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- (71) **Applicants:** **INTERDIGITAL PATENT HOLDINGS, INC.** [US/US]; 200 Bellevue Parkway, Suite 300, Wilmington, Delaware 19809 (US). **NEW YORK UNIVERSITY** [US/US]; Six MetroTech Center, Brooklyn, New York 11201 (US).
- (72) **Inventors:** **LOU, Hanqing**; 2 Huntington Quadrangle, 4th Floor, South Wing, Melville, New York 11747 (US). **LU, I-Tai**; 4 Carol Court, Dix Hills, New York 11746 (US). **FANG, Juan**; 2132 West 10th Street, Brooklyn, New York 11223 (US).
- (74) **Agent:** **KERNER, Dawn C.**; Volpe and Koenig, P.C., United Plaza, 30 S. 17th Street, Philadelphia, Pennsylvania 19103 (US).

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(54) **Title:** METHODS AND APPARATUS FOR CHANNEL ESTIMATION AND PRECODING BASED ANALOG CHANNEL STATE INFORMATION FEEDBACK

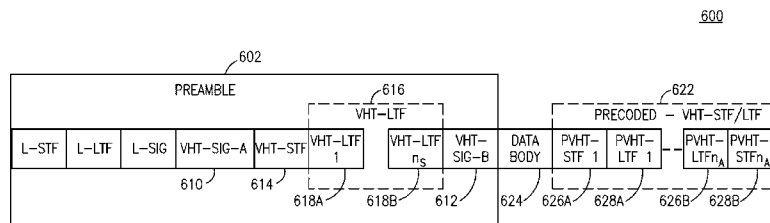


FIG. 6

(57) **Abstract:** Methods and apparatus for channel estimation and precoding based analog channel state information feedback are described. A method, implemented in a network node, includes receiving, from another network node, a sounding frame with a reference sequence that is known to the network node. At least one channel state information (CSI) matrix is estimated using the received sounding frame and the reference sequence to generate at least one estimated CSI matrix, and the at least one generated estimated CSI matrix is applied as at least one precoded estimated CSI matrix to a feedback packet. The feedback packet is sent to the other network node and includes at least one training field carrying the at least one precoded estimated CSI matrix and at least one training field that carries CSI information that is not precoded.

METHODS AND APPARATUS FOR CHANNEL ESTIMATION AND PRECODING BASED ANALOG CHANNEL STATE INFORMATION FEEDBACK

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/188,083, which was filed on July 2, 2015, and U.S. Provisional Patent Application No. 62/320,818, which was filed on April 11, 2016, the contents of which are hereby incorporated by reference herein.

SUMMARY

[0002] Methods and apparatus for channel estimation and precoding based analog channel state information feedback are described. Methods and apparatus for channel estimation and precoding based analog channel state information feedback are described. A method, implemented in a network node, includes receiving, from another network node, a sounding frame with a reference sequence that is known to the network node. At least one channel state information (CSI) matrix is estimated using the received sounding frame and the reference sequence to generate at least one estimated CSI matrix, and the at least one generated estimated CSI matrix is applied as at least one precoded estimated CSI matrix to a feedback packet. The feedback packet is sent to the other network node and includes at least one training field carrying the at least one precoded estimated CSI matrix and at least one training field that carries CSI information that is not precoded. This enables a substantial reduction in overhead in the CSI feedback as compared with, for example, explicit and implicit feedback methods.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] A more detailed understanding may be had from the following description, given by way of example in conjunction with the accompanying drawings wherein:

[0004] FIG. 1A is a system diagram of an example communications system in which one or more disclosed embodiments may be implemented;

[0005] 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;

[0006] 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;

[0007] FIG. 2 is a signal diagram of an example channel state information (CSI) feedback procedure for downlink (DL) multi-user multiple input multiple output (MU-MIMO);

[0008] FIG. 3 is a signal diagram of an example CSI feedback procedure for single-user (SU) beamforming;

[0009] FIG. 4 is a diagram of an example null data packet announcement (NDPA) frame;

[0010] FIG. 5 is a diagram of an example station (STA) information field;

[0011] FIG. 6 is a diagram of a CSI feedback frame for precoding feedback; and

[0012] FIG. 7 is a flow diagram of an example method of channel estimation and precoding based analog CSI feedback;

[0013] FIG. 8A is a flow diagram of an example method of retrieving a CSI matrix from a precoding based CSI feedback packet;

[0014] FIG. 8B is a diagram of the example methods of channel estimation, precoding and retrieving a CSI matrix from a precoding based CSI feedback packet showing more detail;

[0015] FIG. 9 is a graph of simulation results of DL MU-MIMO with four users where each user has one antenna;

[0016] FIG. 10 is a graph of simulation results of DL MU-MIMO with two users where each user has two antennas; and

[0017] FIG. 11 is a graph of the simulation results of DL MU-MIMO with four users where each user has two antennas.

DETAILED DESCRIPTION

[0018] 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 systems 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.

[0019] As shown in FIG. 1A, the communications system 100 may include wireless transmit/receive units (WTRUs) 102a, 102b, 102c, 102d, a radio access network (RAN) 104, a core network 106, 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.

[0020] The communications systems 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, the Internet 110, and/or the other 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.

[0021] The base station 114a may be part of the RAN 104, 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, i.e., 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.

[0022] The base stations 114a, 114b may communicate with one or more of the WTRUs 102a, 102b, 102c, 102d over an air interface 116, which may be any suitable wireless communication link (e.g., radio frequency (RF), microwave, infrared (IR), ultraviolet (UV), visible light, etc.). The air interface 116 may be established using any suitable radio access technology (RAT).

[0023] 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 104 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 116 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).

[0024] 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 116 using Long Term Evolution (LTE) and/or LTE-Advanced (LTE-A).

[0025] In other embodiments, the base station 114a and the WTRUs 102a, 102b, 102c may implement radio technologies such as IEEE 802.16 (i.e., 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.

[0026] 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.

[0027] The RAN 104 may be in communication with the core network 106, 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 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 104 and/or the core network 106 may be in direct or indirect communication with other RANs that employ the same RAT as the RAN 104 or a different RAT. For example, in addition to being connected to the RAN 104, which may be utilizing an E-UTRA radio technology, the core network 106 may also be in communication with another RAN (not shown) employing a GSM radio technology.

[0028] The core network 106 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 104 or a different RAT.

[0029] Some or all of the WTRUs 102a, 102b, 102c, 102d in the communications system 100 may include multi-mode capabilities, i.e., 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.

[0030] 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.

[0031] 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.

[0032] 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 116. 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.

[0033] 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 116.

[0034] 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.

[0035] 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).

[0036] 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.

[0037] 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 116 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 method while remaining consistent with an embodiment.

[0038] 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.

[0039] FIG. 1C is a system diagram of the RAN 104 and the core network 106 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 106.

[0040] The RAN 104 may include eNode-Bs 140a, 140b, 140c, 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 140a, 140b, 140c 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 140a, 140b, 140c may implement MIMO technology. Thus, the eNode-B 140a, for example, may use multiple antennas to transmit wireless signals to, and receive wireless signals from, the WTRU 102a.

[0041] Each of the eNode-Bs 140a, 140b, 140c 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. 1C, the eNode-Bs 140a, 140b, 140c may communicate with one another over an X2 interface.

[0042] The core network 106 shown in FIG. 1C may include a mobility management entity gateway (MME) 142, a serving gateway 144, and a packet data network (PDN) gateway 146. 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.

[0043] The MME 142 may be connected to each of the eNode-Bs 140a, 140b, 140c in the RAN 104 via an S1 interface and may serve as a control node. For example, the MME 142 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 142 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.

[0044] The serving gateway 144 may be connected to each of the eNode Bs 140a, 140b, 140c in the RAN 104 via the S1 interface. The serving gateway 144 may generally route and forward user data packets to/from the WTRUs 102a, 102b, 102c. The serving gateway 144 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.

[0045] The serving gateway 144 may also be connected to the PDN gateway 146, 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.

[0046] The core network 106 may facilitate communications with other networks. For example, the core network 106 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 106 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 106 and the PSTN 108. In addition, the core network 106 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.

[0047] Other network 112 may further be connected to an IEEE 802.11 based wireless local area network (WLAN) 160. The WLAN 160 may include an access router 165. The access router may contain gateway functionality. The access router 165 may be in communication with a plurality of access points (APs) 170a, 170b. The communication between access router 165 and APs 170a, 170b may be via wired Ethernet (IEEE 802.3 standards), or any type of wireless communication protocol. AP 170a is in wireless communication over an air interface with WTRU 102d.

[0048] A wireless local area network (WLAN) in infrastructure basic service set (BSS) mode includes an access point (AP) for the BSS and one or more stations (STAs) associated with the AP. The AP may have access to, or interface with, a distribution system (DS) or other type of wired or wireless network that may carry traffic into, and out of, the BSS. Traffic originating from outside the BSS that is destined for STAs in the BSS may arrive at the AP, which may deliver it to the STAs. Traffic originating from STAs to destinations outside the BSS may be sent to the AP for delivery to the respective destinations. Traffic between STAs within the BSS may either be sent through the AP or may sent directly between source and destination STAs with a direct link setup (DLS) using an Institute of Electrical and Electronics Engineers (IEEE) 802.11e DLS or an IEEE 802.11z tunneled DLS (TDLS). Such traffic may be referred to as peer-to-peer traffic. A WLAN

using an independent BSS (IBSS) mode may have no AP and STAs may communicate directly with each other. This mode of communication may be referred to as an ad-hoc mode of operation.

[0049] Using an IEEE 802.11ac infrastructure mode of operation, the AP may transmit a beacon on a fixed channel, such as the primary channel. This channel may be, for example, 20 MHz wide and may be the operating channel of the BSS. This channel may also be used by STAs to establish a connection with the AP. The fundamental access mechanism in an IEEE 802.11 system may be carrier sense multiple access with collision avoidance (CSMA/CA). In this mode of operation, every STA, including the AP, may sense the primary channel. If the channel is detected to be busy, the STA may back off. Thus, using this mode of operation, only one STA may transmit at any given time in a given BSS.

[0050] In IEEE 802.11ac, very high throughput (VHT) STAs may support 20 MHz, 40 MHz, 80 MHz and/or 160 MHz wide channels. The 40 MHz and 80 MHz channels may be formed by combining contiguous 20 MHz channels, similar to IEEE 802.11n. A 160 MHz channel may be formed, for example, by combining 8 contiguous 20 MHz channels or by combining 2 non-contiguous 80 MHz channels. Combining 2 non-contiguous 80 MHz channels may be referred to as an 80+80 configuration. For an 80+80 configuration, after channel coding, the data may be passed through a segment parser, which may divide the data into two streams. Inverse fast Fourier transform (IFFT) and time domain processing may be performed separately on each stream. The streams may then be mapped onto the two channels, and the data may be transmitted. At the receiver, this mechanism may be reversed, and the combined data may be sent to the medium access control (MAC) layer.

[0051] IEEE 802.11af and 802.11ah support operation in bands below 1 GHz (Sub 1 GHz modes of operation), and the channel operating bandwidths may be reduced relative to those used in IEEE 802.11ac. IEEE 802.11af supports 5 MHz, 10 MHz and 20 MHz bandwidths in the television white space (TVWS) spectrum, and IEEE 802.11ah supports 1 MHz, 2 MHz, 4 MHz, 8 MHz and 16 MHz bandwidths using non-TVWS spectrum. In embodiments,

IEEE 802.11ah may support meter type control (MTC) devices in a macro coverage area, and these devices may have limited capabilities, including support for only limited bandwidths, but may also have very long battery life.

[0052] WLAN systems that support multiple channels and channel widths, such as IEEE 802.11n, 802.11c, 802.11af, and 802.11ah systems, may include a channel that is designated as the primary channel. The primary channel may have a bandwidth that is equal to the largest common operating bandwidth supported by all STAs in the BSS. The bandwidth of the primary channel may, therefore, be limited by the STA in the BSS that supports the smallest bandwidth operating mode. In IEEE 802.11ah systems, for example, the primary channel may be 1 MHz wide if there are STAs, such as MTC type devices, in the BSS that only support a 1 MHz mode, even if the AP and other STAs in the BSS are capable of supporting a 2 MHz, 4 MHz, 8 MHz, 16 MHz, or other channel bandwidth operating mode. All carrier sensing and network allocation vector (NAV) settings may depend on the status of the primary channel. For example, if the primary channel is busy due, for example, to a STA that only supports a 1 MHz operating mode transmitting to the AP, then all available frequency bands may be considered busy even though the majority of them remain idle and available.

[0053] In the United States, frequency bands that are available for use by IEEE 802.11ah are from 902 MHz to 928 MHz. In Korea, the bands available for such use are from 917.5 MHz to 923.5 MHz. In Japan, the bands available for such use are from 916.5 MHz to 927.5 MHz. Thus, the total bandwidth available for use by IEEE 802.11ah is from 6 MHz to 26 MHz, depending on the country code.

[0054] IEEE 802.11 has begun exploring the possibility to enhance the quality of service all users experience for a broad spectrum in many usage scenarios, including high-density scenarios in the 2.4 GHz and 5 GHz band (high efficiency WLAN (HEW)). HEW may aid in improving conditions for dense deployments of APs, STAs and associated radio resource management (RRM) technologies. Potential applications for HEW include emerging usage scenarios, such as data delivery for stadium events, and high user density

scenarios, such as train stations or enterprise/retail environments, and also evidence an increased dependence on video delivery and wireless services for medical applications. HEW may enhance the performance of IEEE 802.11 networks to address spectral efficiency, area throughput, robustness to collisions, and interference in densely deployed systems. To improve spectral efficiency, for example, multi-user simultaneous transmission, including OFDMA and MU-MIMO transmissions for both downlink and uplink, may be adopted.

