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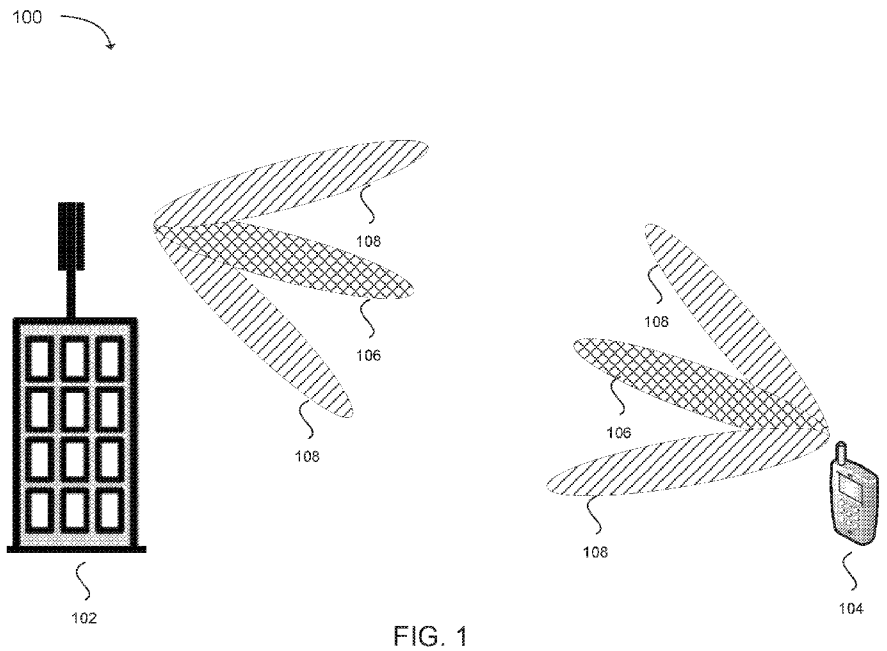


FIG. 1

(57) Abstract: Technology for a user equipment (UE) operable to maintain a plurality of received beams is disclosed. The UE can decode an interference measurement resource (IMR) configuration for the UE that is received from a transmission reception point (TRP). The UE can identify a receive (Rx) beam of the plurality of Rx beams that is associated with the IMR configuration. The UE can perform an interference measurement and a channel measurement using the identified Rx beam. The UE can encode a measurement report for transmission to the TRP, wherein the measurement report is based on the interference measurement and the channel measurement. The UE can have a memory interface configured to send to a memory the IMR configuration.

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INTERFERENCE MEASUREMENTS WITH UE BEAM INDICATION

BACKGROUND

[0001] Wireless systems typically include multiple User Equipment (UE) devices communicatively coupled to one or more Base Stations (BS). The one or more BSs may be Long Term Evolved (LTE) evolved NodeBs (eNB) or New Radio (NR) next generation NodeBs (gNB) that can be communicatively coupled to one or more UEs by a Third-Generation Partnership Project (3GPP) network.

Next generation wireless communication systems are expected to be a unified network/system that is targeted to meet vastly different and sometimes conflicting performance dimensions and services. New Radio Access Technology (RAT) is expected to support a broad range of use cases including Enhanced Mobile Broadband (eMBB), Massive Machine Type Communication (mMTC), Mission Critical Machine Type Communication (uMTC), and similar service types operating in frequency ranges up to 100 GHz.

BRIEF DESCRIPTION OF THE DRAWINGS

[0002] Features and advantages of the disclosure will be apparent from the detailed description which follows, taken in conjunction with the accompanying drawings, which together illustrate, by way of example, features of the disclosure; and, wherein:

[0003] FIG. 1 illustrates signaling between an eNodeB and a user equipment (UE) to indicate a multiple beamformed transmission and multiple reception in new radio wireless system, in accordance with an example;

[0004] FIG. 2 illustrates a working flow of a UE reporting its capability of maintaining multiple beamforming, in accordance with an example;

[0005] FIG. 3 depicts functionality of a user equipment (UE) operable to maintain a plurality of received beams in accordance with an example;

[0006] FIG. 4 depicts functionality of transmission reception point (TRP) operable to

maintain a plurality of received beams in accordance with an example;

[0007] FIG. 5 depicts functionality of a user equipment (UE) operable to measure interference using non-zero power (NZP) channel state information reference symbols (CSI-RS) in accordance with an example;

[0008] FIG. 6 depicts functionality of transmission reception point (TRP) operable to determine intra-cell performance in accordance with an example

[0009] FIG. 7 illustrates an architecture of a network in accordance with an example;

[0010] FIG. 8 illustrates a diagram of a wireless device (e.g., UE) and a base station (e.g., eNodeB) in accordance with an example;

[0011] FIG. 9 illustrates example interfaces of baseband circuitry in accordance with an example; and

[0012] FIG. 10 illustrates a diagram of a wireless device (e.g., UE) in accordance with an example.

[0013] Reference will now be made to the exemplary embodiments illustrated, and specific language will be used herein to describe the same. It will nevertheless be understood that no limitation of the scope of the technology is thereby intended.

DETAILED DESCRIPTION

[0014] Before the present technology is disclosed and described, it is to be understood that this technology is not limited to the particular structures, process actions, or materials disclosed herein, but is extended to equivalents thereof as would be recognized by those ordinarily skilled in the relevant arts. It should also be understood that terminology employed herein is used for the purpose of describing particular examples only and is not intended to be limiting. The same reference numerals in different drawings represent the same element. Numbers provided in flow charts and processes are provided for clarity in illustrating actions and operations and do not necessarily indicate a particular order or sequence.

