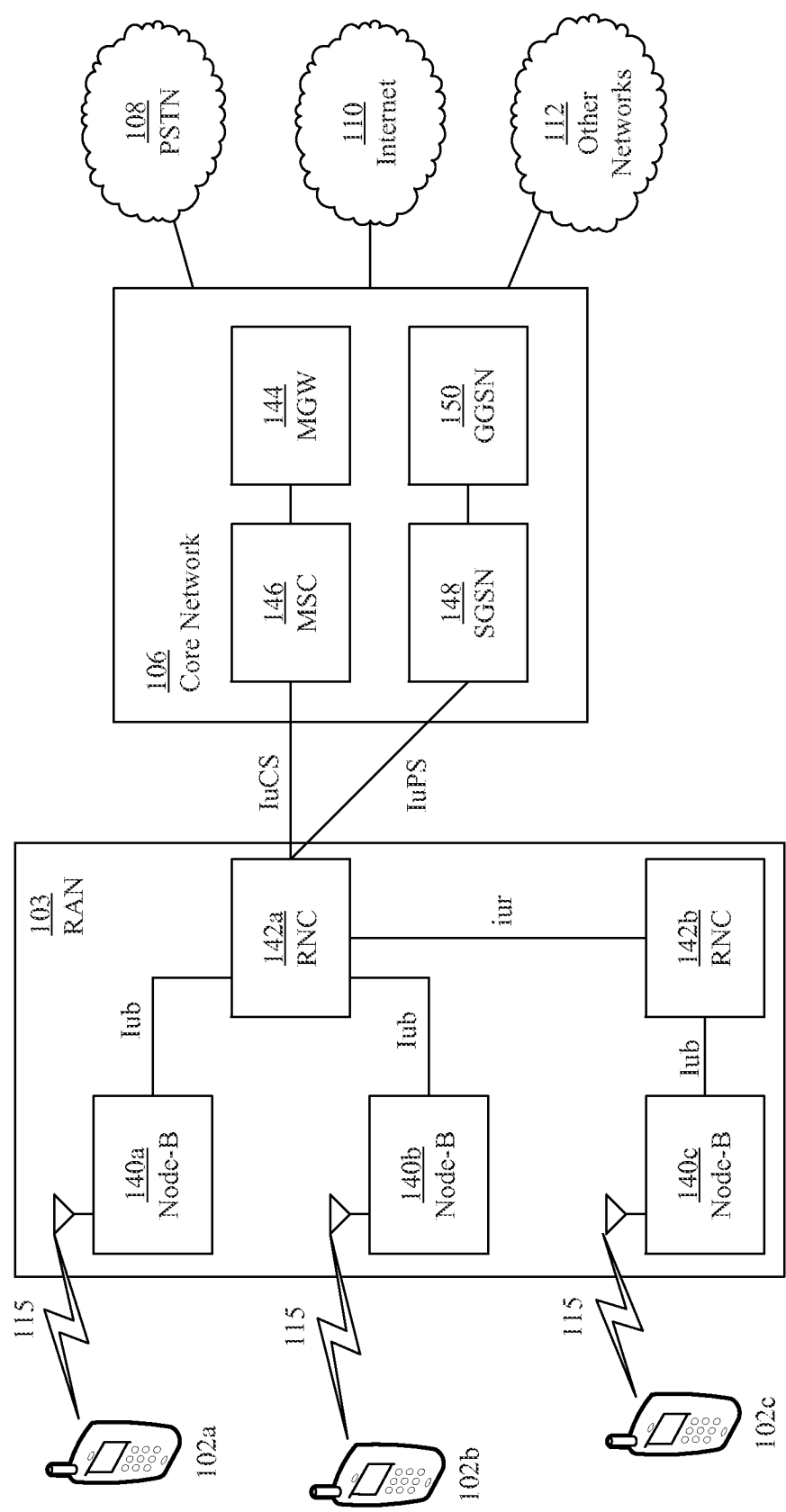


FIG. 1C

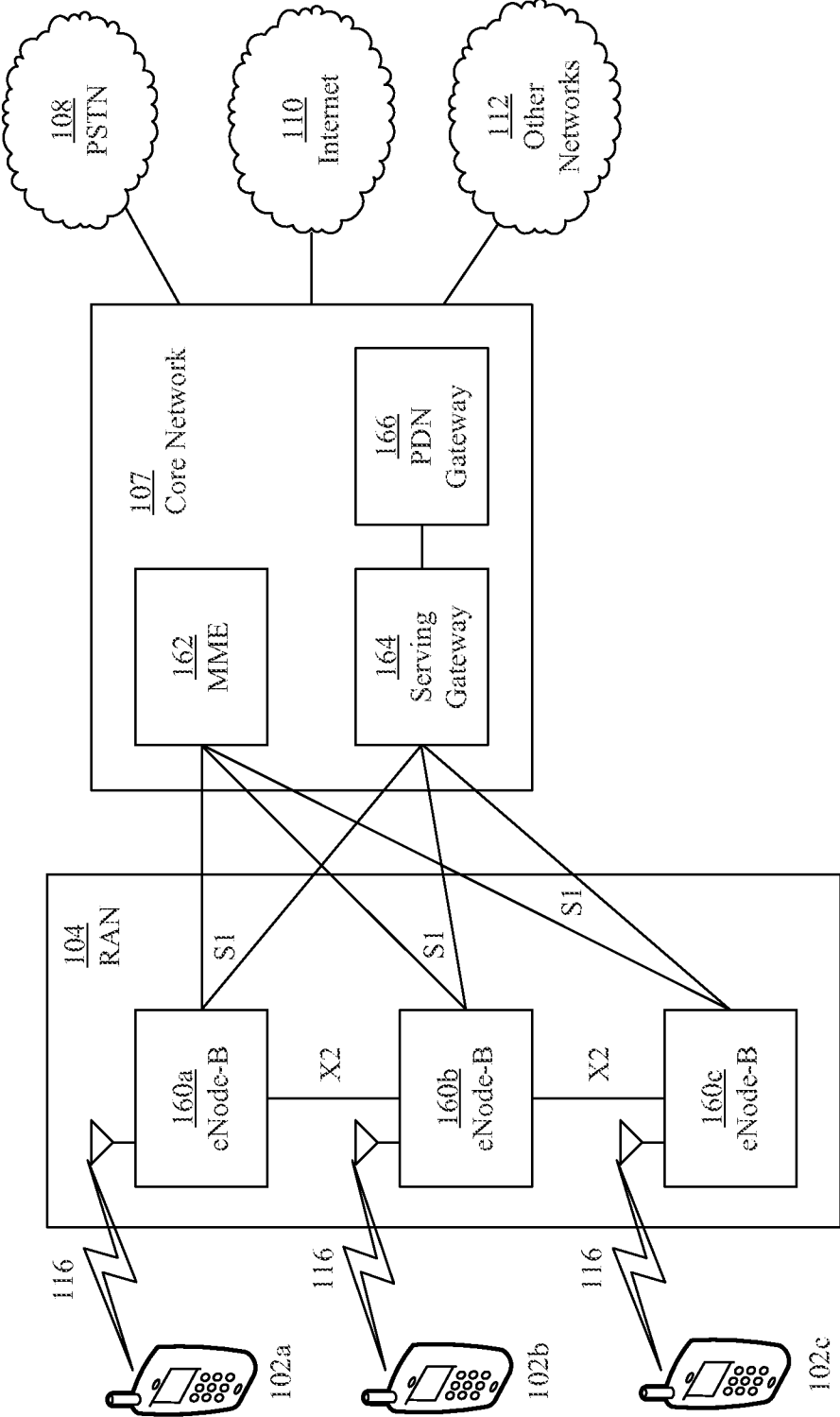


FIG. 1D

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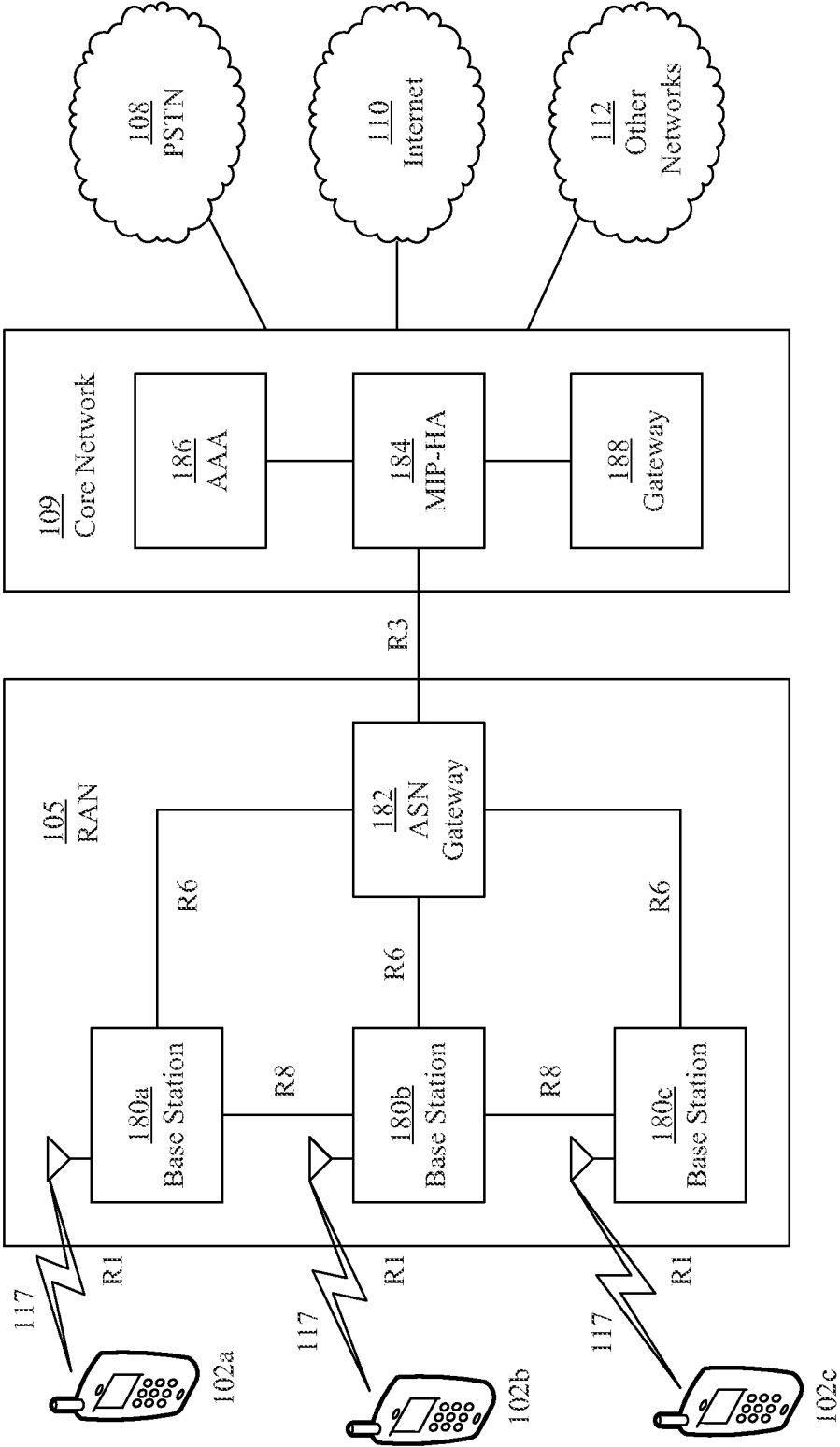