[0055] DL MU-MIMO may allow an AP to transmit multiple data streams to multiple STAs simultaneously over the same frequency band and may enable high transmission rates (e.g., gigabit transmission rates). However, in order to facilitate this spectrally-efficient simultaneous transmission feature, accurate DL CSI is needed at the transmitting device (or network node or beamformer (BFer)), such as the AP, for use by a precoder to suppress co-channel interference (CCI).

[0056] The transmitter may acquire CSI based on different feedback approaches, including, for example, explicit and implicit feedback. Using implicit feedback, the receiver may send a sounding sequence, and the transmitter may estimate the CSI based on the sounding sequence. Implicit feedback assumes that the physical channel is reciprocal. However, the assumption may not actually be true in practice because the effective baseband channel observed by the receiver (or network node or beamformee (BFee)) is a combination of the reciprocal physical channel and the non-reciprocal radio frequency (RF) hardware devices, such as amplifiers and mixers, at both the transmitter and the receiver. An efficient calibration may, therefore, be required to compensate the difference between the uplink (UL) and DL effective channels. Thus, although the implicit CSI feedback approach consumes a relatively small overhead, the calibration process itself requires a considerably large overhead in order to provide accurate calibration results. Further, interferences experienced by the transmitter and the receiver may generally not be the same and may not be easily compensated for by the calibration.

[0057] Using explicit feedback, the receiver may explicitly feed the CSI back to the transmitter. The transmitter may, for example, send sounding frames to the receiver for the receiver to estimate the DL CSI. After compression and quantization, the receiver may feed the quantized and compressed DL CSI back to the transmitter.

[0058] By way of example, DL MU-MIMO in IEEE 802.11ac supports up to four users, and each user may have up to four space-time streams (STSs) with the limitation that the total number of STSs may not exceed eight. With DL MU-MIMO, a transmitter may concurrently transmit to multiple receivers, where the receivers are separated from each other in the spatial domain. The transmitter may need to use a spatial domain MU precoder to eliminate CCI between receivers.

[0059] In this example, to provide CSI feedback to the transmitter, the receiver may first estimate the channel matrix using frequency domain channel estimation based on the received long training field (LTF). For example, let $\hat{H}_m^{DL}(k)$ (with size $N_r \times N_t$, where N_r and N_t are the numbers of receive and transmit antennas in DL transmission, respectively) be the estimated channel matrix on the k^{th} subcarrier at the m^{th} receiver. Singular value decomposition (SVD) may be applied on the estimated channel matrix, $\hat{H}_m^{DL}(k)$, as follows:

$$\hat{H}_m^{DL}(k) = U_m(k) \cdot S_m(k) \cdot V_m'(k) \quad (1),$$

where $S_m(k)$ is the diagonal singular value matrix containing the singular value in a decreasing order on the diagonal, $U_m(k)$ is the left singular matrix containing the left singular vectors in corresponding order, and $V_m(k)$ is the right singular matrix containing right singular vectors in the same order.

[0060] $V_m(k)$ may then be compressed in the form of angles and fed back to the transmitting using initialization, realization and diagonalization. For initialization, the last row of $V_m(k)$ may be made to become non-negative real values by post-multiplying $V_m(k)$ by a proper diagonal matrix, $B(k)$, which may be parameterized by N_r angles $\theta_1 \ \theta_2 \ \cdots \ \theta_{N_r}$. Then, $V_m(k)$ may be updated. For realization, the first column of $V_m(k)$ may be made to become non-negative real values by pre-multiplying $V_m(k)$ by a proper diagonal

matrix, $C_1(k)$, which may be parameterized by $N_t - 1$ angles $\phi_{1,1} \ \phi_{2,1} \ \dots \ \phi_{N_t-1,1}$. Then, $V_m(k)$ may be updated. For diagonalization, $V_m(k)$ may be pre-multiplied by a Givens rotation matrix $G_{2,1}$ and overwrite $V_m(k)$. $G_{2,1}$ may be obtained by replacing the first 2×2 sub-matrix of the identity matrix by the following matrix:

$$G_{2,1}^s = \begin{bmatrix} \cos(\psi_{2,1}) & \sin(\psi_{2,1}) \\ -\sin(\psi_{2,1}) & \cos(\psi_{2,1}) \end{bmatrix} \quad (2).$$

As a result, the second entry in the first column may become zero. The pre-multiplication matrix may be parameterized by the angle $\psi_{2,1}$. Realization may be repeated until all entries in the first column (except the diagonal entry) become zero. Initialization, realization and diagonalization may be repeated for all columns until all entries in all columns (except the diagonal entries) become zero.

[0061] Using the initialization, realization and diagonalization, an $N_t \times N_r$ semi-unitary matrix $V_m(k)$ may be decomposed in the form of angles. IEEE 802.11ac requires that only the angles ϕ 's and ψ 's be fed back to the transmitter. Two quantization choices are specified: (i) Type 0: 5 bits for ψ 's and 7 bits for ϕ 's and (ii) Type 1: 7 bits for ψ 's and 9 bits for ϕ 's. Since this feedback is for each sub-carrier, IEEE 802.11ac also allows grouping of either 1, 2 or 4 sub-carriers in a group in order to reduce the feedback overhead. The group length may be defined by $n_g = [1, 2, 4]$.

[0062] In addition to the channel feedback as described above, in order to derive precoder matrices for MU-MIMO, the signal to noise ratio (SNR) per carrier may also need to be reported for each receiver. This may be done by reporting the average SNR across carriers as well as the delta-SNR, which is the difference in SNR from the mean for each carrier. As a result, the precoder matrix for the m^{th} STA $F_m(k)$ may be determined by the transmitter using the channel matrices' information compressed in the form of angles, $V_m(k)$, with SNR information from the receiver, m , ($m = 1, 2, \dots, N_{user}$).

[0063] The explicit CSI feedback procedure may provide accurate CSI feedback because the DL channel estimation may include the effects of onboard radio frequency (RF) hardware components. However, it may also

require a large amount of radio resources to achieve high quality CSI feedback due to the fact that the CSI, for each subcarrier in a MIMO system, is generally expressed as a complex matrix, which is fed back to the transmitter per subcarrier. Thus, even using data compression, a large amount of complex numbers must be fed back to the transmitter. This may be especially true when the number of transmit and receive antennas and the number of subcarriers are large. Further, to send these complex numbers back to the transmitter, additional MAC and physical layer (PHY) headers may be needed. Thus, a large feedback overhead may be required in the explicit feedback approach for providing high quality CSI to the transmitter.

[0064] Embodiments described herein provide for efficient approaches to CSI feedback that may significantly reduce overhead associated with the feedback and provide high spectral efficiency. While examples provided above describe CSI feedback with regard to specific IEEE 802.11 specifications, and embodiments described herein are illustrated with respect to a modified IEEE 802.11ac frame structure, the embodiments described herein may be used with any wireless technology, including, for example, other IEEE 802 specification-compliant devices and systems, including Time Division Duplex (TDD) and/or Frequency Division Duplex (FDD) systems, and 5G technologies. Numerically simulated results show that the embodiments described herein may achieve the same performance as the above-described explicit feedback procedures but with a much lower overhead. Embodiments described herein may be applicable with respect to all types of beamforming, including, for example SU beamforming and MU-MIMO.

[0065] FIG. 2 is a signal diagram 200 of an example CSI feedback procedure for MU-MIMO. In the example illustrated in FIG. 2, a beamformer (BFer) 202 is associated with a number of beamformees (BFees) 204 and 206. In embodiments, the BFer 202 may select a group of any number of BFees, such as 204 and 206, for DL-MU-MIMO transmission.

[0066] The BFer 202 may transmit a null data packet announcement (NDPA) frame 208. The NDPA frame 208 may be used to gain control of the channel and may identify intended BFees 204 and 206 by their addresses and

include a requested CSI feedback type, such as explicit, implicit and/or precoded CSI feedback, and granularity of the CSI feedback. In response to receiving the NDPA frame 208, the BFees 204 and 206 may prepare for performing channel estimation and preparing the requested feedback. Other BFees with addresses that are not included in the NDPA frame 208 may defer channel access and may hibernate.

[0067] The BFER 202 may follow the NDPA 208 with an NDP sounding packet 210. The NDP 210 may include training fields that the BFees 204 and 206 may analyze to calculate the channel response $H_1^{DL}(k)$ and $H_2^{DL}(k)$, respectively, where k is the subcarrier index.

[0068] In embodiments, n_t and n_r respectively denote the numbers of transmit and receive antennas in a MIMO OFDM system, and each of the n_t antennas in the transmitter may transmit a channel sounding signal to the receiver. The n_t sounding signals may be transmitted sequentially to avoid self-interferences. In this manner, the receiver may estimate the CSI corresponding to the transmit antenna and all n_r receive antennas. Thus, the entire $n_r \times n_t$ CSI estimation process may require n_t training symbols. In other embodiments, the n_t sounding signals may be more practically transmitted simultaneously in order to evenly distribute the transmit power to all transmit antennas in all times. Thus, there may be n_t spatial data streams, where each data stream may be transmitted by one of the n_t transmit antennas.

[0069] In order to mitigate self-interferences, an orthonormal mapping matrix may be used for precoding the n_t data streams. Further, in order to enable the receiver to estimate the $n_r \times n_t$ CSI, each spatial data stream may include n_t training symbols. An example is provided below, where the n^{th} training symbol of the i^{th} spatial stream in the time domain may be:

$$s_{in}(t) = C \sum_{k=k_1}^{k_2} A_{in} c_k \exp(j2\pi k \Delta_F (t - T_{GI} - T_{CS}^i)) \quad (3),$$

where $1 \leq i, n \leq n_t$ and k is the subcarrier index with $k_1 \leq k \leq k_2$. C is a normalization constant so that the transmit power constraints may be satisfied. $A = [A_{in}]_{n_t \times n_t}$ is an orthogonal mapping matrix so that the CSI with

respect to different transmit/receive antenna pairs may be conveniently separated and estimated at the receiver. c_k is the frequency-domain training code. Δ_F is the frequency spacing. T_{GI} is the guard time interval between adjacent symbols to mitigate the inter-symbol interference. T_{CS}^i is the cyclic shift for the i^{th} spatial data stream to impose different phase shifts for different subcarriers and/or spatial data streams.

[0070] Since the n_t spatial data streams may be simultaneously transmitted, the k^{th} subcarrier component of the n^{th} received symbol at the j^{th} receive antenna may be expressed as in the frequency domain as:

$$Y_{jn}(k) = C c_k \sum_{i=1}^{n_t} A_{in} H_{ji}(k) \exp(-j2\pi k \Delta_F T_{CS}^i) + Z_{jn}(k) \quad (4),$$

where $1 \leq j \leq n_r$, $H_{ji}(k)$ is the channel transfer function from the i^{th} transmit antenna to the j^{th} receive antenna and $Z_{jn}(k)$ is the received noise at the j^{th} receive antenna for the k^{th} subcarrier.

[0071] The equivalent channel transfer function may be defined as $\tilde{H}_{ji}(k) = H_{ji}(k) \exp(-j2\pi k \Delta_F T_{CS}^i)$, and (4) may be rewritten in matrix form as:

$$Y(k) = C c_k \tilde{H}(k) A + Z(k) \quad (5),$$

where various matrices are defined below:

$$Y(k) = [Y_{jn}(k)]_{n_r \times n_t}, \quad \tilde{H}(k) = [\tilde{H}_{ji}(k)]_{n_r \times n_t}, \quad Z(k) = [Z_{jn}(k)]_{n_r \times n_t} \quad (6).$$

[0072] $s_{in}(t)$ may be known to the receiver, and equation (5) may be solved in various ways to estimate $\tilde{H}(k)$ at the receiver. A zero forcing solution is shown below:

$$\tilde{H}(k) \approx \bar{H}(k) = Y(k) A^{-1} \frac{1}{C c_k} \quad (7),$$

where the statistics of noise may not be needed. Then, the estimate of CSI $H_{ji}(k)$ may be obtained from $\bar{H}(k)$ as

$$\bar{\bar{H}}(k) = \bar{H}(k) P(k), \quad (8)$$

$$P(k) = \text{diagonal}[p_{ii}(k)], p_{ii}(k) = \exp(j2\pi k \Delta_F T_{CS}^i).$$

[0073] To send complex analog information to the receiver based on the channel estimation, the transmitter may transmit the following information carried in symbols right after transmitting the channel sounding symbols:

$$\hat{s}_{il}(t) = D_l \sum_{k=k_1}^{k_2} B_{il}(k) c_k \exp(j2\pi k \Delta_F (t - T_{GI} - T_{CS}^i)), \quad (9)$$

where $1 \leq i \leq n_t$ and $1 \leq l \leq n_l$. $B_{il}(k)$ is the complex information to be transmitted by the i^{th} transmit antenna, and the range of symbol index l , n_l , is determined by the amount of information to be transmitted. D_l is the normalization constant so that the transmit power constraints may be satisfied. Unlike the normalization constant C in (3), D_l in (9) is l -dependent because $B_{il}(k)$ is arbitrary. Both B_{il} and D_l may not be known to the receiver.