EXAMPLE EMBODIMENTS

[0015] An initial overview of technology embodiments is provided below and then specific technology embodiments are described in further detail later. This initial summary is intended to aid readers in understanding the technology more quickly but is not intended to identify key features or essential features of the technology nor is it intended to limit the scope of the claimed subject matter.

[0016] Wireless mobile communication technology uses various standards and protocols to transmit data between a node (e.g., a transmission station) and a wireless device (e.g., a mobile device). Some wireless devices communicate using orthogonal frequency-division multiple access (OFDMA) in a downlink (DL) transmission and single carrier frequency division multiple access (SC-FDMA) in uplink (UL). Standards and protocols that use orthogonal frequency-division multiplexing (OFDM) for signal transmission include the third generation partnership project (3GPP) long term evolution (LTE), the Institute of Electrical and Electronics Engineers (IEEE) 802.16 standard (e.g., 802.16e, 802.16m), which is commonly known to industry groups as WiMAX (Worldwide interoperability for Microwave Access), and the IEEE 802.11 standard, which is commonly known to industry groups as WiFi.

[0017] In 3GPP radio access network (RAN) LTE systems (e.g., Release 13 and earlier), the node can be a combination of Evolved Universal Terrestrial Radio Access Network (E-UTRAN) Node Bs (also commonly denoted as evolved Node Bs, enhanced Node Bs, eNodeBs, or eNBs) and Radio Network Controllers (RNCs), which communicates with the wireless device, known as a user equipment (UE). In 3GPP fifth generation (5G) LTE communication systems, the node is commonly referred to as a new radio (NR) or next generation Node B (gNodeB or gNB). The downlink (DL) transmission can be a communication from the node (e.g., eNodeB or gNodeB) to the wireless device (e.g., UE), and the uplink (UL) transmission can be a communication from the wireless device to the node.

[0018] Wireless systems typically include multiple User Equipment (UE) devices communicatively coupled to one or more Base Stations (BS). The one or more BSs may be Long Term Evolved (LTE) evolved NodeBs (eNB) or New Radio (NR) next generation NodeBs (gNB) that can be communicatively coupled to one or more UEs by a Third-

Generation Partnership Project (3GPP) network. The UE can be one or more of a smart phone, a tablet computing device, a laptop computer, an internet of things (IOT) device, and/or another type of computing devices that is configured to provide digital communications. As used herein, digital communications can include data and/or voice communications, as well as control information.

[0019] The present technology describes a 5G system, where beam forming can be used at both a Transmission Reception Point (TRP) side and a UE side. The UE and the TRP can maintain the best several TRP beams and UE beams for communication and measurement. For example, each pair of TRP transmission beams and UE reception beams can change dynamically due to the channel variation.

[0020] In order to perform link adaptation, it can be important to estimate the interference so that the channel quality indicator (CQI) can be calculated accurately. The interference measurement resource (IMR) can be configured to perform the interference measurement experienced by the data channel of the UE. The IMR transmission can be periodic or aperiodic and the IMR can be based on a selected reference symbol framework, such as a channel state information reference symbol (CSI-RS) framework or another desired reference symbol framework.

[0021] In one example, the UE and the TRP can maintain several TRP beams and UE beams. The interference measurements using the IMR can be performed considering the UE beamforming. Accordingly, a TRP can indicate to the UE which beam can be used for the interference measurement. The interference characteristics for different beams can vary a lot and/or be randomized. Accordingly, the configurations disclosed of the IMR can include a UE beam indication so that the UE can know which UE beam should be used when performing interference measurement for CQI.

[0022] Additionally, in LTE, the Interference Measurement Resource (IMR) has been introduced to allow interference measurements on the predetermined resources configured for the UE. Similarly the IMR can be used in a 5G new radio (NR) system for the UE to obtain interference information to achieve better link adaptation performance. In NR, the IMR can be based on Zero Power CSI-RS (ZP CSI-RS) or Non-Zero Power CSI-RS (NZP CSI-RS). The ZP CSI-RS can be used to obtain the inter-TRP interference. And NZP CSI-RS can be used to perform interference measurement in a multi-user

multiple input multiple output (MU-MIMO) case to get the intra-TRP interference information. In general, there can be embodiments to configure NZP CSI-RS with a low density for interference measurement in an MU-MIMO operation.

[0023] In MU-MIMO, when NZP CSI-RS is used, it can use a high density of NZP CSI-RS to get an accurate CQI information from multiple UEs. In one embodiment, the present technology provides a scheme to configure NZP CSI-RS with a relatively low density of RS for MU-MIMO operation.

[0024] As previously discussed, in a 5G system both control and data channels at a millimeter- or centimeter-wave frequency band are characterized by a beamformed transmission. With beamforming, the antenna gain pattern is shaped like a cone pointing to a spatial area so that a high antenna gain can be achieved. At the transmitter, beamforming is achieved by applying a phase shift to an antenna array that is either one-dimension or two-dimension periodically placed. Dependent on the phase shift, multiple beams can be formed at a transmission point (TP) at a time and beams from different TPs can point to the same location. Similarly, the receiver can apply a phase shift to its antenna array to achieve a receive gain for a signal arriving from a specific spatial angle. As shown in FIG. 1, the best receive signal quality can be achieved when transmit and receive beams are aligned.

[0025] As used herein, the term "Base Station (BS)" includes "Base Transceiver Stations (BTS)," "NodeBs," "evolved NodeBs (eNodeB or eNB)," and/or "next generation NodeBs (gNodeB or gNB)," and refers to a device such as a transmission reception point (TRP) or configured node of a mobile phone network that communicates wirelessly with UEs.