FIG. 1E

200

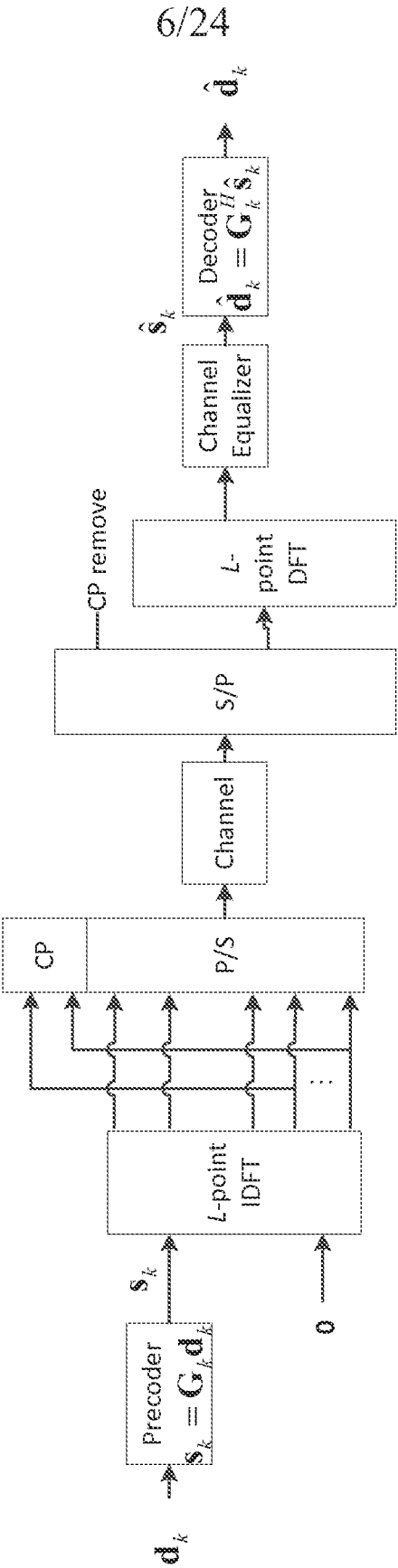


FIG. 2

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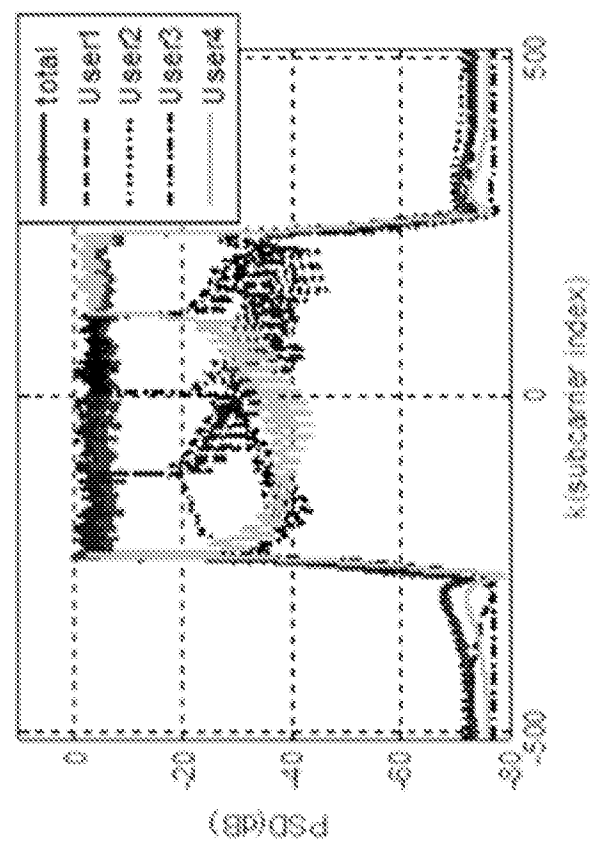