[0074] As shown in (6), the k^{th} subcarrier component of the l^{th} received symbol at the j^{th} receive antenna may be expressed as in the frequency domain as:

$$\hat{Y}_{jl}(k) = D_l c_k \sum_{i=1}^{n_t} B_{il}(k) H_{ji}(k) \exp(-j2\pi k \Delta_F T_{CS}^i) + \hat{Z}_{jl}(k) \quad (10),$$

where $\hat{Z}_{jl}$ is the received noise, and the channel transfer function $H_{ji}(k)$ may be assumed to remain unchanged during the period of channel estimation and analog information transmission. Equation (10) may then be written in matrix form as:

$$\hat{Y}(k) = c_k \tilde{H}(k) B(k) D + \hat{Z}(k) \quad (11),$$

where various matrices are defined below:

$$\hat{Y}(k) = [\hat{Y}_{jl}(k)]_{n_r \times n_l}, B(k) = [B_{il}(k)]_{n_t \times n_l}, \quad (12). \\ D = \text{diagonal}[D_l]_{n_l \times n_l}, \hat{Z}(k) = [\hat{Z}_{jn}(k)]_{n_r \times n_t}$$

[0075] Equation (11) may be solved in various ways to estimate $\mathbf{B}(k)\mathbf{D}$ if $\tilde{\mathbf{H}}(k)$ is approximated by the CSI estimate $\bar{\mathbf{H}}(k)$. A zero forcing solution is shown below:

$$\mathbf{B}(k) \approx \frac{1}{c_k} \bar{\mathbf{H}}(k)^+ \hat{\mathbf{Y}}(k) \mathbf{D}^{-1} \quad (13).$$

[0076] Here, $\bar{\mathbf{H}}(k)^+$ is a pseudo inverse of $\bar{\mathbf{H}}(k)$ if $\bar{\mathbf{H}}(k)$ is not a square matrix. To have a unique estimation from (11), $n_r \geq n_t$, in (13), the unknown $\mathbf{D}$ may be transmitted to the receiver from the transmitter by a conventional digital data transmission scheme.

[0077] Referring back to FIG. 2, on a condition that the intended BFees receive the NDPA and NDP frames, the BFees may estimate the MIMO channel and generate a CSI feedback frame 212. In embodiments, n_A and n_S denote the numbers of antennas in the BFer and BFee, respectively. It may be assumed that $n_A \geq n_S$. First, the DL MIMO CSI may be estimated at the BFee. The $n_S \times n_A$ DL MIMO CSI matrix and its estimation may be denoted as $\mathbf{H}^{DL}(k)$ and $\bar{\mathbf{H}}^{DL}(k)$, respectively. Following the channel estimation process described above, $\bar{\mathbf{H}}^{DL}(k)$ may be obtained using (8), where $n_t = n_A$ and $n_r = n_S$.

[0078] The equivalent UL MIMO CSI may then be estimated. The $n_A \times n_S$ UL MIMO CSI matrix may be denoted as $\mathbf{H}^{UL}(k)$. Then the equivalent UL MIMO CSI matrix in (6) may be given as $\tilde{\mathbf{H}}^{UL}(k) = \mathbf{H}^{UL}(k) \mathbf{P}^{-1}(k)$, where $\mathbf{P}(k)$ is defined in (8). Using the procedure described above, the estimate of $\tilde{\mathbf{H}}^{UL}(k)$ may be given as $\bar{\mathbf{H}}^{UL}(k)$ in (7). Here, $n_t = n_S$ and $n_r = n_A$.

[0079] The procedure described above for information transmission may be applied to feed back the DL MIMO CSI estimate $\bar{\mathbf{H}}^{DL}(k)$. Here, $n_t = n_S$ and $n_r = n_A$. Thus, the dimension of the analog information matrix $\mathbf{B}(k)$ in (11) may be $n_S \times n_S$. If $n_S = n_A$, $\mathbf{B}(k) = \bar{\mathbf{H}}^{DL}(k)$. Then, $\bar{\mathbf{H}}^{DL}(k)$ may be estimated using (13). If $n_S < n_A$, $\mathbf{B}(k)$ may only be part of $\bar{\mathbf{H}}^{DL}(k)$. Therefore, the information transmission process described above may need to be repeated until the entire $\bar{\mathbf{H}}^{DL}(k)$ is fully transmitted and estimated using (13).

[0080] In embodiments, to generate the CSI feedback frame 212, the BFees may generate a preamble with signal (SIG) fields and LTF fields. In the SIG fields, the BFee may signal the CSI feedback frame or the frame including CSI feedback information. The LTF fields may include N_{r2} LTF symbols, where N_{r2} is the number of transmit antennas of the BFee. The BFee may quantize the normalization factors and include them in the data body field.

[0081] The BFee may use N pair of PHE-STF/PHE-LTF, PVHF-STF/PVHF-LTF or other types of STF/LTF fields to feed back the CSI, where $N = \left\lfloor \frac{K1 \times N_{r1} \times N_t}{K2 \times N_{r2}} \right\rfloor$. $K1$, N_{r1} , and N_t are the number of subcarriers, number of receive antennas and number of transmit antennas of the CSI being fed back, respectively. $K2$ and N_{r2} are the number of subcarriers and the number of transmit antennas utilized by the BFee to feedback the CSI feedback frame. For the n^{th} pair, $n=1, \dots, N$, the PHE-STF and PHE-LTF may be precoded using $K2 N_{r2} \times 1$ vectors, one on each sub-carrier. A cyclic shift diversity (CSD) scheme may be applied on both the PHE-STF and PHE-LTF fields. For MU-MIMO, this may be repeated for all intended BFees. More details about the CSI precoding feedback frame are provided below with respect to FIG. 6.

[0082] BFee 204 may feed the CSI corresponding to $H_1^{DL}(k)$ back to the BFer 202 in the feedback frame 212. The BFer 202 may then poll the BFee 206 with a poll frame 214 to request the CSI feedback from the BFee 206. In response to the poll frame 214, the BFee may feed the CSI corresponding to $H_2^{DL}(k)$ back to the BFer 202 in a feedback frame 216. Although not illustrated in FIG. 2, the BFer 202 may continue to poll any additional BFees addressed in the NDPA 208 until feedback frames have been received from all of the addressed BFees.

[0083] On a condition that the BFer 202 receives the CSI feedback frames 212, 216, the BFer 202 may estimate the physical channel using the LTF in the preamble, retrieve normalization factors (NFs) by detecting the data body field in the CSI feedback frame 216, estimate the effective channel precoded with CSI matrices using the PHE-LTF, PVHF-LTF, or other type of LTF fields and retrieve the CSI information fed back from the BFee. More

detailed procedures for such physical channel estimation and retrieval of the fed back CSI information are described below.

[0084] In embodiments, the BFER 202 may design a precoding matrix for each subcarrier based on the fed back CSI, $H_1^{DL}(k)$ and $H_2^{DL}(k)$. A linear precoder, such as a block diagonalization (BD) precoder or max-signal-to-leakage-and-noise-ratio (max-SLNR) precoder may be used. The BFER 202 may then transmit precoded MU-MIMO packets to BFees 204 and 206 (218). LTFs and data packets may need to be precoded using the same precoder so that the precoded virtual channel may be estimated at each BFEE. More details about how the BFER 202 may design the precoder are provided in embodiments below. Each BFEE 204, 206 receiving a data transmission 218 may send an acknowledgement (ACK) 220, 222 for the transmission 218 on a condition that it is successfully received and decoded.

[0085] FIG. 3 is a signal diagram 300 of an example CSI feedback procedure for SU beamforming, which is similar to the example described above for DL-MU-MIMO except that only one BFEE 304 is involved. In particular, in the example illustrated in FIG. 3, the BFER 302 transmits an NDPA frame 306 and an NDP sounding packet 308 to the BFEE 304. In response, the BFEE 304 sends a feedback frame 310. Based on the feedback frame 310, the BFER 302 retrieves the CSI feedback and transmits a data transmission 312 to the BFEE 304. The BFEE 304 sends an ACK 314 if the data transmission 312 is successfully received and decoded.

[0086] FIG. 4 is a diagram of an example NDPA frame 400. The example NDPA frame 400 illustrated in FIG. 4 includes a frame control field 402, a duration field 404, an address region 406, a sounding sequence number (SSN) field 410, a STA or BFEE information region 412 and a frame check sequence (FCS) field 416. The frame control field 402 may specify one or more control elements that may be used to process the frame. The duration field 404 may specify an estimated time needed to complete the signaling exchanges and the data delivery described above with respect to FIG. 2. The address region 406 may specify the medium access control (MAC) address of one or more STAs or BFEEs. In the example illustrated in FIG. 4, two STAs

are specified, and the address region 406 includes STA 1 information field 408A and STA 2 information field 408B. In an embodiment where information is multicast to more than one STA, the STA 1 information field 408A may specify the receiving address for the multicast transmission and the STA 2 information field 408B may specify the transmitting address for the multicast transmission. The FCS field 416 may provide cyclic redundancy check (CRC) for the entire frame 400.

[0087] The SSN field 410 may specify the sounding sequence number associated with the current sounding. The STA or BFee information region 412 may include information for one or more receiving BFees or STAs. In the example illustrated in FIG. 4, two STAs are specified, the region 412 includes two STA information fields 414A and 414B. In the case of K receiving STAs, the region 412 may include K STA information fields 414. An example STA information field 414 is illustrated in FIG. 5.

[0088] FIG. 5 is a diagram 500 of an example BFee or STA information field 414. The example field 414 includes an association ID 502, a feedback type 504 and an Nc index 506. The association ID 502 may be the association ID of the BFee or STA is expected to process the following NDP frame and prepare for CSI feedback. The feedback type 504 specifies the type of feedback requested. In embodiments, the requested feedback type 504 may be implicit feedback, explicit compressed feedback, or precoding feedback. The Nc index 506 may specify a rank order requested for the feedback.

[0089] FIG. 6 is a diagram of a CSI feedback frame 600 for precoding feedback. The CSI feedback frame 600 may be used by a BFee to send precoding-based CSI feedback to a BFer, as described above with respect to FIGs. 2 and 3. For MU-MIMO, where a BFer may communicate with multiple BFees, the CSI feedback frames may be sent by all or some of the BFees.

[0090] The example CSI feedback frame 600 includes a preamble 602, a data body 624, and a pre-coded appendix 622. In the example illustrated in FIG. 6, the preamble 602 uses a very high throughput (VHT) preamble. However, other preamble formats, such as HE, and other formats, may be used as long as they are suitable for use in estimating the PHY channel.

[0091] In the example illustrated in FIG. 6, the preamble 602 includes VHT-LTF fields 618A - 618B in a VHT-LTF region 616, which the BFER may use to estimate the PHY channel without precoding. The number of VHT-LTF fields 618 included in the VHT-LTF region 616 may depend on the number of antennas used to precode the CSI. For example, if all of the N_r antennas are used to transmit the CSI feedback frame, N_r VHT-LTF fields 618 may be included in the VHT-LTF region 616. In the illustrated example, n_s is the required number of VHT-LTF symbols according to the number of space time streams. The preamble 602 may be generated, for example, based on IEEE 802.11ac to provide accurate channel estimation for the UL transmission, although other types of preambles, IEEE 802 or otherwise, may also be generated consistent with the embodiments described herein.

[0092] The illustrated preamble 602 also includes VHT-SIG fields 610 and 612. These fields may indicate the precoding based CSI feedback frame and the length of extra precoded CSI feedback reference signals (e.g., precoded VHT-STF (PVHT-STF) and PVHT-LTF fields 626, 628).

[0093] The data body field 624 may follow the preamble and may include data, control or other management information. In embodiments, the data body field may also carry the quantized NFs.

[0094] The illustrated precoded appendix 622 includes a number of PVHT-STF fields 626 and PVHT-LTF fields 628. These fields may carry the precoded CSI matrices. The number of PVHT-STF and PVHT-LTF fields 626, 628 used may depend on the size of the CSI information to be fed back. For example, for an OFDM system, if $K1 N_{r1} \times N_t$ CSI matrices are to be fed back to the BFER using $K2$ sub-carriers and with N_{r2} antennas available, the BFER may use $N = \left\lceil \frac{K1 \times N_{r1} \times N_t}{K2 \times N_{r2}} \right\rceil$ pair of PVHT-STF and PVHT-LTF symbols 626, 628. Each pair of PVHT-STF and PVHT-LTF 626, 628 may be precoded with up to $K2 N_{r2} \times 1$ CSI vectors. The PVHT-STF fields 626 may be used to adjust automatic gain control (AGC), and the PVHT-LTF fields 628 may include the precoded reference symbols.

[0095] In embodiments, the PVHT-LTF symbols 628 carry the normalized estimated DL channel matrix, $\bar{\bar{H}}_m^{DL}(k)$, and may be generated by

setting the value of B and D in equation (10) as follows. Using $n_A = 2n_S$ as an example, the feedback approach described above may need to be performed twice. The $n_S \times n_A$ $\bar{\bar{H}}_m^{DL}(k)$ matrix may be partitioned into two $n_S \times n_S$ matrices $\bar{\bar{H}}_m^{DL}(k)'$ and $\bar{\bar{H}}_m^{DL}(k)''$. Then, the $B(k)'$ in the first feedback may be equal to $\bar{\bar{H}}_m^{DL}(k)'$ and the $B(k)''$ in the second feedback may be equal to $\bar{\bar{H}}_m^{DL}(k)''$. The practical implementation is shown in FIG. 6, and the j^{th} PVHT-LTF symbol contains the j^{th} column of $\bar{\bar{H}}_m^{DL}(k)$ and there are n_A PVHT-LTF symbols. Then the first feedback precoding matrix $B(k)'$ may be carried by the first n_S PVHT-LTF symbols and the second feedback precoding matrix $B(k)''$ may be carried by the second n_S PVHT-LTF symbols. Each PVHT-LTF symbol should be accompanied by a PVHT-STF symbol for AGC since the different PVHT-LTF symbols may not have the same power. The normalization factor $D = \text{diagonal}[D_j]$ may be computed using the equation below:

$$D_j = \frac{1}{\sqrt{\frac{1}{k_2 - k_1} \sum_{k=k_1}^{k_2} \sum_{i=1}^{n_S} \left| [\bar{\bar{H}}_m^{DL}(k)]_{i,j} \right|^2}}$$

$$j = 1, 2, \dots, n_A,$$

where the average over subcarriers k_1 to k_2 may be used. In the example described above, D may be transmitted to the AP in the data body section of the frame illustrated in FIG. 6.