[0026] FIG. 1 illustrates signaling between a base station 102, such as an eNodeB, transmission reception point (TRP), or gNodeB and a user equipment (UE) 104 to indicate a beamformed transmission and reception in new radio wireless system, such as a LTE, 5G, or other enhanced wireless communication system 100. The beamformed transmission can be a multiple beam transmission, and the reception can be configured for multiple beam reception. In one example, in order to benefit from such beamformed transmissions, a UE 104 can be configured to perform measurements on the available beams 106, 108 and inform the base station 102 to use a beam 106 that points to the base

station's location. In this way, the signal to interference and noise ratio (SINR) of reception signal can be improved.

[0027] In one example, due to factors like initial access, mobility of the UE 104, a change of propagation environment, and/or a rotation of a UE 104 antenna, the beam direction that is best for the UE 104 may not be known or can be subject to change. As a result, the UE 104 can be configured to monitor the receive signal quality from all possible beams 108 and notify the base station what single beam 106 or set of beams is considered good for its reception. Additionally, a beam received by a device or UE can depend on the orientation or location of the UE in relation to one or more of the TRP, gNB, base station or eNB. FIG. 1 indicates only one UE and one base station, however, the configuration can also include multiple UE's and multiple nodes, gNBs, base stations or eNBs operable to receive and transmit multiple beams that can be received in any order and transmitted in any order.

[0028] In one example, due to the existence of a large number of beams and possibly high mobility speed, a low complexity measurement process that allows efficient implementation can provide significant advantages. The process can allow for detection of beams at a low signal to noise ratio (SNR) so that the beam can be monitored and switched to when beam quality is improved.

[0029] In one example, In order to facilitate such measurement, a reference signal such as a beam reference signal (BRS) can be employed at the base station 102. The BRS may be Channel State Information Reference Signal (CSI-RS) or synchronization signal (SS)/Physical Broadcast Channel (PBCH) block. The New Radio (NR) can be configured to support CSI-RS and a SS/PBCH block for beam management. The BRS can be a predefined sequence that is associated with a beam for its transmission. With orthogonal frequency-division multiplexing (OFDM) communication systems, a large number of closely spaced orthogonal subcarrier signals are used to carry information symbols.

Interference Measurement

[0030] In the 5G NR system, beam forming can be used at both the TRP side and the UE side. The UE and the TRP can maintain the best several TRP beams and UE beams for communication and measurement.

[0031] Generally, the TRP and the UE can use the best pair of one TRP beam and one UE beam for communication. But in some cases, more than one UE beam can be maintained for better performance and measurement. In one example, there can be two strong channel clusters in the system. In this case, the UE can maintain two UE beams pointing at different directions.

[0032] The interference measurement can be important to obtain the interference characteristic to assist link adaptation and scheduling in a 5G NR system. When the UE maintains more than one receive (Rx) beams, there can be some consideration for interference measurement, i.e. which UE beam is used for the interference measurement. For different beams, the interference characteristic can vary substantially. Accordingly, there can be one or more UE beam indications for the interference measurement.

[0033] In one embodiment, the UE beam for IMR can be indicated via Downlink Control Information. The UE beam for IMR can be matched to the beam indicated in the DCI for for CSI-RS measurement. In one example, the gNodeB (TRP) does not need to indicate the UE beam index explicitly. Instead, the TRP can indicate which beam is used for CSI-RS and the interference measurements on IMR can rely on the same UE beam as the associated CSI-RS.

[0034] In one example, the UE can be configured with N CSI-RS resources or Channel State Information (CSI) processes which can be received and processed by different UE beams. A UE beam indicator can take $[\log_2 N]$ bits. This indicator can also be included with the QCL indication between the IMR and CSI-RS. Alternatively this UE beam indication of IMR can be predefined or configured via higher layer signaling.

[0035] In NR, the IMR can be introduced and utilized for interference measurement. Accurate interference information is helpful to achieve better link adaptation performance. Additionally, the IMR could be based on zero power (ZP) CSI-RS and NZP CSI-RS.

[0036] The ZP CSI-RS is suitable for inter-TRP interference measurement. The ZP CSI-RS can be supported by not transmitting PDSCH on the REs allocated for the interference measurements. In addition, due to the dynamic scheduling of MU-MIMO, the interference realization can also be dynamic.

[0037] For MU-MIMO, NZP CSI-RS can be used to capture the intra-cell interference from different UEs. Based on the UE specific NZP CSI-RS, each UE can obtain the channel information from the channel estimation. Then the UE can subtract it from the received signal to get the interference. In general, this approach requires high NZP CSI-RS density to get interference from different UEs, especially when the number of UEs with MU-MIMO operation is relatively large.

[0038] In order to reduce the overhead, one possible solution is proposed in this IDF to capture the intra-TRP interference using NZP CSI-RS with a relatively lower density. The approach can be based on interference emulation. Basically the UE can use the CSI-RS transmitted to other UEs to estimate the channel, denoted as H_i. Then the interference from a given *ith* UE can be calculated as $R_i = H_i * H_i^H$, where $()^H$ means the conjugate transpose operation. With this approach, it is possible to construct, at the UE, different possible combinations of the intra-cell interference by combining different R_i.

[0039] The TRP can configure the UE to identify which combinations of UE interference are to be measured and to be reported. Also the TRP can signal the UE with the CSI-RS information for other UEs. With the proposed approach, the network side can obtain much more CQI information. And in principle, the approach does not require a high density of NZP CSI-RS.