FIG. 3

400

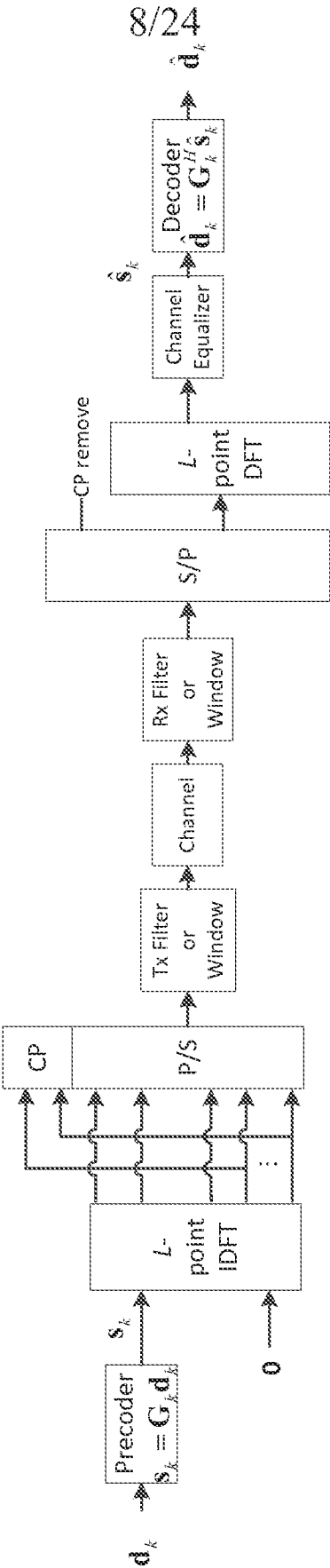


FIG. 4

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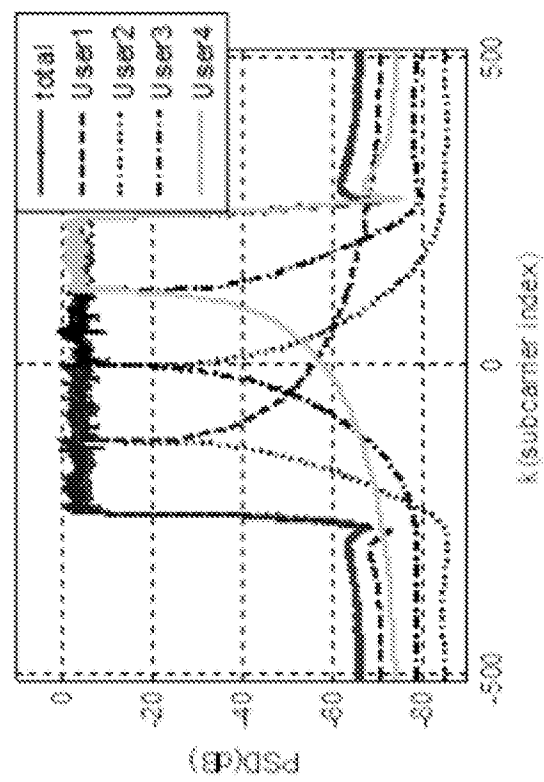


FIG. 5

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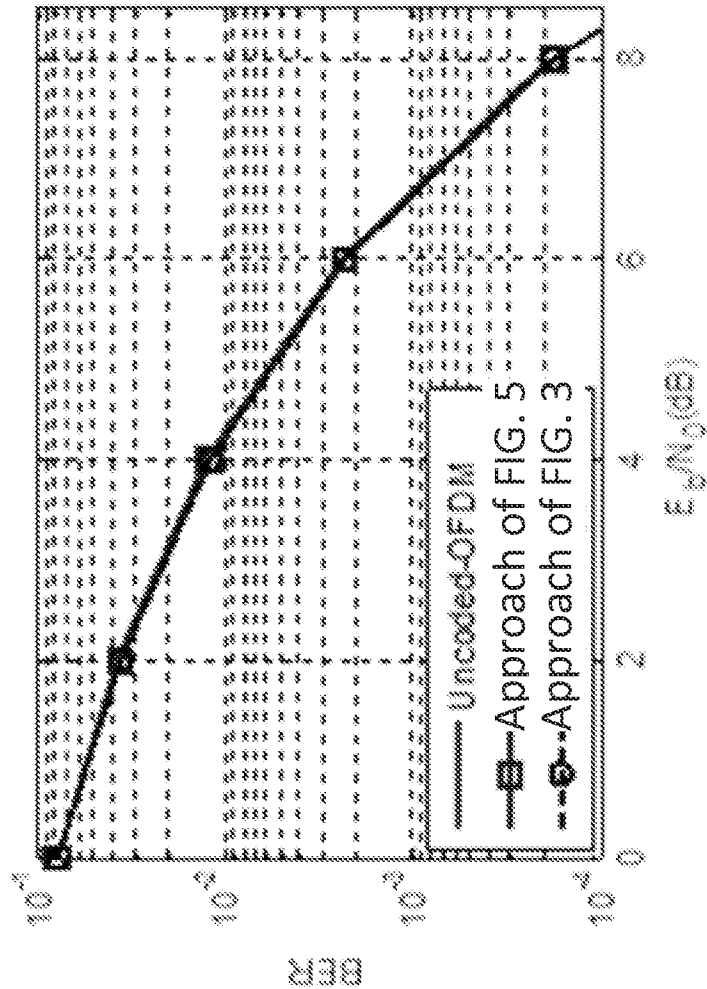


FIG. 6

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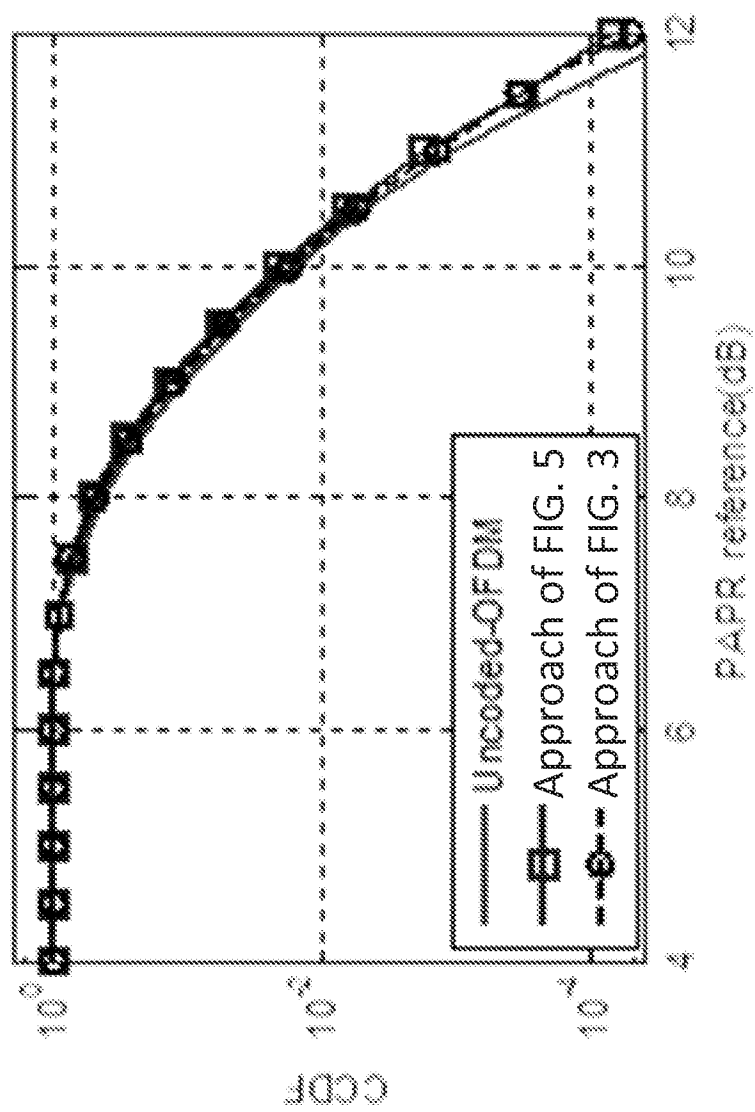


FIG. 7

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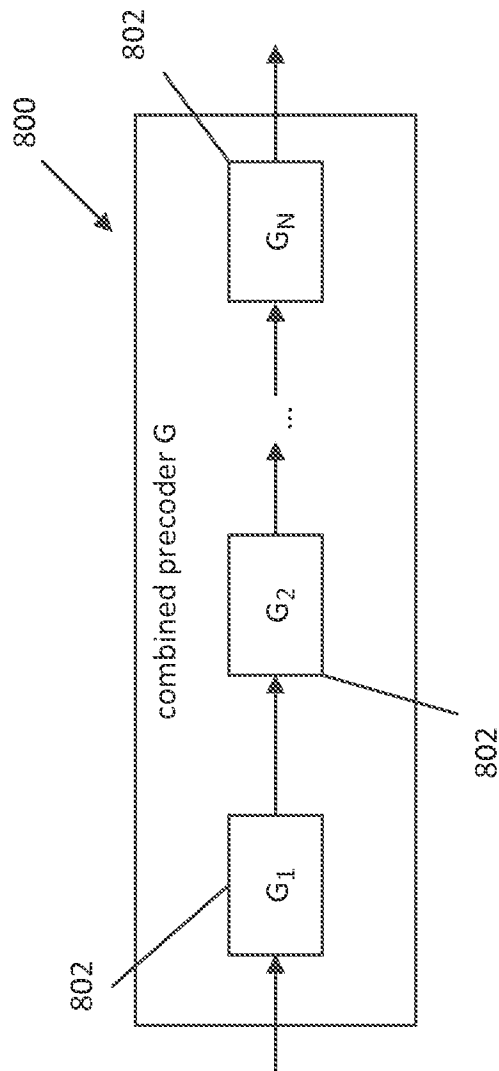