[0096] Embodiments are described below for a BFee to generate and provide a CSI feedback frame, such as the CSI feedback frame 600 for precoding feedback described above, to the BFer, and for the BFer to retrieve a CSI matrix from such a frame 600. The CSI feedback approaches described below may be referred to as precoding based CSI feedback algorithms and may provide accurate CSI feedback with significantly reduced control signaling overhead. These algorithms may be used, for example, for all closed loop precoded transmissions where multiple antennas are used, such as beamforming and MU-MIMO, including WLAN and other technologies, as described above. To implement these algorithms, channel reciprocity may not be assumed.

[0097] FIG. 7 is a flow diagram 700 of an example method of channel estimation and precoding based analog CSI feedback. In the embodiment

illustrated in FIG. 7, a network node receives a sounding frame and a reference sequence from another network node (702). The reference sequence may be known to the network node. The network node may estimate a respective CSI matrix for each of a plurality of subcarriers using the received sounding frame and the reference sequence to generate a plurality of estimated CSI matrices (704). To estimate the channel (704), a BFee network node may compare the received sounding frame and the known reference sequence. For example, let $H^{1 \rightarrow 2}(k)$ be the $N_r \times N_t$ channel matrix on the k^{th} subcarrier from the BFer to the BFee, where N_t is the number of transmit antennas at the BFer, N_r is the number of receive antennas at the BFee, and $k=1 \dots K$, and K is the total number of data sub-carriers. $\hat{H}^{1 \rightarrow 2}(k)$ is the estimated channel matrix obtained at the BFee side.

[0098] The network node may apply each of the plurality of generated estimated CSI matrices as precoded estimated CSI matrices to a feedback packet (706). The estimated CSI matrices may, for example, be a matrices derived from the channel matrices, such as matrices composed of eigenvectors of the channel matrix. For example, on the k^{th} subcarrier, the estimated channel matrix may be $\hat{H}^{1 \rightarrow 2}(k) = (\hat{H}_1^{1 \rightarrow 2}(k) \ \hat{H}_2^{1 \rightarrow 2}(k) \ \dots \ \hat{H}_{N_t}^{1 \rightarrow 2}(k))$, where each component $\hat{H}_{n_t}^{1 \rightarrow 2}(k) = [\hat{H}_{n_t}^1(k) \ \dots \ \hat{H}_{n_t}^{N_r}(k)]^T$, $n_t = 1, \dots, N_t$. The total transmit power of the n_t^{th} precoded OFDM symbol over all data sub-carriers and N_r transmitted antennas may be expressed as:

$$P_{n_t} = \frac{1}{L} \sum_{k=0}^{L-1} \|\hat{H}_{n_t}^{1 \rightarrow 2}(k)\|^2.$$

[0099] From the above, the following may be true: $\hat{H}_{n_t}^{1 \rightarrow 2}(k) = P_{n_t} \bar{\hat{H}}_{n_t}^{1 \rightarrow 2}(k)$, where $\bar{\hat{H}}_{n_t}^{1 \rightarrow 2}(k)$ is the normalized vector, and P_{n_t} is the normalization factor. The BFee may need to feed back both $\bar{\hat{H}}_{n_t}^{1 \rightarrow 2}(k)$ and P_{n_t} , $n_t = 1, \dots, N_t$. In embodiments, the precoding based CSI feedback frame may be aggregated with other data, management or control frames.

[0100] The network node may send the feedback packet to the other network node (708). The feedback packet may include at least one training field carrying the precoded estimated CSI matrices and at least one training field that carries CSI information that is not precoded. Continuing with the

above example, to feed the vectors $\bar{H}_{n_t}^{1 \rightarrow 2}(k)$, $n_t = 1, \dots, N_t$ back to the BFer, the BFer may use the N_r antennas to transmit a precoded reference symbol/pilot $\bar{H}_{n_t}^{1 \rightarrow 2}(k)s_k$ at the n_t^{th} time/frequency slot. Here, s_k is the reference symbol on subcarrier k known to both the transmitter and receiver.

[0101] In this algorithm, the channel matrix estimated on subcarrier k may be precoded on subcarrier k . However, it may be possible to precode the CSI of the k^{th} subcarrier on the n^{th} subcarrier. This may be possible especially when the CSI is estimated on subcarrier set A, while the feedback frame is transmitted on subcarrier set B, and $A \neq B$. In one example using an OFDM system, the BFer may use the same set of subcarriers ($A=B$) to feed back the estimated channel. In the first OFDM symbol, the BFer may transmit $\bar{H}_1^{1 \rightarrow 2}(k)s_k$ on the k^{th} subcarrier. $\bar{H}_2^{1 \rightarrow 2}(k)s_k$ may be transmitted on the second OFDM symbol, and $\bar{H}_{N_t}^{1 \rightarrow 2}(k)s_k$ may be transmitted over the N_t^{th} OFDM symbol. Thus, with N_t OFDM symbols, the BFer may feed back the estimated channel. In another example using an OFDMA system, the BFer may use a subset of subcarriers ($B \subset A$) to feed back the CSI. In this case, the BFer may need to use more OFDM symbols to precode the CSI matrices. In other embodiments, the BFer may feed back the CSI with less granularity. Instead of feeding back the estimated channel matrix on all the subcarriers, the BFer may feed back CSI of pre-selected subcarriers. In another example using an OFDMA system, the BFer may use a larger set of subcarriers to feed back the CSI matrices ($A \subset B$). The BFer may use less OFDM symbols to feed back the CSI matrices.

[0102] To feed the normalization factors (NFs) $\{P_{n_t}, n_t = 1, \dots, N_t\}$ back to the BFer, extra feedback data symbols may be needed to carry the NFs, which are real numbers. In embodiments, quantized NFs may be fed back to the BFer. In other embodiments, a quantized mean value of the NFs may be calculated and fed back to the BFer. The difference between each NF and the mean value may be quantized and fed back to the BFer.

[0103] It should be noted that, in the embodiments described herein, the BFer may need to send extra reference symbols and/or pilots without precoding such that the BFer may use them to estimate the physical MIMO

channel and decode any data signal without precoding. The BFER may obtain the CSI information by detecting the precoding based CSI feedback frame.

[0104] FIG. 8A is a flow diagram 800 of an example method of retrieving a CSI matrix from a precoding based analog CSI feedback packet. In the example illustrated in FIG. 8A, a network node may transmit a sounding frame to another network node (802). The sounding frame may include a reference sequence that is known to the other network node. The network node may receive a feedback packet from the other network node (804). The feedback packet may include a first training field with an estimated CSI matrix applied as a precoding matrix and a second training field that does not have CSI precoded. The network node may retrieve the CSI matrix from the feedback packet (806), for example, by comparing a channel estimated from the first training field with a channel estimated from the second training field.

[0105] In embodiments, the BFER may estimate the physical channel matrix, $\hat{H}^{2 \times 1}(k)$, by detecting reference symbols or pilots (i.e., the reference symbols/pilots that were transmitted without precoding). The BFER may estimate the effective channel by detecting precoded reference symbols/pilots and NFs. In embodiments, the effective channel may be expressed as:

$$He^{2 \times 1}(k) = \text{diag}\left(\frac{1}{\sqrt{P_1}} \quad \frac{1}{\sqrt{P_2}} \quad \cdots \quad \frac{1}{\sqrt{P_{N_t}}}\right) H^{2 \times 1}(k) \bar{\bar{H}}^{1 \times 2}(k).$$

[0106] In this example, the BFER may retrieve the CSI information fed back from the BFER using an equalizer, such as:

$$\hat{\bar{H}}^{1 \times 2}(k) = \text{diag}(\sqrt{P_1} \quad \sqrt{P_2} \quad \cdots \quad \sqrt{P_{N_t}}) \hat{H}^{2 \times 1}(k)^{\dagger} \hat{H} e^{2 \times 1}(k).$$

[0107] Some of the examples described above imply the usage of an OFDM system. However, these examples may be easily generalized to other types of systems by one skilled in the art.

[0108] FIG. 8B is a diagram 850 of the example methods of channel estimation, precoding and retrieving a CSI matrix from a precoding based CSI feedback packet showing more detail. The example illustrated in FIG. 8B shows how overhead can be substantially reduced using the embodiments described herein.

[0109] In the example illustrated in FIG. 8B, a network node, such as an AP 860, performs sounding (862), and another network node, such as a STA 870, performs channel estimation (866) based on the sounding 862. The STA 870 may apply estimated CSI matrices as precoded estimated CSI matrices to a feedback packet 874 (868). In one example, CSI information may be precoded with known symbols, normalized and transmitted over multiple antennas using multiple time slots. The normal channel training sequence may need to be transmitted in another time slot. The STA 870 may send the feedback packet 874 to the AP 860 (872) for CSI retrieval (876).

[0110] By way of example, without precoding, a 4 x 2 channel matrix may be represented by 5 psi and 5 phi angles. If (7, 9) bits are needed to feed back an angle set (phi, psi), 80 bits (5*7 + 5*9) are required. With BPSK and rate 1/2 coding, 160 symbols (2*80) are needed. For a similar configuration, the precoding based CSI feedback described herein may only need four symbols plus some space for normalization factors (two antennas can transmit different coded symbols each time). In another example, without precoding, an 8 x 4 channel matrix may be represented by 22 psi and 22 phi angles. If (7, 9) bits are needed to feed back an angle set (phi, psi), 352 bits (22*7 + 22*9) are required. With BPSK and rate 1/2 coding, 704 symbols (2*352) are needed. For a similar configuration, the precoding based CSI feedback described herein may only need eight symbols plus some space for normalization factors (two antennas can transmit different coded symbols each time). Accordingly, overhead may be substantially reduced.

[0111] Example precoder designs for use with the above-described embodiments are provided. In the DL MU-MIMO scenario, the BFER (with n_A antennas) may simultaneously transmit multiple data streams to multiple co-channel BFers. For simplicity, it may be assumed that the BFers have the same number of data streams, n_{sts} , and have the same number of antennas n_S . Thus, the $n_S \times 1$ receive signal vector for subcarrier k at the m^{th} BFER may be given by:

$$y_m(k) = H_m^{DL}(k)F_m(k)s_m(k) + H_m^{DL}(k) \sum_{n=1, n \neq m}^{n_{user}} F_n(k)s_n(k) + n_m(k) \quad (14)$$

where $F_n(k)$ is a $n_A \times n_{sts}$ precoding matrix for the n^{th} STA, $s_n(k)$ is a $n_{sts} \times 1$ data vector to be transmitted from the AP to the n^{th} user, n_{user} is the number of users, and $n_m(k)$ is the $n_S \times 1$ receive noise vector. It may be assumed that the sources and noises of different users are all independent of each other and zero-mean, the source covariance matrix $\Phi_{s_n}(k) = E(s_n(k)s_n(k)^*) = \sigma_{s_n}^2(k)I_{n_{sts}}$ and the noise covariance matrix: $\Phi_{n_m}(k) = E(n_m(k)n_m(k)^*) = \beta_m(k)I_{n_S}$.

[0112] The second term in equation (14) represents the CCI. To suppress the CCI among the users, based on the knowledge of DL CSI, it may be essential for the AP or BFER to design an optimal MU-MIMO precoding scheme to maximize the output signal-to-interference-plus-noise ratio (SINR) for each user.

[0113] After obtaining the estimated CSI fed back by each BFER, the BFER may design the precoder for the m^{th} BFER as the form of $F_m(k) = F_m^L(k)F_m^R(k)$ by first designing its $n_A \times n_S$ left precoder $F_m^L(k)$ for CCI mitigation and then its $n_S \times n_{sts}$ right precoder $F_m^R(k)$ for performance enhancement. To avoid intra data stream interference for the m^{th} user, $n_A \geq n_S \geq n_{sts}$ may be needed. For mitigating the CCI, the left precoder $F_m^L(k)$ may be chosen as the null space of

$$G_m = [\vec{H}_1^{DL}(k), \vec{H}_2^{DL}(k), \dots, \vec{H}_n^{DL}(k), \dots, \vec{H}_{n_{user}}^{DL}(k)], \quad (15)$$

$$n \neq m, n = 1, 2, \dots, n_{user}$$

where $\vec{H}_n^{DL}(k)$ is the estimate of $H_n^{DL}(k)$ at the BFER. This may be done by making the SVD of A_m :

$$G_m = U_m(k) \cdot S_m(k) \cdot V_m^H(k) \quad (16)$$

and choosing the last n_S columns of $V_m(k)$ as the left precoder, $F_m^L(k)$. The BFER may choose the left precoder for each user according to:

$$H_n^{DL}(k)F_m(k) = H_n^{DL}(k)F_m^L(k)F_m^R(k) \approx 0, \quad (17)$$

$$n \neq m, n = 1, 2, \dots, n_{user}.$$

[0114] If the CSI estimate at the BFER is exact for every n , $\vec{H}_n^{DL}(k) = H_n^{DL}(k)$, the left term in (17) may be exactly zero and there may be no CCI among the users. As a result, for each user, the entire system may be a simple single user MIMO system where $F_m^R(k)$ and $H_m^{DL}(k)F_m^L(k)$ are the equivalent

precoder and channel matrix, respectively. Using (17), (14) can be simplified as:

$$y_m(k) = (H_m^{DL}(k)F_m^L(k))F_m^R(k)s_m(k) + n_m(k) \quad (18).$$

[0115] Based on the knowledge of $H_m^{DL}(k)F_m^L(k)$, the BFER may design $F_m^R(k)$ to optimize the performance of the m^{th} user for subcarrier k subject to some power constraint on $F_m(k)$. Results of performance tests for several conventional precoder design approaches for single-user MIMO systems are described below, including practical minimum mean square error (PMMSE), practical maximum mutual information (PMMI), and practical minimum symbol error rate (PMBER) subject to average total power (ATP) constraint.