[0040] FIG. 2 illustrates a working flow of a UE reporting its capability of maintaining multiple beamforming. The UE can report its capability on UE beamforming. If the UE can maintain more than one Rx beams, then the network side can configure the IMR with a UE Rx beam indication. Based on the IMR with the UE Rx beam indication, the UE can perform the interference measurement with the indicated Rx beam and also performs the CSI-RS measurement using the same Rx beam. The UE can then send the measurement report to the TRP accordingly.

[0041] In another embodiment, the UE can maintains a single Rx beam. In the case of a single RX beam, the network side can configure the IMR without an Rx beam indication. The UE can then perform a measurement and send the measurement report, wherein the measurement report may be a CSI report including a Channel Quality Indicator (CQI)

report.

[0042] Initially, the UE can report its capability to support multiple Rx beams and the operability to provide for UE beamforming. Additionally, the TRP can check whether the UE can maintain more than one Rx beams. If more than one Rx beams can be supported or maintained, the TRP can configure IMR with a UE Rx beam indication. The UE can then perform IMR measurements and CSI-RS measurements using the same indicated Rx beam. The UE can then send the measurement report to the TRP.

[0043] In another embodiment, the TRP can check whether the UE can maintain more than one Rx beams. If more than one Rx beams cannot be maintained, the TRP can configure IMR without a UE Rx beam indication. Additionally, the UE can perform measurements and send a measurement report to the TRP.

[0044] FIG. 3 depicts functionality 300 of a user equipment (UE) operable to maintain a plurality of received beams. The UE can comprise of one or more processors configured to decode an interference measurement resource (IMR) configuration for the UE that is received from a transmission reception point (TRP) 310. The UE can comprise of one or more processors configured to identify a receive (Rx) beam of the plurality of Rx beams that is associated with the IMR configuration 320. The UE can comprise of one or more processors configured to perform an interference measurement and a channel measurement using the identified Rx beam 330. The UE can comprise of one or more processors configured to encode a measurement report for transmission to the TRP, wherein the measurement report is based on the interference measurement and the channel measurement 340.

[0045] In one embodiment, the one or more processors are further configured to decode a CSI-RS configuration for the UE that is received from the TRP, wherein the CSI-RS configuration includes a UE Rx beam indication associated with each CSI-RS resource configured in the CSI-RS configuration for the UE.

[0046] In one embodiment, the one or more processors are further configured to identify the Rx beam that is associated with the IMR configuration by determining a UE Rx beam indication associated with each CSI-RS resource and using a same Rx beam to perform each IMR measurement at the UE.

[0047] In one embodiment, the UE Rx beam indication comprises log2 N bits, wherein N is a number of CSI-RS resources configured for the UE.

[0048] In one embodiment, the UE Rx beam indication is included in a quasi-co-location (QCL) indicator, wherein the QCL indicator is associated with a non-zero power (NZP) CSI-RS resource or a SS/PBCH block, wherein the QCL indicator corresponds to one or more spatial Rx parameters.

[0049] In one embodiment, the one or more processors are further configured to identify the Rx beam that is associated with the interference measurement by decoding a UE Rx beam indication that is received in the IMR configuration and is associated with the interference measurement.

[0050] In one embodiment, the IMR configuration is received via one or more of downlink control information (DCI) or higher layer signaling.

[0051] In one embodiment, the measurement report is a channel state information (CSI) report or a reference signal receive power (RSRP) report, wherein the CSI report or RSRP report comprises one or more of: a CSI reference signal (CSI-RS) resource index (CRI); a channel quality indicator (CQI); a precoding matrix indicator (PMI); or a rank indicator (RI).

[0052] FIG. 4 depicts functionality 400 of transmission reception point (TRP) operable to maintain a plurality of received beams. The UE can comprise of one or more processors configured to decode a user equipment (UE) capability report received from a UE 410. The UE can comprise of one or more processors configured to identify a number of receive (Rx) beams the UE is capable of maintaining simultaneously 420. The UE can comprise of one or more processors configured to encode an interference measurement resource (IMR) configuration for the UE, wherein each IMR in the IMR configuration is associated with a UE Rx beam when the number of received beams is greater than one 430. The UE can comprise of one or more processors configured to decode a measurement report received from the UE, wherein the measurement report is based on an interference measurement and a channel measurement performed at the UE 440.

[0053] In one embodiment, the one or more processors are further configured to encode a CSI-RS configuration for the UE, wherein the CSI-RS configuration includes a UE Rx

beam indication associated with each CSI-RS resource configured in the CSI-RS configuration for the UE.

[0054] In one embodiment, the one or more processors are further configured to encode the IMR configuration for the UE, wherein the IMR configuration includes a UE Rx beam indication associated with each IMR in the IMR configuration.

[0055] In one embodiment, the UE Rx beam indication comprises log2 N bits, wherein N is a number of CSI-RS resources configured for the UE.

[0056] In one embodiment, the one or more processors are further configured to encode an interference measurement resource (IMR) configuration for the UE, wherein each IMR in the IMR configuration is not associated with a UE Rx beam when the number of received beams is equal to one.

[0057] In one embodiment, the UE Rx beam indication is included in a quasi-co-location (QCL) indicator wherein the QCL indicator is associated with a non-zero power (NZP) CSI-RS resource or a SS/PBCH block, wherein the QCL indicator corresponds to one or more spatial Rx parameters.

[0058] In one embodiment, the one or more processors are further configured to encode the IMR configuration for transmission to the UE using one or more of downlink control information (DCI) or higher layer signaling.