FIG. 8

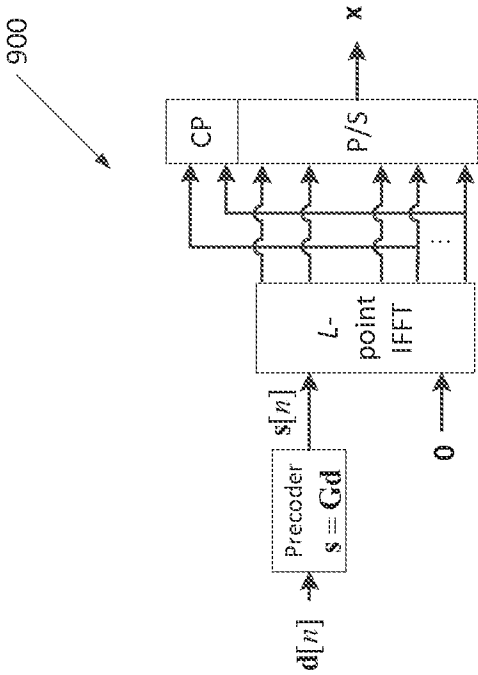


FIG. 9

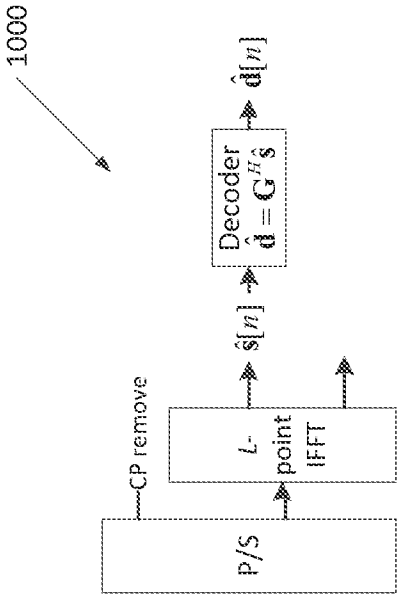


FIG. 10

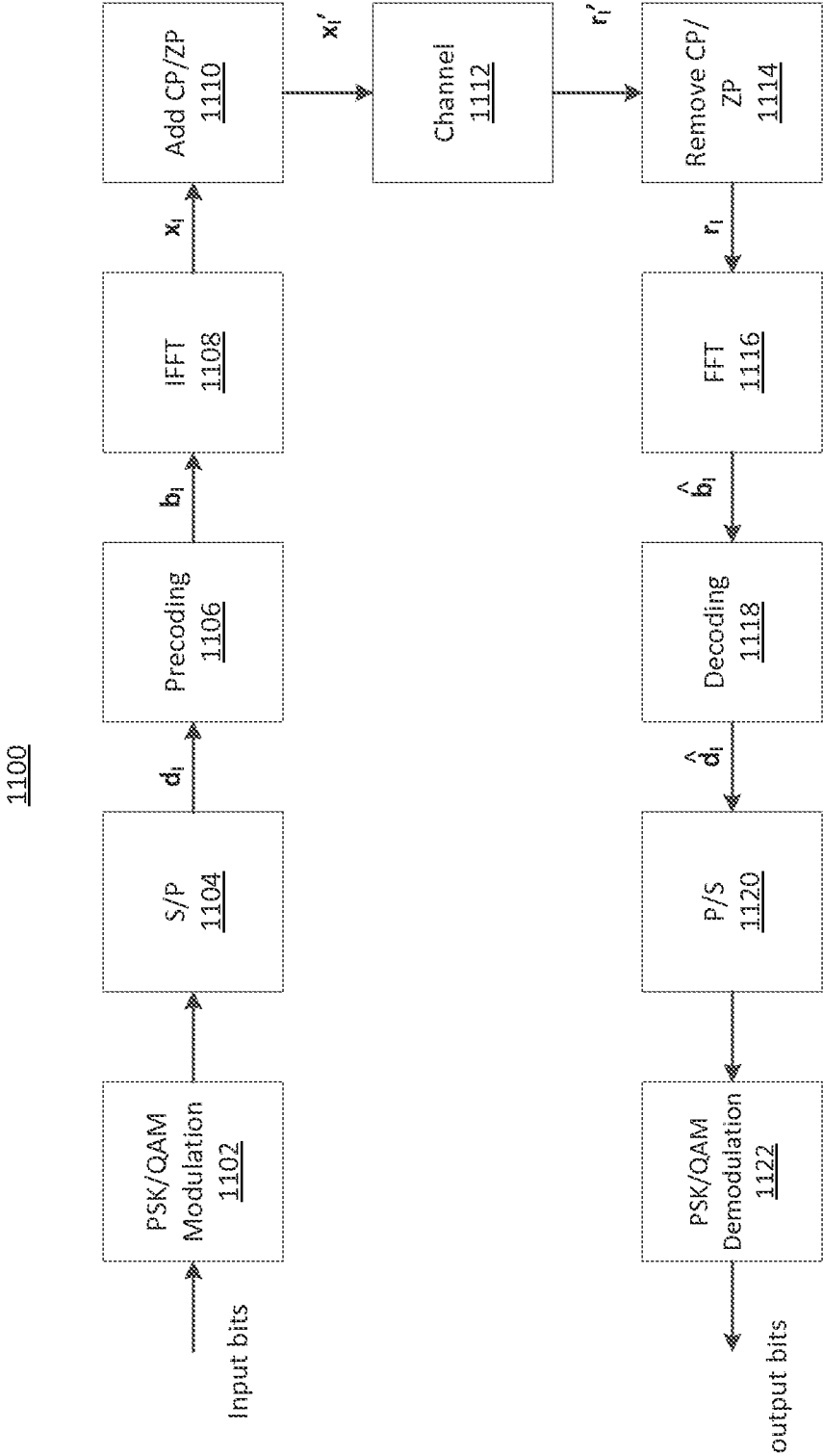


FIG. 11

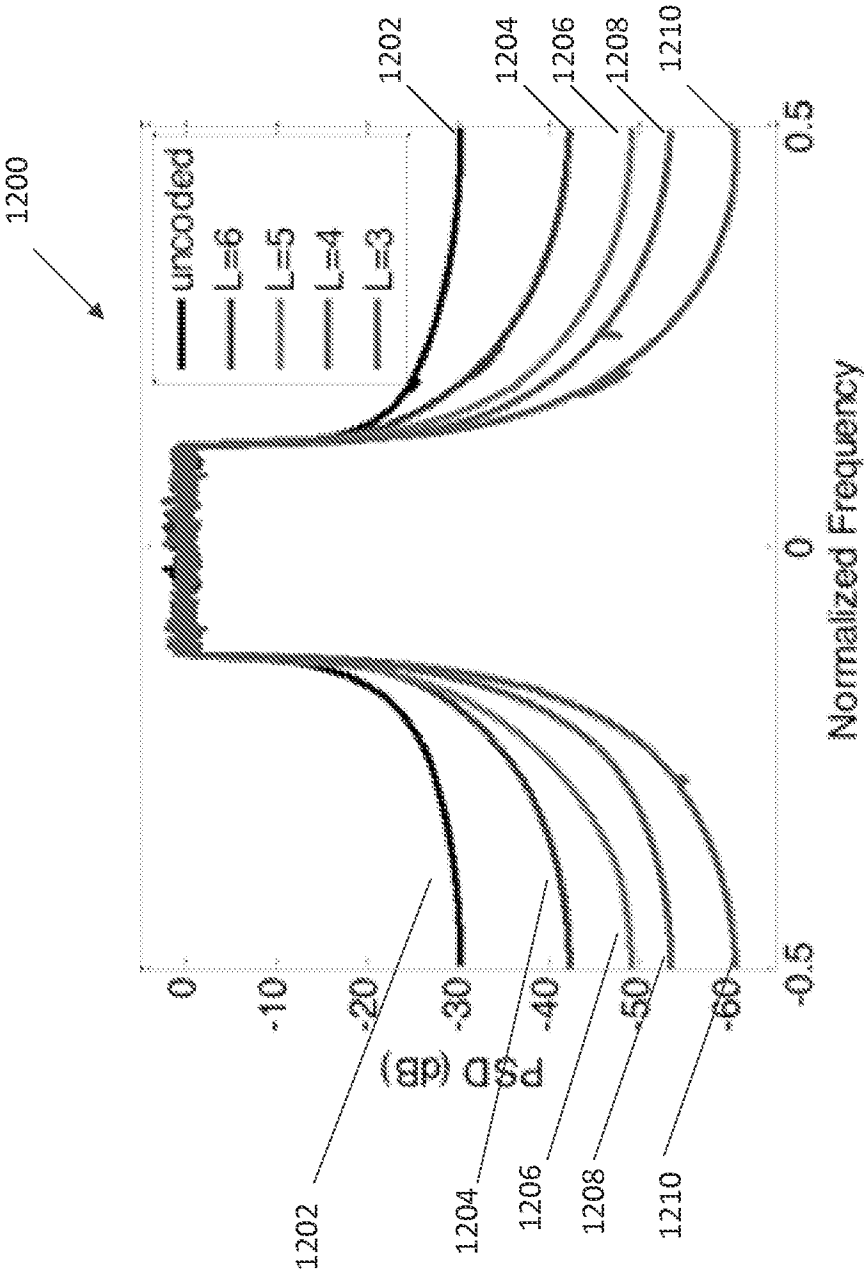


FIG. 12

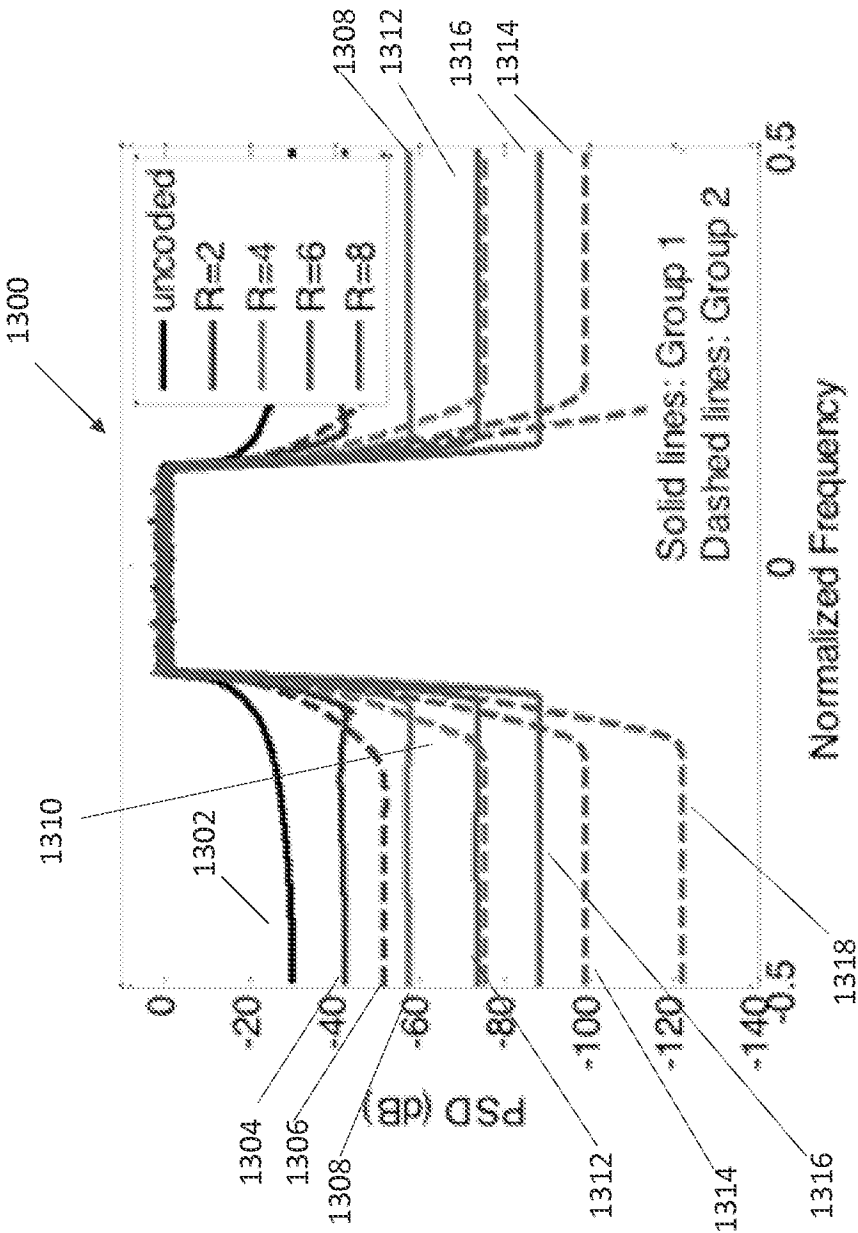


FIG. 13

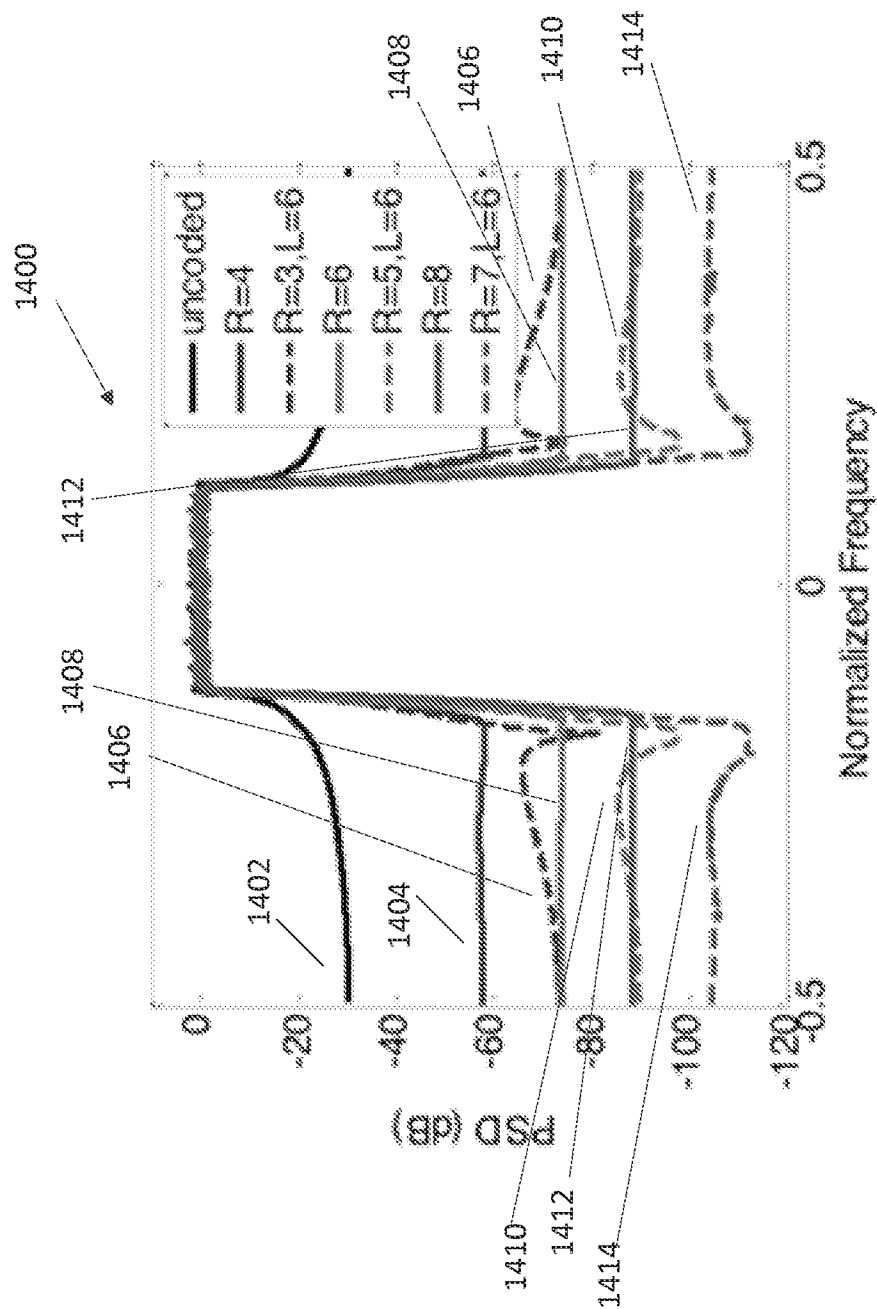


FIG. 14

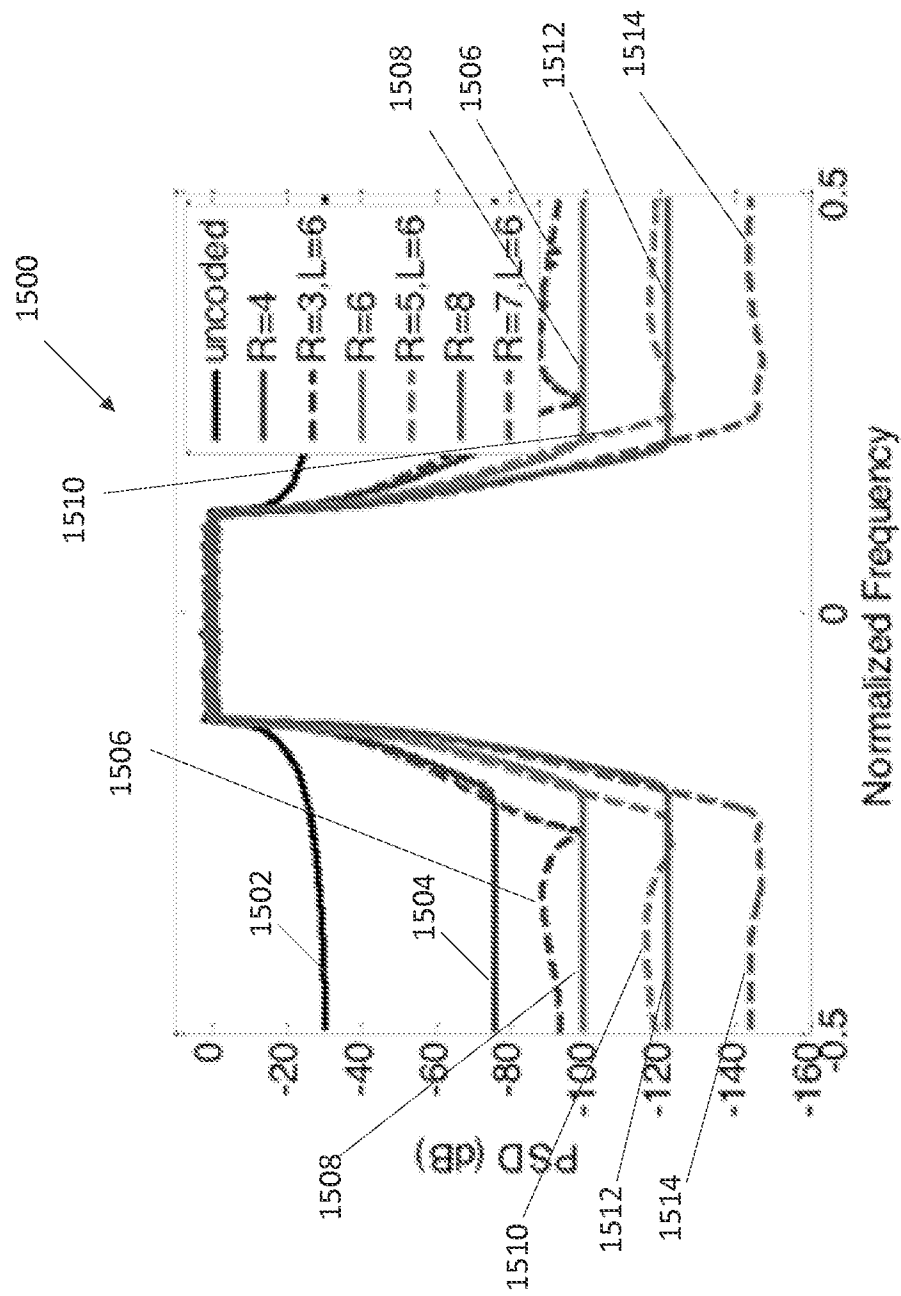


FIG. 15

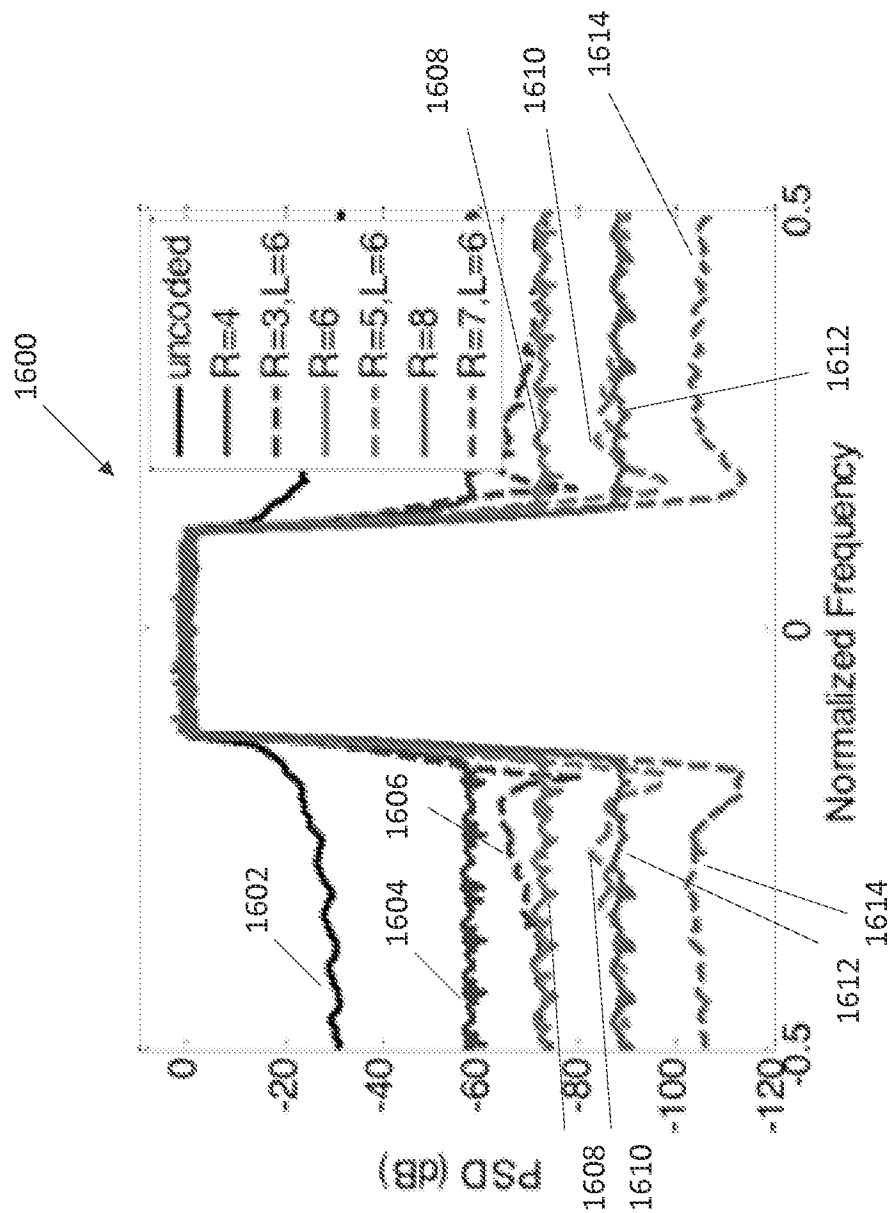


FIG. 16

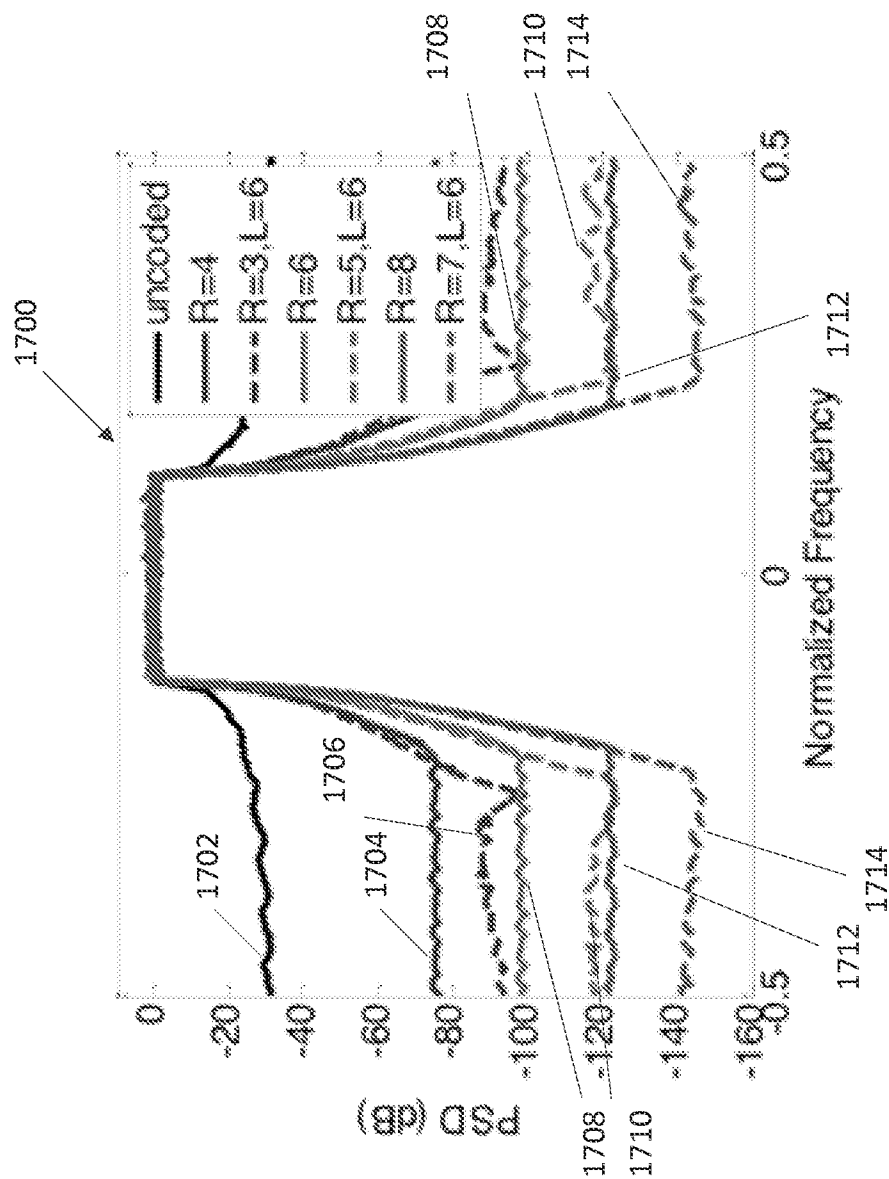