[0116] The estimated SLNR for the m^{th} user at the subcarrier k , $SLNR_m(k)$, may be defined as the ratio of the estimated received signal power on the desired user to that leaked to other users plus the noise power:

$$SLNR_m(k) = \frac{\text{Tr}\left(\left(\bar{H}_m^{DL}(k)F_m(k)\right)^H \bar{H}_m^{DL}(k)F_m(k)\right)}{\text{Tr}\left(F_m(k)^H \left(\frac{n_S}{n_{STS}}\beta_m(k)I + \sum_{mn \neq m} \left(\bar{H}_m^{DL}(k)\right)^H \bar{H}_m^{DL}(k)\right)F_m(k)\right)} \quad (19)$$

[0117] According to SLNR criterion, the precoder $F_m(k)$ may be obtained based on the following metric:

$$F_m^{opt}(k) = \arg \max_{F_m(k) \in \mathbb{C}^{n_A \times n_{STS}}} SLNR_m(k) \quad (20)$$

[0118] The CSI feedback approach described herein has been compared with the explicit feedback approach based on CSI feedback overhead and the DL MU-MIMO bit error rate (BER). Three particular cases were investigated: case 1 (BFER has four antennas to transmit data packets to four users, each user having one receive antenna, case 2 (BFER has four antennas to transmit data packets to two users, each user having two receive antennas), and case 3 (BFER has eight antennas to transmit data packets to four users, each user having two antennas).

[0119] Based on the IEEE 802.11n and IEEE 802.11ac protocols, $\sin$ in equation (1) above is a symbol in VHT-LTF. For a 20 MHz bandwidth and $n_A = 4$, the parameters in equation (1) are given below:

$$\begin{aligned}
C &= \sqrt{\frac{1}{n_t 56}}, \quad k_1 = -28, \quad k_2 = 28, \\
\mathbf{A} = [A_{in}] &= \begin{bmatrix} 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \\ -1 & 1 & 1 & 1 \end{bmatrix} \\
[c_k] &= [1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, \\
&\quad 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 0, 1, \\
&\quad -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, \\
&\quad -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1, -1, -1] \\
\Delta_F &= \frac{20 \text{ MHz}}{64} = 312.5 \text{ kHz}, T_{GI} = 0.8 \mu s, \\
[T_{CS}^i] &= [0, -400, -200, -600] \text{ ns}
\end{aligned} \tag{21}$$

[0120] The CSI feedback may be determined by the feedback frame length. It is known that the explicit compressed feedback requires a large overhead since each STA needs to feedback the quantized angles corresponding to a $n_A \times n_S$ complex channel matrix for each group of subcarriers. On the contrary, the proposed approach may be used to convey the same amount of information to the AP using only $2n_A$ PVHT-STFs/LTFs symbols with several additional symbols representing n_A real normalization coefficients for the same group of subcarriers. The overhead of the proposed approach may be small comparing with that of explicit compressed feedback, especially when the dimension of the channel matrix is large. This point will be illustrated by a 20 MHz bandwidth mode using 52 data tones while assuming the AP requires the STA to feedback CSI for each data tone.

[0121] With Givens rotation in explicit compressed feedback, the STA needs to feed back 3, 5 and 13 pairs of angles $\{\phi, \psi\}$ in cases 1, 2 and 3 respectively, for each subcarrier. In addition, average SNR and delta-SNR are required for feedback. Assuming Type 1 feedback, each ψ uses 7 bits and each ϕ uses 9 bits. The average SNR is quantized to 8 bits. The delta-SNRs are quantized to 4 bits and computed for each space-time stream of two subcarriers in this example. Table 1 shows the number of bits needed for the VHT compressed BF field, l_{VHT_BF} , (carrying the angles and average SNR) and MU exclusive BF report field, l_{MU_BF} (carrying delta-SNR).

TABLE 1

	VHT Compressed BF Type1 (l_{VHT_BF})	MU Exclusive BF report (l_{MU_BF})
Case 1	$(7+9)*3*52+8=2504$	$4*30 = 120$
Case 2	$(7+9)*5*52+8=4168$	$4*30*2 = 240$
Case 3	$(7+9)*13*52+8=10824$	$4*30*2 = 240$

[0122] Both the VHT compressed BF field and the MU exclusive beamforming report field may be transmitted in the VHT compressed beamforming frame. Other than the two fields mentioned above, the frame may also include other information, such as a category field (8 bits), a VHT action field (8 bits), and a VHT MIMO control field (24 bits). Since the VHT compressed beamforming frame is an action frame, the 28 bytes overhead due to the MAC header and FCS should also be considered. Assuming that the beamforming feedback frame is transmitted using the most robust mode, which is BPSK and rate $\frac{1}{2}$ coding, the data bits per OFDM symbol are 26 for 20 MHz channel. With the VHT preamble, the preamble length, n_{pre} , for case 1 is 10 OFDM symbols if a single data stream is transmitted; the preamble length, n_{pre} , for case 2 and case 3 is 11 symbols if two data streams are transmitted. Then, the size of the feedback frame in terms of symbols, n_{fdbk} , may be obtained as:

$$n_{fdbk} = \left\lceil \frac{(l_{VHT_BF} + l_{MU_BF} + 24 + 8 + 8 + 28 * 8)}{26} \right\rceil + n_{pre} \quad (22),$$

where $\lceil x \rceil$ is the smallest integer not less than x . The frame size of the explicit compressed feedback for case 1, 2, and 3 are shown in Table 2.

TABLE 2

	Size of the Feedback frame in terms of symbols
Case 1	122
Case 2	191
Case 3	447

[0123] For the proposed CSI feedback, each STA needs to use $2n_A$ symbols to transmit PVHT-STFs/LTFs to feed back channel matrix

information plus several symbols to report the n_A power normalization coefficients, $D_j, j = 1, 2, \dots, n_A$ as shown in Fig. 6. Since the feedback frame may be seen as a normal data frame, the 28 bytes overhead due to MAC header and FCS should be considered. If D_j is transmitted with 8 bits and the frame is transmitted using the most robust mode, which is BPSK and rate $\frac{1}{2}$ coding, the size of the frame in terms of OFDM symbols, n_{fdbk} may be obtained as:

$$n_{fdbk} = \left\lceil \frac{(n_A * 8 + 24 + 8 + 8 + 28 * 8)}{26} \right\rceil + n_{pre} + 2n_A \quad (23).$$

[0124] The frame size of the proposed feedback approach for cases 1, 2, and 3 are shown in Table 3.

TABLE 3

	Size of the Feedback frame in terms of symbols
Case 1	30
Case 2	31
Case 3	40

[0125] Comparing Table 2 with Table 3, the overhead of the embodiments described herein is much smaller than that of the explicit feedback approach, especially when the dimension of the channel matrix is large, such as case 3.

[0126] The BER performance of a DL MU-MIMO transmission using the proposed CSI feedback approach has also been compared with that using the explicit compressed channel feedback approach. For reference, the BER performance using the ideal channel feedback is also described. It may be assumed that the randomly generated channel in each test stays the same for the entire channel sounding and data transmission period. The channel bandwidth is 20 MHz. Each BER point is obtained by averaging over 10^4 tests and the number of symbols is 10^3 in each test. QPSK (or 4QAM) modulation is used.

[0127] For case 1, BD and max-SLNR precoders are used at the AP for ideal scenarios, the embodiments described herein and explicit feedback scenarios. For cases 2 and 3, besides BD and max-SLNR precoders, the BD precoder combined with the PMMSE SU-MIMO precoder are used at the AP

for ideal scenarios, the embodiments described herein and the explicit feedback scenarios. For the scenario based on the embodiments described herein, it may be assumed that the information of power normalization coefficients is transmitted to the AP without errors. For the explicit compressed feedback scenarios, it may be assumed that the information of SNR values is transmitted to the AP without errors.

[0128] FIG. 9 is a graph of the simulation results of DL MU-MIMO with four users where each user has one antenna. FIG. 10 is a graph of the simulation results of case 1 (DL MU-MIMO with two users where each user has two antennas). FIG. 11 is a graph of the simulation results of case 2 (DL MU-MIMO with 4 users and each user has two antennas). The number of data streams in all three cases is the same as the number of receive antennas. It can be seen that, in all three cases, the approach based on the embodiments described herein and the explicit feedback approaches have the same BER performance and both feedback approaches are only slightly worse than the ideal channel feedback approach. The max-SLNR is better than BD in all three CSI feedback approaches for all three cases because BD tends to amplify noise. However, the BD performance improves at high SNRs when it is combined with an optimum single user MIMO joint precoder-decoder design such as PMMSE.

[0129] FIGs. 10 and 11 show that, when SNR is low, max-SLNR works better than BD-PMMSE. However, when SNR is large, BD-PMMSE works better than max-SLNR. The reason may be that, when the SNR is low, the noise enhancement due to the BD approach dominates the CCI effects due to max-SLNR approach, but, when the SNR is high, the CCI affects becomes dominant.

[0130] Although features and elements are described above in particular combinations, one of ordinary skill in the art will appreciate that each feature or element can be used alone or in any combination with the other features and elements. In addition, the methods described herein may be implemented in a computer program, software, or firmware incorporated in a computer-readable medium for execution by a computer or processor. Examples of

computer-readable media include electronic signals (transmitted over wired or wireless connections) and 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 internal hard disks and removable disks, magneto-optical media, and optical media such as CD-ROM disks, and 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, or any host computer.

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CLAIMS

What is Claimed:

1. A network node comprising:
 - an antenna;
 - a processor, operatively connected to the antenna, configured to receive, from another network node, a sounding frame with a reference sequence that is known to the network node,
 - the processor being further configured to estimate at least one channel state information (CSI) matrix using the received sounding frame and the reference sequence to generate at least one estimated CSI matrix,
 - the processor being further configured to apply the at least one generated estimated CSI matrix as at least one precoded estimated CSI matrix to a feedback packet, and
 - the processor being further configured to send the feedback packet to the other network node, the feedback packet including at least one training field carrying the at least one precoded estimated CSI matrix and at least one training field that carries CSI information that is not precoded.
2. The network node of claim 1, wherein the processor is further configured to receive, from the other network node, a null data packet announcement (NDPA) frame, the NDPA frame including an identifier of a requested CSI feedback type, the requested CSI feedback type being one of explicit CSI feedback, implicit CSI feedback and precoding CSI feedback.
3. The network node of claim 1, wherein the processor is configured to estimate a respective CSI matrix for each of a plurality of subcarriers using the receiving sounding frame and the reference sequence to generate a plurality of estimated CSI matrices, and to apply each of the plurality of generated estimated CSI matrices to the feedback packet.

4. The network node of claim 3, wherein the feedback packet includes a preamble and a precoded appendix, wherein the preamble includes the at least one training field that carries the CSI information that is not precoded and the appendix includes the at least one training field carrying the precoded estimated CSI matrices.

5. The network node of claim 4, wherein each of the at least one training field in the appendix is a long training field (LTF) and is configured to carry a plurality of the precoded estimated CSI matrices.

6. The network node of claim 5, wherein the processor is further configured to feed back the CSI using one of the same set of the plurality of subcarriers on which the CSI matrices were estimated, a subset of the plurality of subcarriers on which the CSI matrices were estimated, and a larger set of subcarriers than the set of the plurality of subcarriers on which the CSI matrices were estimated.

7. The network node of claim 1, wherein the at least one generated precoded estimated CSI matrix is normalized, and the feedback packet includes a data body that includes normalization factors used during the normalizing.

8. The network node of claim 1, wherein the network node is an IEEE 802.11 station (STA).

9. The network node of claim 1, wherein the processor is further configured to signal a number of symbols used to carry the at least one precoded CSI matrix in a signaling field of the feedback packet.

10. A method, implemented in a network node, the method comprising:
receiving, from another network node, a sounding frame with a reference sequence that is known to the network node;

estimating at least one channel state information (CSI) matrix using the received sounding frame and the reference sequence to generate at least one estimated CSI matrix;

applying the at least one generated estimated CSI matrix as at least one precoded estimated CSI matrix to a feedback packet; and

sending the feedback packet to the other network node, the feedback packet including at least one training field carrying the at least one precoded estimated CSI matrix and at least one training field that carries CSI information that is not precoded.

11. The method of claim 10, further comprising receiving a null data packet announcement (NDPA) frame, from the other network node, the NDPA frame including an identifier of a requested CSI feedback type, the requested CSI feedback type being one of explicit CSI feedback, implicit CSI feedback and precoding CSI feedback.

12. The method of claim 10, wherein the estimating comprising estimating a respective CSI matrix for each of a plurality of subcarriers using the received sounding frame and the reference sequence to generate a plurality of estimated CSI matrices, and the applying comprises applying each of the plurality of generated estimated CSI matrices as precoded estimated CSI matrices to the feedback packet.

13. The method of claim 12, wherein the feedback packet includes a preamble and a precoded appendix, wherein the preamble includes the at least one training field that carries that CSI information that is not precoded and the appendix includes the at least one training field carrying the precoded estimated CSI matrices.

14. The method of claim 13, wherein each of the at least one training field in the appendix is a long training field (LTF) and is configured to carry a plurality of the precoded estimated CSI matrices.

15. The method of claim 14, wherein the CSI is fed back using one of the same set of the plurality of subcarriers on which the CSI matrices were estimated, a subset of the plurality of subcarriers on which the CSI matrices were estimated, and a larger set of the plurality of subcarriers on which the CSI matrices were estimated.

16. The method of claim 10, wherein the plurality of generated precoded estimated CSI matrices are normalized, and the feedback packet includes a data body that includes normalization factors (NFs) used during the normalizing.

17. The method of claim 10, wherein the network node is an IEEE 802.11 station (STA).

18. The method of claim 10, further comprising signaling a number of symbols used to carry the at least one precoded CSI matrix in a signaling field of the feedback packet.

19. A network node comprising:
an antenna; and
a processor, operatively connected to the antenna, configured to transmit, to another network node, a sounding frame with a reference sequence that is known to the other network node,
the processor being further configured to receive, from the other network node, a feedback packet, the feedback packet including at least one first training field with at least one estimated channel state information (CSI) matrix applied thereto as at least one precoded estimated CSI matrix and at least one second training field that includes CSI information that is not precoded, and
the processor being further configured to compare a channel estimated from the at least one first training field with a channel estimated from the at least one second training field to retrieve at least one CSI matrix.