[0059] FIG. 5 depicts functionality 500 of a user equipment (UE) operable to measure interference using non-zero power (NZP) channel state information reference symbols (CSI-RS). The UE can comprise of one or more processors configured to decode channel state information reference signal (CSI-RS) configuration information received from a transmission reception point (TRP) for the UE 510. The UE can comprise of one or more processors configured to decode CSI-RS configuration information received from the TRP for one or more additional UEs associated with multi-user multiple input multiple output (MU-MIMO) operation or additional UEs associated with one or more neighboring TRPs 520. The UE can comprise of one or more processors configured to estimate a channel, H_i, for an *i*-th UE of the one or more additional UEs 530. The UE can comprise of one or more processors configured to calculate an interference, R_i, for the one or more additional UEs using $R_i = H_i * H_i^H$, wherein $()^H$ is a conjugate transpose

operation, and *i* is the *i*-th UE of the one or more additional UEs 540. The UE can comprise of one or more processors configured to encode the interference of the one or more additional UEs in a CSI report for transmission to the TRP 550.

[0060] In one embodiment, the one or more processors are further configured to decode the interference measurement configuration information comprising which of the one or more additional UEs to calculate the interference for.

[0061] In one embodiment, the one or more processors are further configured to decode the interference measurement configuration information comprising selected combinations of the one or more additional UEs to report the interference for.

[0062] In one embodiment, the one or more processors are further configured to add the interference, Ri, for the selected combinations of the one or more additional UEs and encode the added Ri for transmission to the TRP in the intra-cell interference or CSI report.

[0063] FIG. 6 depicts functionality 600 of transmission reception point (TRP) operable to determine intra-cell performance. The UE can comprise of one or more processors configured to encode an interference measurement resource (IMR) configuration comprising a channel state information reference signal (CSI-RS) configuration information for a user equipment (UE) 610. The UE can comprise of one or more processors configured to encode CSI-RS configuration information for one or more additional UEs associated with multi-user multiple input multiple output (MU-MIMO) operation for transmission to the UE, to enable the UE 620. The UE can be enabled to estimate a channel, H_i, for an *i*-th UE of the one or more additional UEs 630. The UE can be enabled to calculate an interference, R_i, for the one or more additional UEs using $R_i = H_i * H_i^H$, wherein $()^H$ is a conjugate transpose operation, and *i* is the *i*-th UE of the one or more additional UEs 640. The UE can be enabled to encode the interference of the one or more additional UEs in an intra-cell interference or CSI report for transmission to the TRP 650.

[0064] In one embodiment, the CSI-RS configuration information includes Non-Zero Power (NZP) CSI-RS.

[0065] FIG. 7 illustrates an architecture of a system 700 of a network in accordance with

some embodiments. The system 700 is shown to include a user equipment (UE) 701 and a UE 702. The UEs 701 and 702 are illustrated as smartphones (e.g., handheld touchscreen mobile computing devices connectable to one or more cellular networks), but may also comprise any mobile or non-mobile computing device, such as Personal Data Assistants (PDAs), pagers, laptop computers, desktop computers, wireless handsets, or any computing device including a wireless communications interface.

[0066] In some embodiments, any of the UEs 701 and 702 can comprise an Internet of Things (IoT) UE, which can comprise a network access layer designed for low-power IoT applications utilizing short-lived UE connections. An IoT UE can utilize technologies such as machine-to-machine (M2M) or machine-type communications (MTC) for exchanging data with an MTC server or device via a public land mobile network (PLMN), Proximity-Based Service (ProSe) or device-to-device (D2D) communication, sensor networks, or IoT networks. The M2M or MTC exchange of data may be a machine-initiated exchange of data. An IoT network describes interconnecting IoT UEs, which may include uniquely identifiable embedded computing devices (within the Internet infrastructure), with short-lived connections. The IoT UEs may execute background applications (e.g., keep-alive messages, status updates, etc.) to facilitate the connections of the IoT network.

[0067] The UEs 701 and 702 may be configured to connect, e.g., communicatively couple, with a radio access network (RAN) 710 — the RAN 710 may be, for example, an Evolved Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access Network (E-UTRAN), a NextGen RAN (NG RAN), or some other type of RAN. The UEs 701 and 702 utilize connections 703 and 704, respectively, each of which comprises a physical communications interface or layer (discussed in further detail below); in this example, the connections 703 and 704 are illustrated as an air interface to enable communicative coupling, and can be consistent with cellular communications protocols, such as a Global System for Mobile Communications (GSM) protocol, a code-division multiple access (CDMA) network protocol, a Push-to-Talk (PTT) protocol, a PTT over Cellular (POC) protocol, a Universal Mobile Telecommunications System (UMTS) protocol, a 3GPP Long Term Evolution (LTE) protocol, a fifth generation (5G) protocol, a New Radio (NR) protocol, and the like.

[0068] In this embodiment, the UEs 701 and 702 may further directly exchange communication data via a ProSe interface 705. The ProSe interface 705 may alternatively be referred to as a sidelink interface comprising one or more logical channels, including but not limited to a Physical Sidelink Control Channel (PSCCH), a Physical Sidelink Shared Channel (PSSCH), a Physical Sidelink Discovery Channel (PSDCH), and a Physical Sidelink Broadcast Channel (PSBCH).

[0069] The UE 702 is shown to be configured to access an access point (AP) 706 via connection 707. The connection 707 can comprise a local wireless connection, such as a connection consistent with any IEEE 802.11 protocol, wherein the AP 706 would comprise a wireless fidelity (WiFi®) router. In this example, the AP 706 is shown to be connected to the Internet without connecting to the core network of the wireless system (described in further detail below).