FIG. 17

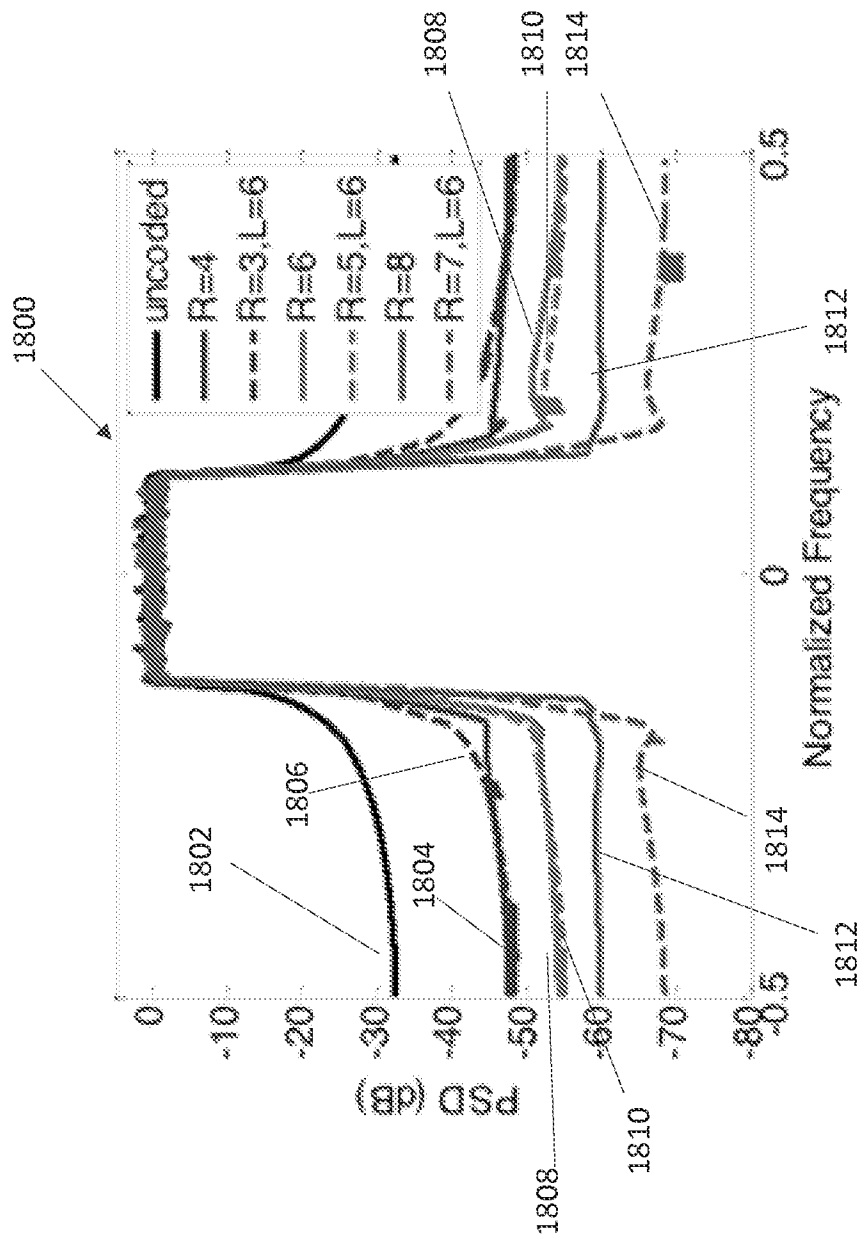


FIG. 18

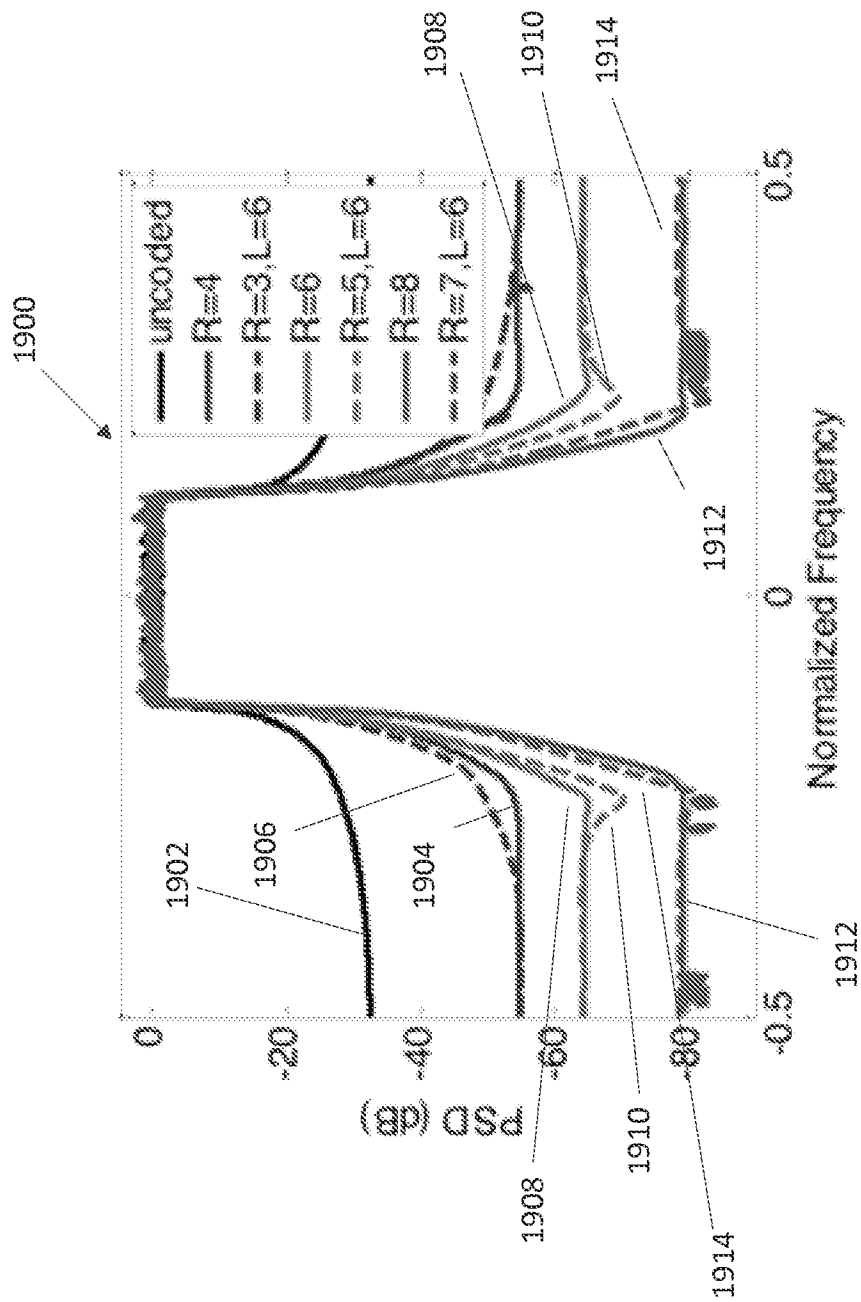


FIG. 19

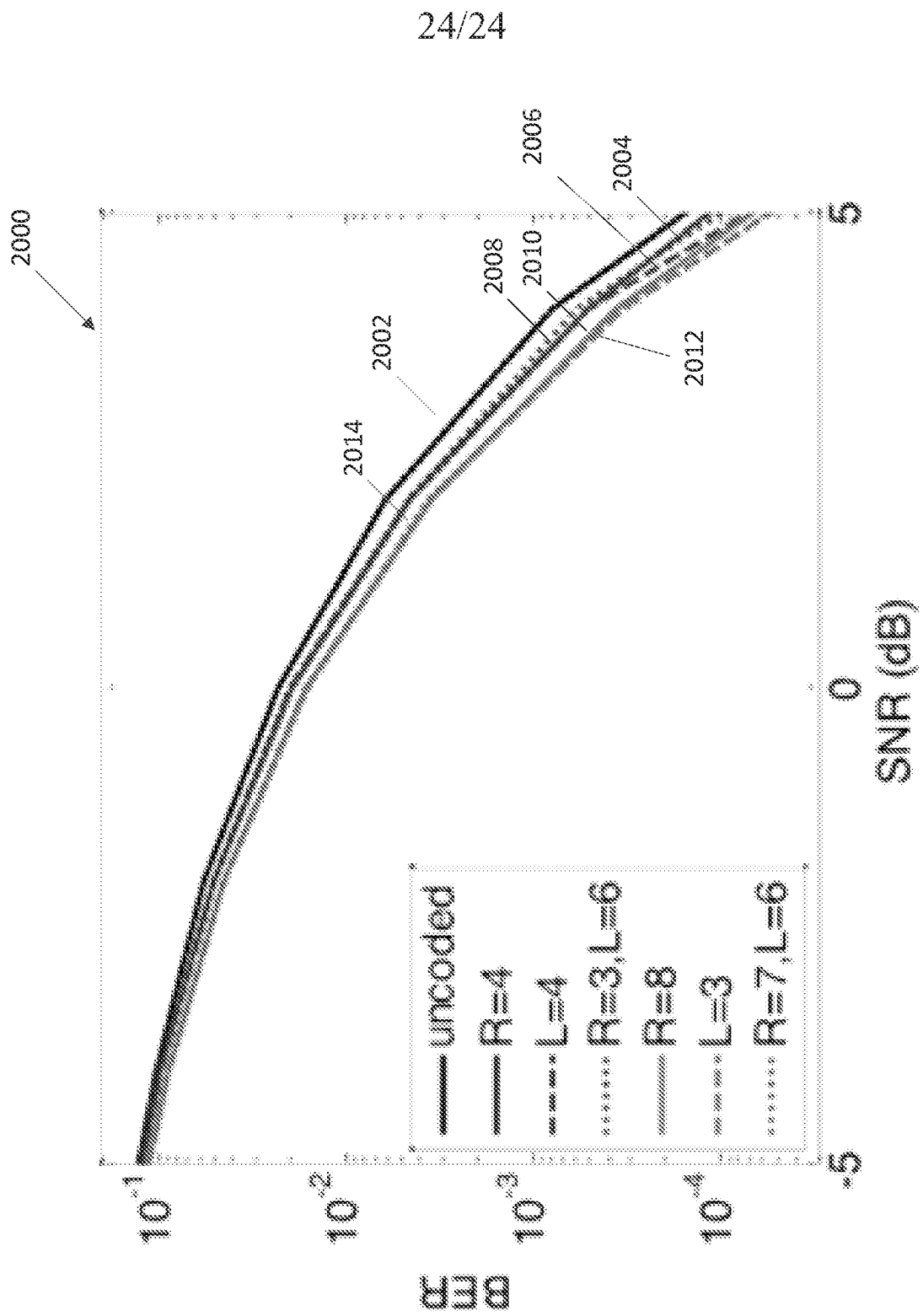


FIG. 20

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/012201A. CLASSIFICATION OF SUBJECT MATTER
INV. H04L25/03 H04L27/26
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	XIANGWEI ZHOU ET AL: "Multiuser Spectral Precoding for OFDM-Based Cognitive Radios", GLOBAL