20. The network node of claim 19, wherein the processor is further configured to transmit, to the other network node, a null data packet announcement (NDPA) frame, the NDPA frame including an identifier of a requested CSI feedback type, the requested CSI feedback type being one of explicit CSI feedback, implicit CSI feedback and precoding CSI feedback.

21. The network node of claim 19, wherein the feedback packet includes a preamble and a precoded appendix, wherein the preamble includes the at least one second training field and the appendix includes the at least one first training field.

22. The network node of claim 21, wherein each of the at least one first training field in the appendix is a long training field (LTF) and is configured to carry a plurality of precoded estimated CSI matrices.

23. The network node of claim 19, wherein the precoding matrices are normalized, and the feedback packet includes a data body that includes normalization factors (NFs) that were used during the normalizing.

24. The network node of claim 19, wherein the network node is an IEEE 802.11 access point (AP).

100

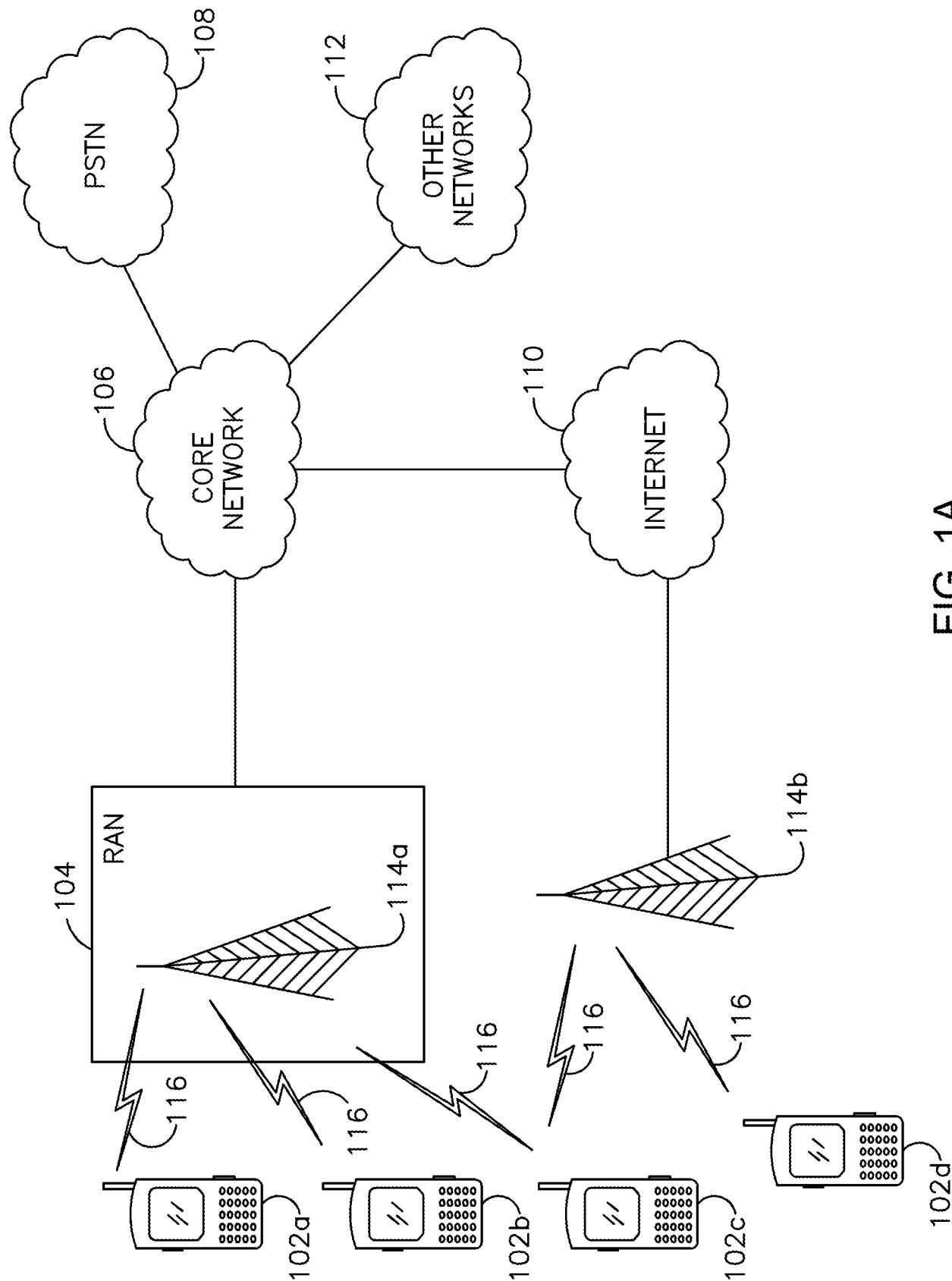


FIG. 1A

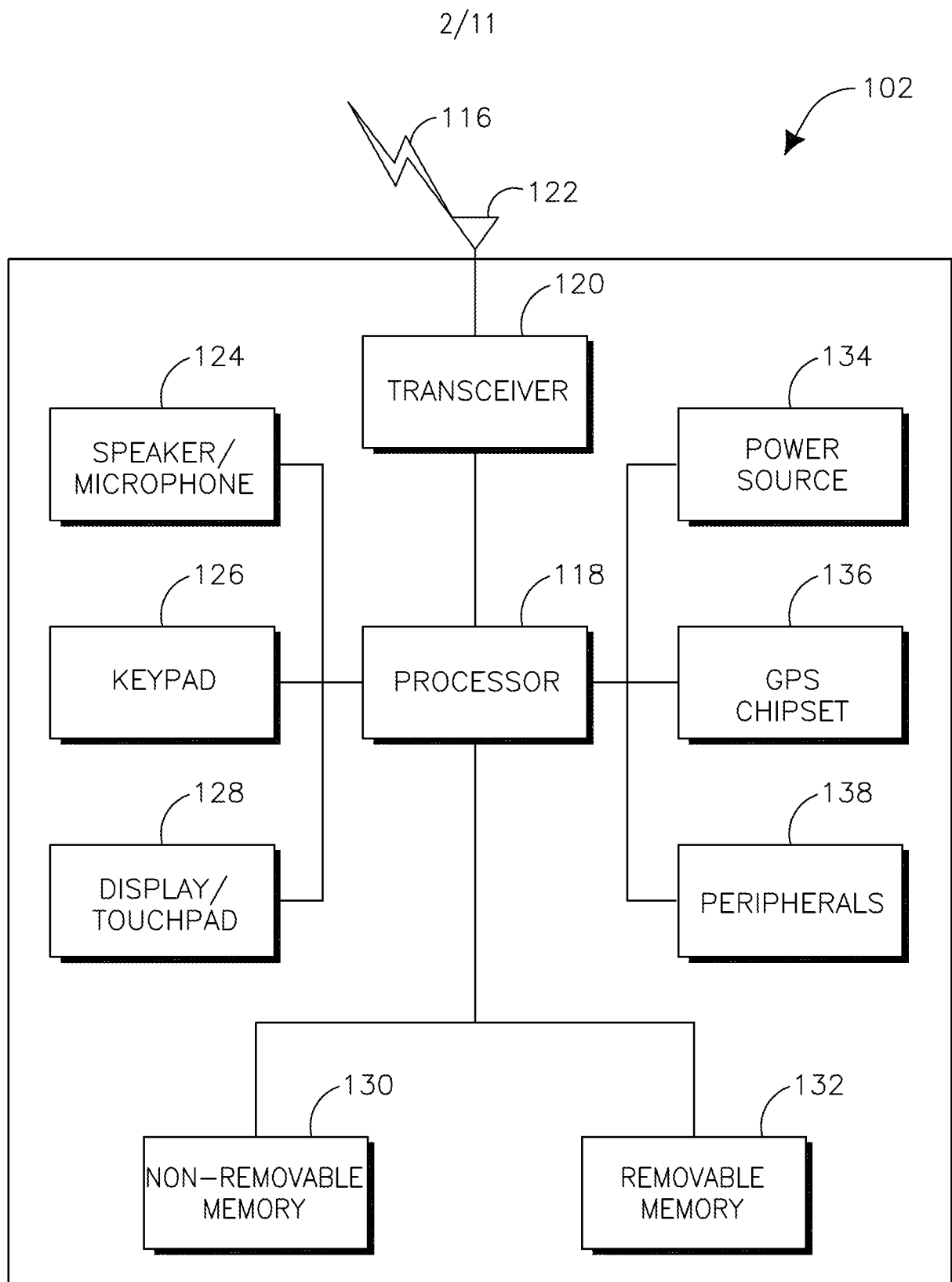


FIG. 1B

3/11

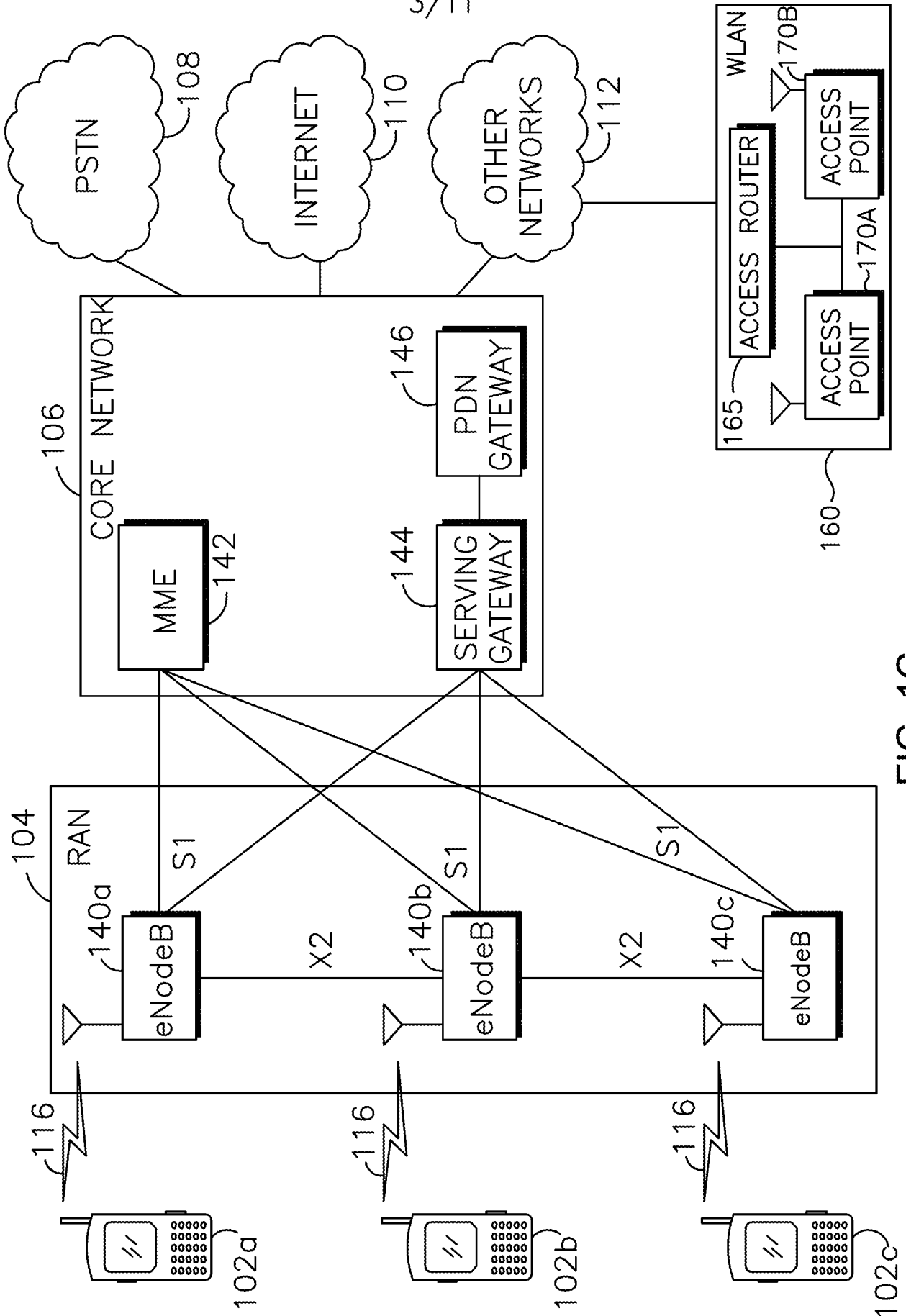


FIG. 1C

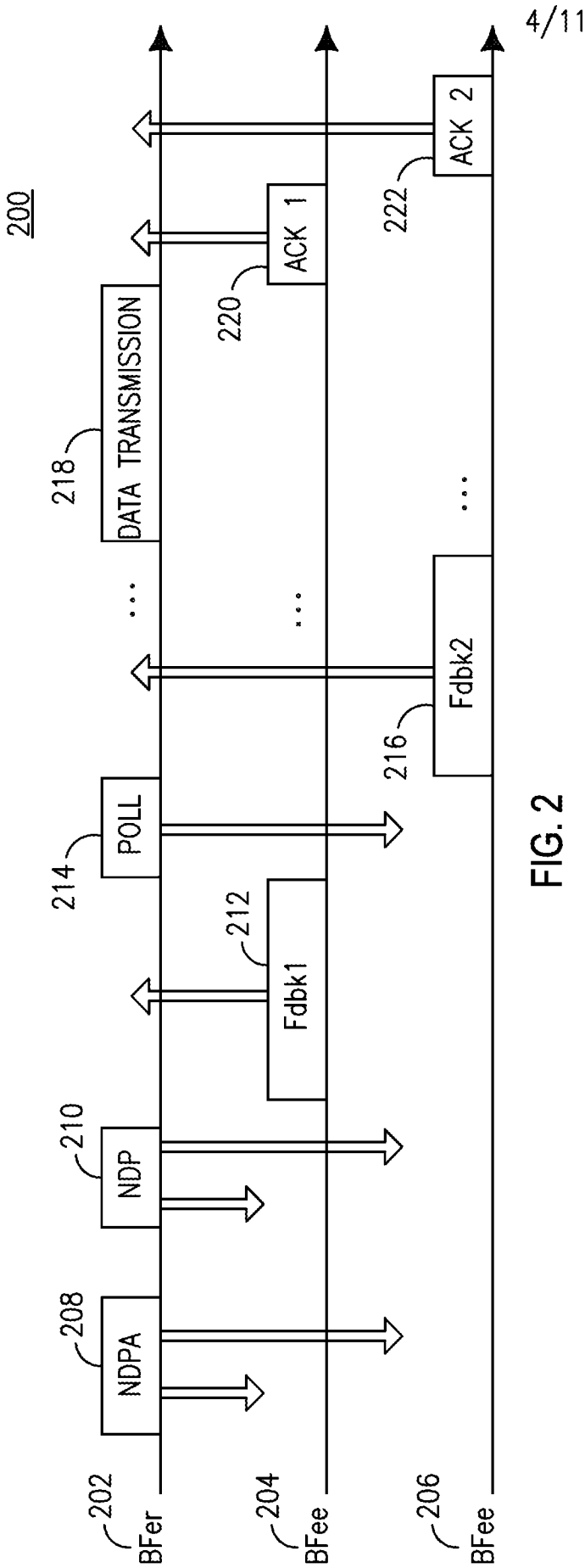


FIG. 2

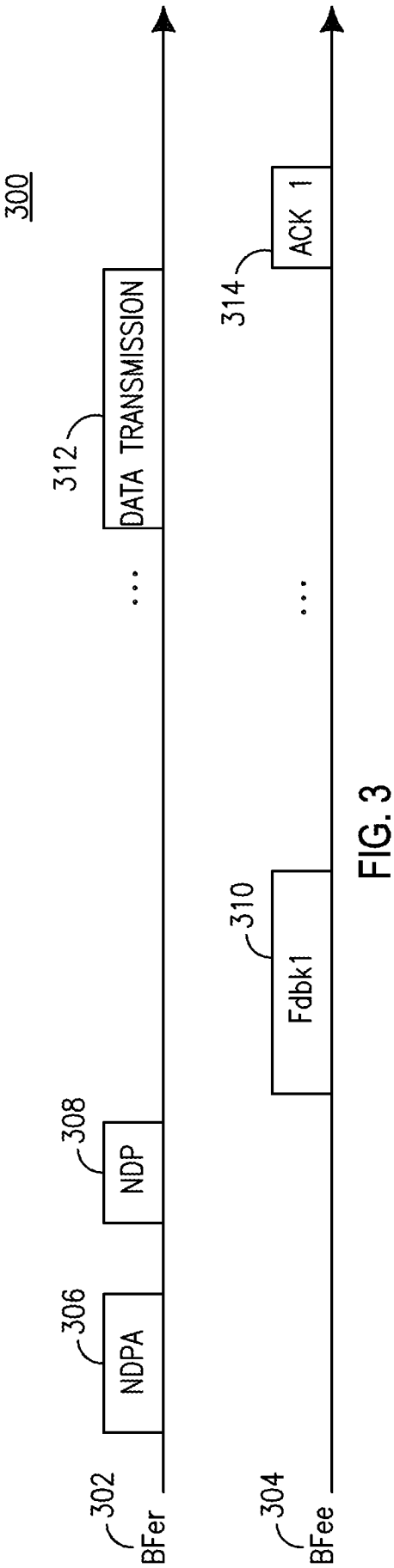


FIG. 3

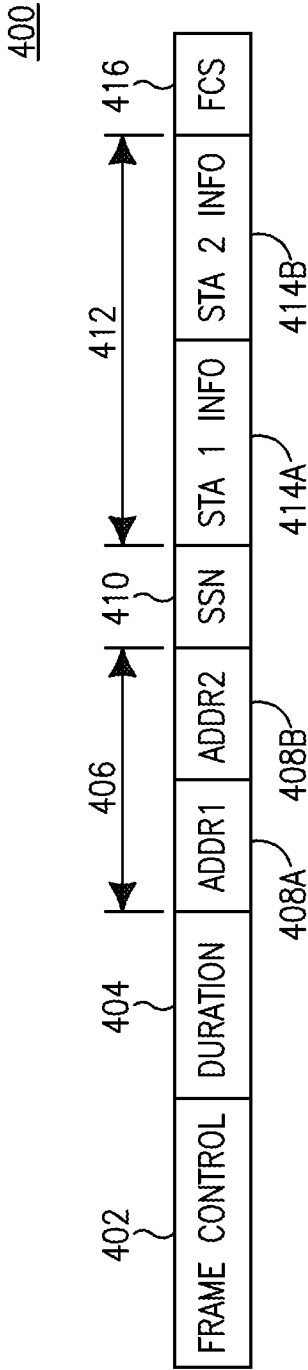


FIG. 4

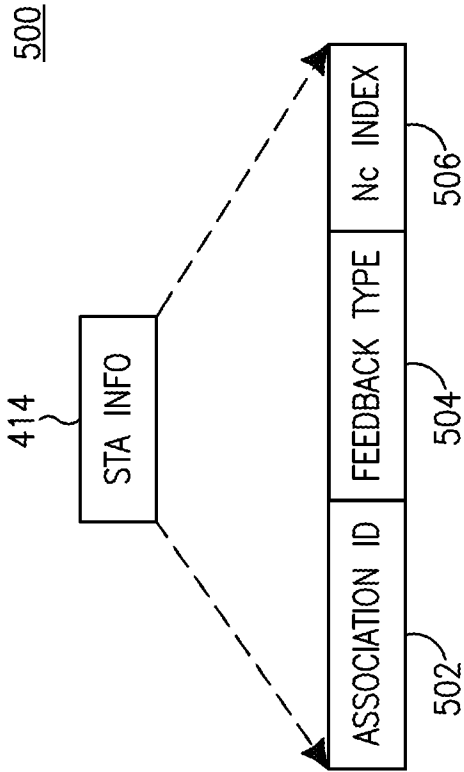
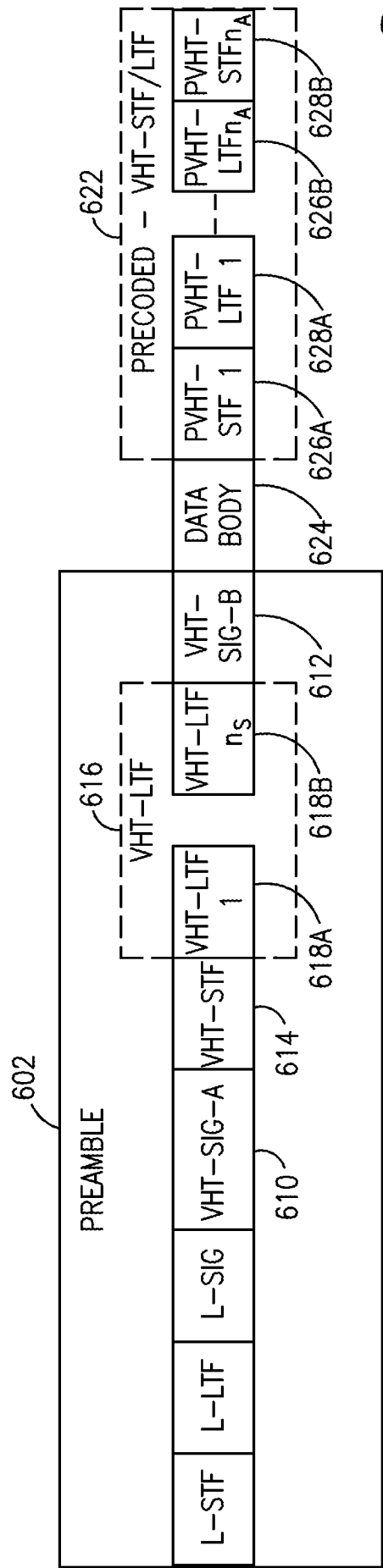