[0070] The RAN 710 can include one or more access nodes that enable the connections 703 and 704. These access nodes (ANs) can be referred to as base stations (BSs), NodeBs, evolved NodeBs (eNBs), Next Generation NodeBs (gNB), RAN nodes, and so forth, and can comprise ground stations (e.g., terrestrial access points) or satellite stations providing coverage within a geographic area (e.g., a cell). The RAN 710 may include one or more RAN nodes for providing macrocells, e.g., macro RAN node 711, and one or more RAN nodes for providing femtocells or picocells (e.g., cells having smaller coverage areas, smaller user capacity, or higher bandwidth compared to macrocells), e.g., low power (LP) RAN node 712.

[0071] Any of the RAN nodes 711 and 712 can terminate the air interface protocol and can be the first point of contact for the UEs 701 and 702. In some embodiments, any of the RAN nodes 711 and 712 can fulfill various logical functions for the RAN 710 including, but not limited to, radio network controller (RNC) functions such as radio bearer management, uplink and downlink dynamic radio resource management and data packet scheduling, and mobility management.

[0072] In accordance with some embodiments, the UEs 701 and 702 can be configured to communicate using Orthogonal Frequency-Division Multiplexing (OFDM) communication signals with each other or with any of the RAN nodes 711 and 712 over a multicarrier communication channel in accordance various communication techniques,

such as, but not limited to, an Orthogonal Frequency-Division Multiple Access (OFDMA) communication technique (e.g., for downlink communications) or a Single Carrier Frequency Division Multiple Access (SC-FDMA) communication technique (e.g., for uplink and ProSe or sidelink communications), although the scope of the embodiments is not limited in this respect. The OFDM signals can comprise a plurality of orthogonal subcarriers.

[0073] In some embodiments, a downlink resource grid can be used for downlink transmissions from any of the RAN nodes 711 and 712 to the UEs 701 and 702, while uplink transmissions can utilize similar techniques. The grid can be a time-frequency grid, called a resource grid or time-frequency resource grid, which is the physical resource in the downlink in each slot. Such a time-frequency plane representation is a common practice for OFDM systems, which makes it intuitive for radio resource allocation. Each column and each row of the resource grid corresponds to one OFDM symbol and one OFDM subcarrier, respectively. The duration of the resource grid in the time domain corresponds to one slot in a radio frame. The smallest time-frequency unit in a resource grid is denoted as a resource element. Each resource grid comprises a number of resource blocks, which describe the mapping of certain physical channels to resource elements. Each resource block comprises a collection of resource elements; in the frequency domain, this may represent the smallest quantity of resources that currently can be allocated. There are several different physical downlink channels that are conveyed using such resource blocks.

[0074] The physical downlink shared channel (PDSCH) may carry user data and higher-layer signaling to the UEs 701 and 702. The physical downlink control channel (PDCCH) may carry information about the transport format and resource allocations related to the PDSCH channel, among other things. It may also inform the UEs 701 and 702 about the transport format, resource allocation, and H-ARQ (Hybrid Automatic Repeat Request) information related to the uplink shared channel. Typically, downlink scheduling (assigning control and shared channel resource blocks to the UE 702 within a cell) may be performed at any of the RAN nodes 711 and 712 based on channel quality information fed back from any of the UEs 701 and 702. The downlink resource assignment information may be sent on the PDCCH used for (e.g., assigned to) each of

the UEs 701 and 702.

[0075] The PDCCH may use control channel elements (CCEs) to convey the control information. Before being mapped to resource elements, the PDCCH complex-valued symbols may first be organized into quadruplets, which may then be permuted using a sub-block interleaver for rate matching. Each PDCCH may be transmitted using one or more of these CCEs, where each CCE may correspond to nine sets of four physical resource elements known as resource element groups (REGs). Four Quadrature Phase Shift Keying (QPSK) symbols may be mapped to each REG. The PDCCH can be transmitted using one or more CCEs, depending on the size of the downlink control information (DCI) and the channel condition. There can be four or more different PDCCH formats defined in LTE with different numbers of CCEs (e.g., aggregation level, L=1, 2, 4, or 8).

[0076] Some embodiments may use concepts for resource allocation for control channel information that are an extension of the above-described concepts. For example, some embodiments may utilize an enhanced physical downlink control channel (EPDCCH) that uses PDSCH resources for control information transmission. The EPDCCH may be transmitted using one or more enhanced the control channel elements (ECCEs). Similar to above, each ECCE may correspond to nine sets of four physical resource elements known as an enhanced resource element groups (EREGs). An ECCE may have other numbers of EREGs in some situations.

[0077] The RAN 710 is shown to be communicatively coupled to a core network (CN) 720 —via an S1 interface 713. In embodiments, the CN 720 may be an evolved packet core (EPC) network, a NextGen Packet Core (NPC) network, or some other type of CN. In this embodiment the S1 interface 713 is split into two parts: the S1-U interface 714, which carries traffic data between the RAN nodes 711 and 712 and the serving gateway (S-GW) 722, and the S1-mobility management entity (MME) interface 715, which is a signaling interface between the RAN nodes 711 and 712 and MMEs 721.