TELECOMMUNICATIONS CONFERENCE (GLOBECOM 2011), 2011 IEEE, IEEE, 5 December 2011 (2011-12-05), pages 1-5, XP032119587, DOI: 10.1109/GLOCOM.2011.6134392 ISBN: 978-1-4244-9266-4 Sections II. and III. ----- -/--	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

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"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

29 April 2014

Date of mailing of the international search report

09/05/2014

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Chave, Julien

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/012201

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	XIANGWEI ZHOU ET AL: "Multiuser Spectral Precoding for OFDM-Based Cognitive Radio Systems", IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, IEEE SERVICE CENTER, PISCATAWAY, US, vol. 31, no. 3, 1 March 2013 (2013-03-01), pages 345-352, XP011494535, ISSN: 0733-8716, DOI: 10.1109/JSAC.2013.130302 Sections II. and III. Section V.A -----	1-20
X,P	FANG JUAN ET AL: "Efficient multiuser spectral precoding for reducing out-of-band emission for OFDM-based cognitive radios", 2013 IEEE LONG ISLAND SYSTEMS, APPLICATIONS AND TECHNOLOGY CONFERENCE (LISAT), IEEE, 3 May 2013 (2013-05-03), pages 1-5, XP032475186, DOI: 10.1109/LISAT.2013.6578229 ISBN: 978-1-4673-6244-3 [retrieved on 2013-08-12] the whole document -----	1-20