FIG. 5

600



6/11

FIG. 6

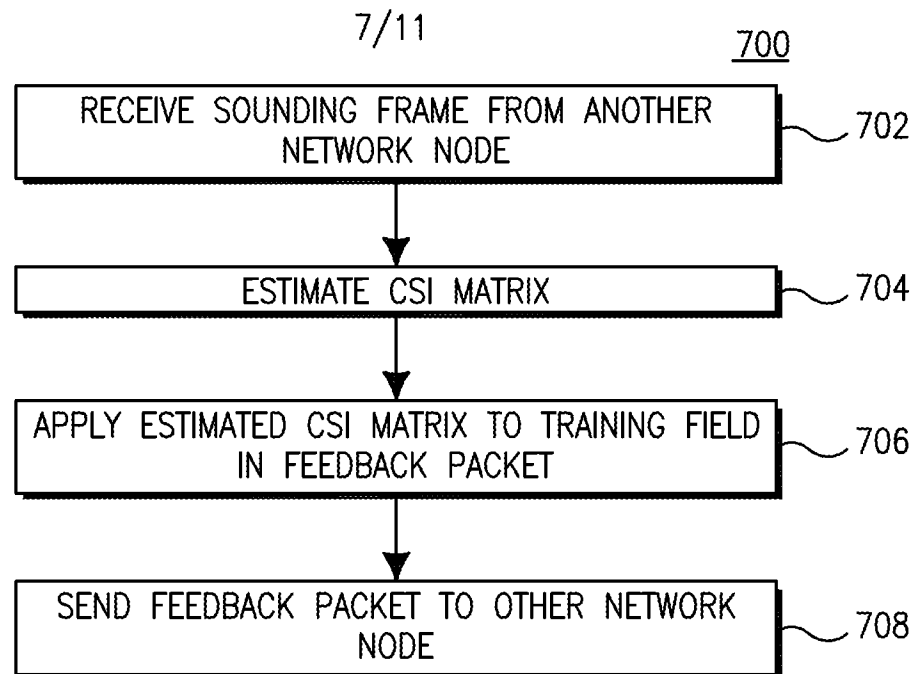


FIG. 7

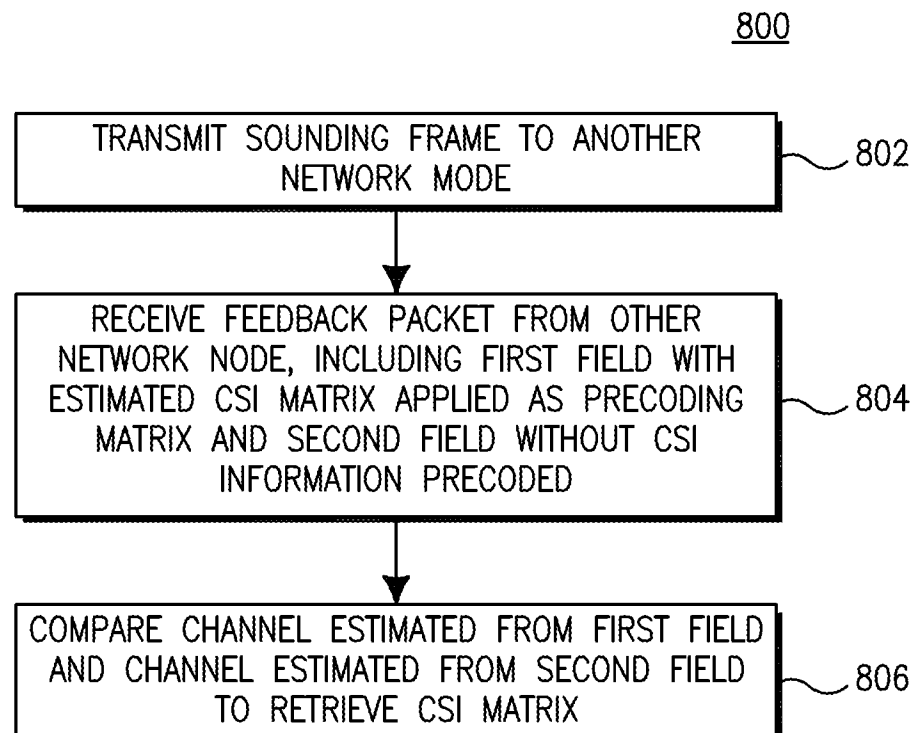


FIG. 8A

850

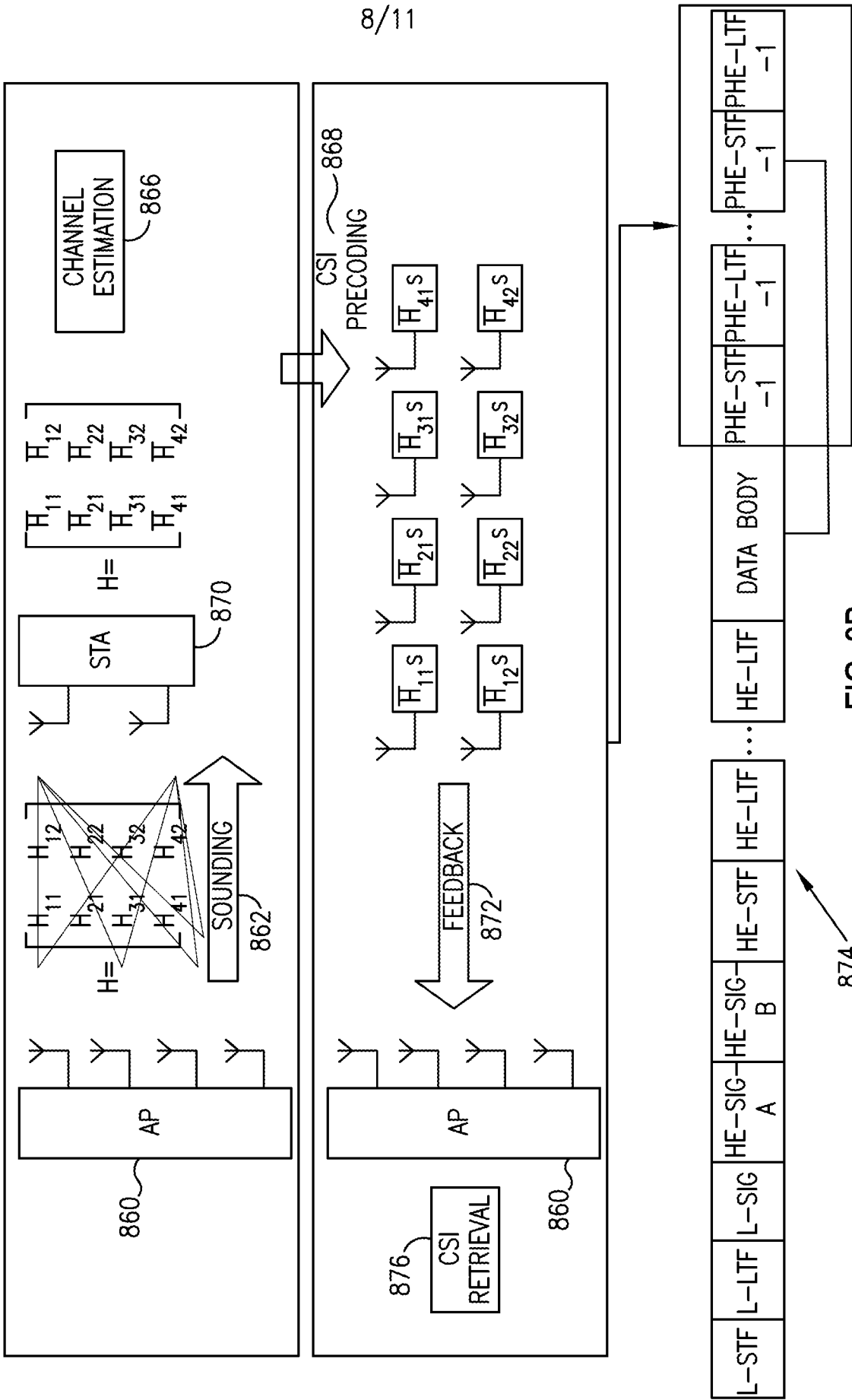


FIG. 8B

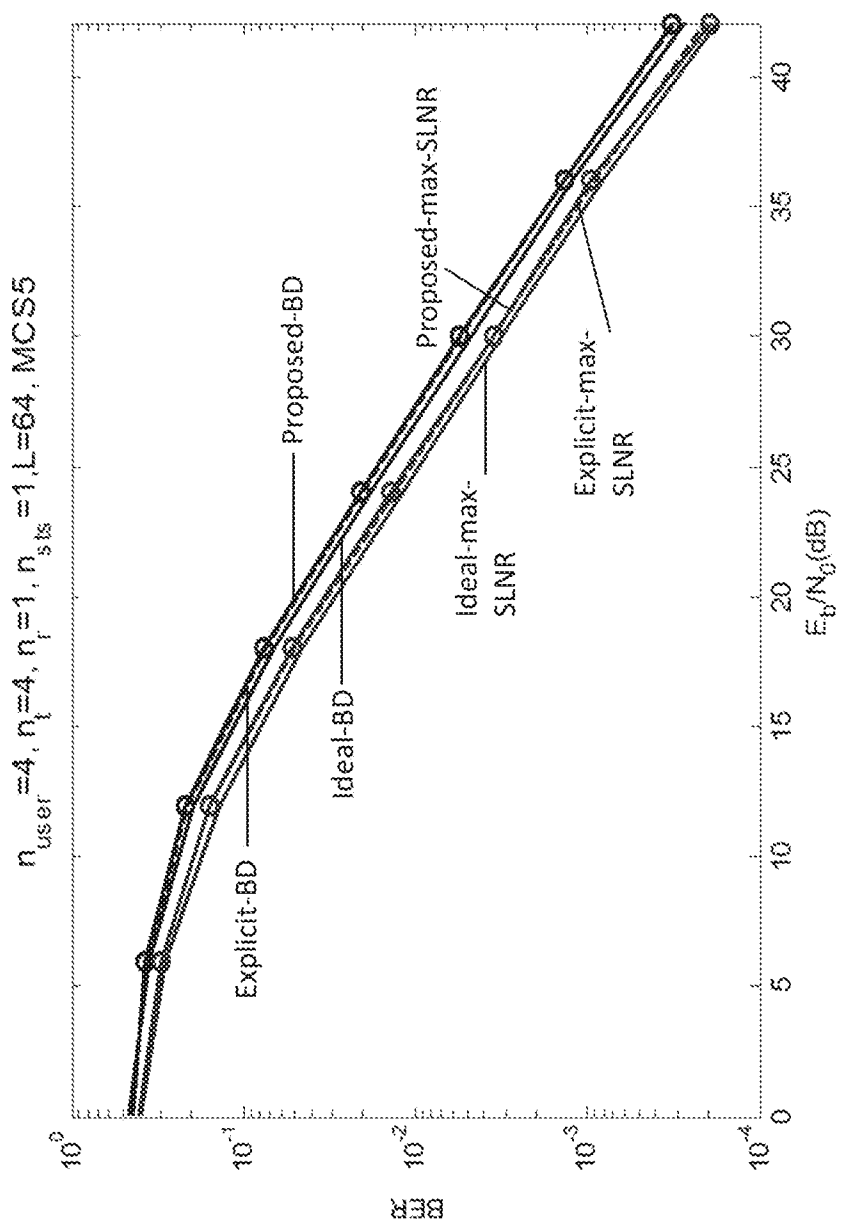


FIG. 9

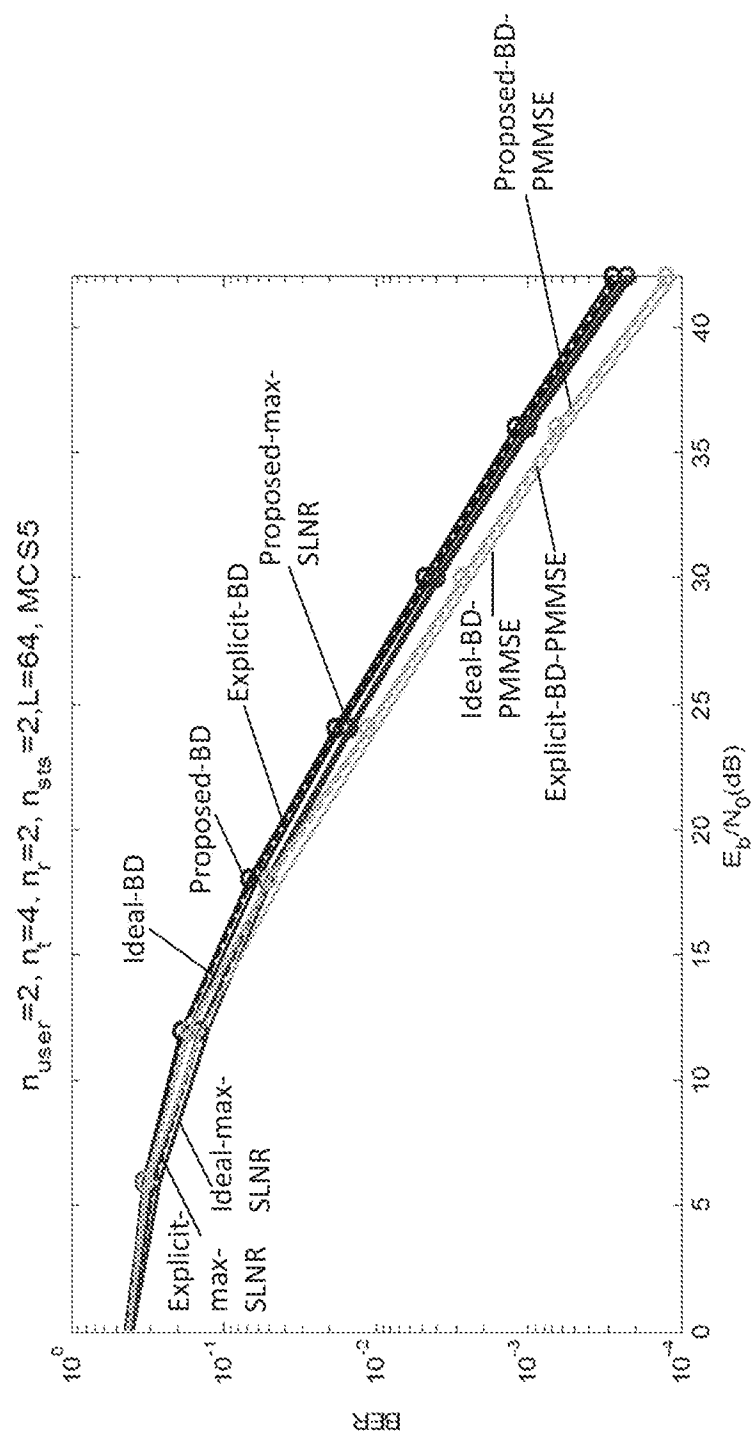


FIG. 10

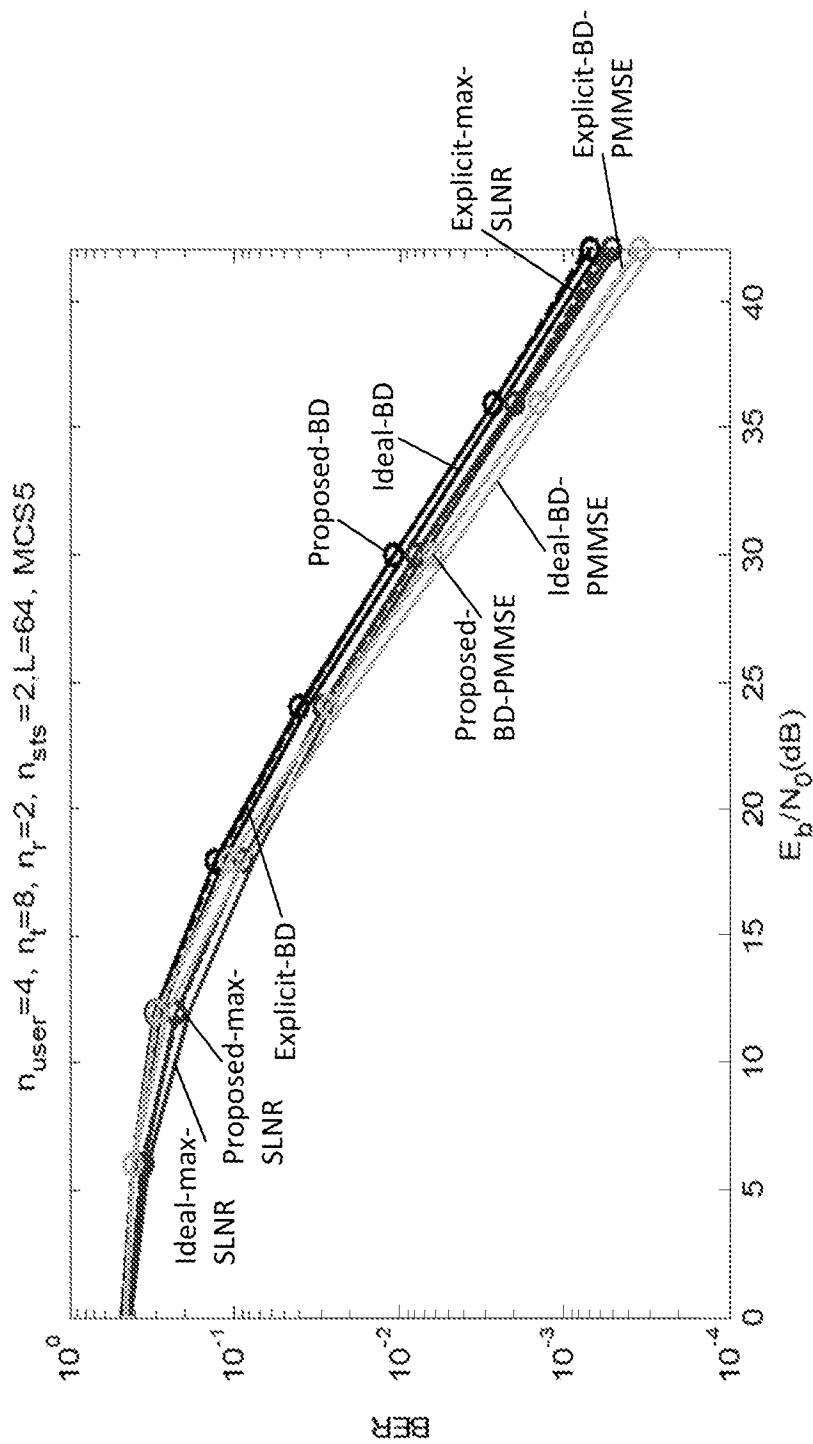


FIG. 11

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2016/040740

A. CLASSIFICATION OF SUBJECT MATTER

INV. H04B7/04 H04B7/06
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)
H04B

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, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010/046643 A1 (MONDAL BISHWARUP [US] ET AL) 25 February 2010 (2010-02-25) paragraph [0015] - paragraph [0020] figure 1	1-24
A	----- WO 2013/088374 A2 (MARVELL WORLD TRADE LTD [BB]) 20 June 2013 (2013-06-20) paragraph [0028] - paragraph [0033] -----	1-24



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"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

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"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

12 October 2016

Date of mailing of the international search report

20/10/2016

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

Authorized officer

Baltersee, Jens

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2016/040740

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2010046643	A1	25-02-2010	NONE

WO 2013088374	A2	20-06-2013	US 2013155921 A1 20-06-2013
			WO 2013088374 A2 20-06-2013