[0078] In this embodiment, the CN 720 comprises the MMEs 721, the S-GW 722, the Packet Data Network (PDN) Gateway (P-GW) 723, and a home subscriber server (HSS) 724. The MMEs 721 may be similar in function to the control plane of legacy Serving General Packet Radio Service (GPRS) Support Nodes (SGSN). The MMEs 721 may

manage mobility aspects in access such as gateway selection and tracking area list management. The HSS 724 may comprise a database for network users, including subscription-related information to support the network entities' handling of communication sessions. The CN 720 may comprise one or several HSSs 724, depending on the number of mobile subscribers, on the capacity of the equipment, on the organization of the network, etc. For example, the HSS 724 can provide support for routing/roaming, authentication, authorization, naming/addressing resolution, location dependencies, etc.

[0079] The S-GW 722 may terminate the S1 interface 713 towards the RAN 710, and routes data packets between the RAN 710 and the CN 720. In addition, the S-GW 722 may be a local mobility anchor point for inter-RAN node handovers and also may provide an anchor for inter-3GPP mobility. Other responsibilities may include lawful intercept, charging, and some policy enforcement.

[0080] The P-GW 723 may terminate an SGi interface toward a PDN. The P-GW 723 may route data packets between the EPC network 723 and external networks such as a network including the application server 730 (alternatively referred to as application function (AF)) via an Internet Protocol (IP) interface 725. Generally, the application server 730 may be an element offering applications that use IP bearer resources with the core network (e.g., UMTS Packet Services (PS) domain, LTE PS data services, etc.). In this embodiment, the P-GW 723 is shown to be communicatively coupled to an application server 730 via an IP communications interface 725. The application server 730 can also be configured to support one or more communication services (e.g., Voice-over-Internet Protocol (VoIP) sessions, PTT sessions, group communication sessions, social networking services, etc.) for the UEs 701 and 702 via the CN 720.

[0081] The P-GW 723 may further be a node for policy enforcement and charging data collection. Policy and Charging Enforcement Function (PCRF) 726 is the policy and charging control element of the CN 720. In a non-roaming scenario, there may be a single PCRF in the Home Public Land Mobile Network (HPLMN) associated with a UE's Internet Protocol Connectivity Access Network (IP-CAN) session. In a roaming scenario with local breakout of traffic, there may be two PCRFs associated with a UE's IP-CAN session: a Home PCRF (H-PCRF) within a HPLMN and a Visited PCRF (V-PCRF)

within a Visited Public Land Mobile Network (VPLMN). The PCRF 726 may be communicatively coupled to the application server 730 via the P-GW 723. The application server 730 may signal the PCRF 726 to indicate a new service flow and select the appropriate Quality of Service (QoS) and charging parameters. The PCRF 726 may provision this rule into a Policy and Charging Enforcement Function (PCEF) (not shown) with the appropriate traffic flow template (TFT) and QoS class of identifier (QCI), which commences the QoS and charging as specified by the application server 730.

[0082] FIG. 8 illustrates example components of a device 800 in accordance with some embodiments. In some embodiments, the device 800 may include application circuitry 802, baseband circuitry 804, Radio Frequency (RF) circuitry 806, front-end module (FEM) circuitry 808, one or more antennas 810, and power management circuitry (PMC) 812 coupled together at least as shown. The components of the illustrated device 800 may be included in a UE or a RAN node. In some embodiments, the device 800 may include less elements (e.g., a RAN node may not utilize application circuitry 802, and instead include a processor/controller to process IP data received from an EPC). In some embodiments, the device 800 may include additional elements such as, for example, memory/storage, display, camera, sensor, or input/output (I/O) interface. In other embodiments, the components described below may be included in more than one device (e.g., said circuitries may be separately included in more than one device for Cloud-RAN (C-RAN) implementations).

[0083] The application circuitry 802 may include one or more application processors. For example, the application circuitry 802 may include circuitry such as, but not limited to, one or more single-core or multi-core processors. The processor(s) may include any combination of general-purpose processors and dedicated processors (e.g., graphics processors, application processors, etc.). The processors may be coupled with or may include memory/storage and may be configured to execute instructions stored in the memory/storage to enable various applications or operating systems to run on the device 800. In some embodiments, processors of application circuitry 802 may process IP data packets received from an EPC.

[0084] The baseband circuitry 804 may include circuitry such as, but not limited to, one or more single-core or multi-core processors. The baseband circuitry 804 may

include one or more baseband processors or control logic to process baseband signals received from a receive signal path of the RF circuitry 806 and to generate baseband signals for a transmit signal path of the RF circuitry 806. Baseband processing circuity 804 may interface with the application circuitry 802 for generation and processing of the baseband signals and for controlling operations of the RF circuitry 806. For example, in some embodiments, the baseband circuitry 804 may include a third generation (3G) baseband processor 804A, a fourth generation (4G) baseband processor 804B, a fifth generation (5G) baseband processor 804C, or other baseband processor(s) 804D for other existing generations, generations in development or to be developed in the future (e.g., second generation (2G), si8h generation (6G), etc.). The baseband circuitry 804 (e.g., one or more of baseband processors 804A-D) may handle various radio control functions that enable communication with one or more radio networks via the RF circuitry 806. In other embodiments, some or all of the functionality of baseband processors 804A-D may be included in modules stored in the memory 804G and executed via a Central Processing Unit (CPU) 804E. The radio control functions may include, but are not limited to, signal modulation/demodulation, encoding/decoding, radio frequency shifting, etc. In some embodiments, modulation/demodulation circuitry of the baseband circuitry 804 may include Fast-Fourier Transform (FFT), precoding, or constellation mapping/demapping functionality. In some embodiments, encoding/decoding circuitry of the baseband circuitry 804 may include convolution, tail-biting convolution, turbo, Viterbi, or Low Density Parity Check (LDPC) encoder/decoder functionality. Embodiments of modulation/demodulation and encoder/decoder functionality are not limited to these examples and may include other suitable functionality in other embodiments.

[0085] In some embodiments, the baseband circuitry 804 may include one or more audio digital signal processor(s) (DSP) 804F. The audio DSP(s) 804F may be include elements for compression/decompression and echo cancellation and may include other suitable processing elements in other embodiments. Components of the baseband circuitry may be suitably combined in a single chip, a single chipset, or disposed on a same circuit board in some embodiments. In some embodiments, some or all of the constituent components of the baseband circuitry 804 and the application circuitry 802 may be implemented together such as, for example, on a system on a chip (SOC).

[0086] In some embodiments, the baseband circuitry 804 may provide for communication compatible with one or more radio technologies. For example, in some embodiments, the baseband circuitry 804 may support communication with an evolved universal terrestrial radio access network (EUTRAN) or other wireless metropolitan area networks (WMAN), a wireless local area network (WLAN), a wireless personal area network (WPAN). Embodiments in which the baseband circuitry 804 is configured to support radio communications of more than one wireless protocol may be referred to as multi-mode baseband circuitry.

[0087] RF circuitry 806 may enable communication with wireless networks using modulated electromagnetic radiation through a non-solid medium. In various embodiments, the RF circuitry 806 may include switches, filters, amplifiers, etc. to facilitate the communication with the wireless network. RF circuitry 806 may include a receive signal path which may include circuitry to down-convert RF signals received from the FEM circuitry 808 and provide baseband signals to the baseband circuitry 804. RF circuitry 806 may also include a transmit signal path which may include circuitry to up-convert baseband signals provided by the baseband circuitry 804 and provide RF output signals to the FEM circuitry 808 for transmission.

[0088] In some embodiments, the receive signal path of the RF circuitry 806 may include mixer circuitry 806a, amplifier circuitry 806b and filter circuitry 806c. In some embodiments, the transmit signal path of the RF circuitry 806 may include filter circuitry 806c and mixer circuitry 806a. RF circuitry 806 may also include synthesizer circuitry 806d for synthesizing a frequency for use by the mixer circuitry 806a of the receive signal path and the transmit signal path. In some embodiments, the mixer circuitry 806a of the receive signal path may be configured to down-convert RF signals received from the FEM circuitry 808 based on the synthesized frequency provided by synthesizer circuitry 806d. The amplifier circuitry 806b may be configured to amplify the down-converted signals and the filter circuitry 806c may be a low-pass filter (LPF) or band-pass filter (BPF) configured to remove unwanted signals from the down-converted signals to generate output baseband signals. Output baseband signals may be provided to the baseband circuitry 804 for further processing. In some embodiments, the output baseband signals may be zero-frequency baseband signals, although this is not a necessity. In some

embodiments, mixer circuitry 806a of the receive signal path may comprise passive mixers, although the scope of the embodiments is not limited in this respect.

[0089] In some embodiments, the mixer circuitry 806a of the transmit signal path may be configured to up-convert input baseband signals based on the synthesized frequency provided by the synthesizer circuitry 806d to generate RF output signals for the FEM circuitry 808. The baseband signals may be provided by the baseband circuitry 804 and may be filtered by filter circuitry 806c.

[0090] In some embodiments, the mixer circuitry 806a of the receive signal path and the mixer circuitry 806a of the transmit signal path may include two or more mixers and may be arranged for quadrature downconversion and upconversion, respectively. In some embodiments, the mixer circuitry 806a of the receive signal path and the mixer circuitry 806a of the transmit signal path may include two or more mixers and may be arranged for image rejection (e.g., Hartley image rejection). In some embodiments, the mixer circuitry 806a of the receive signal path and the mixer circuitry 806a may be arranged for direct downconversion and direct upconversion, respectively. In some embodiments, the mixer circuitry 806a of the receive signal path and the mixer circuitry 806a of the transmit signal path may be configured for super-heterodyne operation.

[0091] In some embodiments, the output baseband signals and the input baseband signals may be analog baseband signals, although the scope of the embodiments is not limited in this respect. In some alternate embodiments, the output baseband signals and the input baseband signals may be digital baseband signals. In these alternate embodiments, the RF circuitry 806 may include analog-to-digital converter (ADC) and digital-to-analog converter (DAC) circuitry and the baseband circuitry 804 may include a digital baseband interface to communicate with the RF circuitry 806.

[0092] In some dual-mode embodiments, a separate radio IC circuitry may be provided for processing signals for each spectrum, although the scope of the embodiments is not limited in this respect.

[0093] In some embodiments, the synthesizer circuitry 806d may be a fractional-N synthesizer or a fractional N/N+1 synthesizer, although the scope of the embodiments is not limited in this respect as other types of frequency synthesizers may be suitable. For

example, synthesizer circuitry 806d may be a delta-sigma synthesizer, a frequency multiplier, or a synthesizer comprising a phase-locked loop with a frequency divider.

[0094] The synthesizer circuitry 806d may be configured to synthesize an output frequency for use by the mixer circuitry 806a of the RF circuitry 806 based on a frequency input and a divider control input. In some embodiments, the synthesizer circuitry 806d may be a fractional N/N+1 synthesizer.

[0095] In some embodiments, frequency input may be provided by a voltage controlled oscillator (VCO), although that is not a necessity. Divider control input may be provided by either the baseband circuitry 804 or the applications processor 802 depending on the desired output frequency. In some embodiments, a divider control input (e.g., N) may be determined from a look-up table based on a channel indicated by the applications processor 802.

[0096] Synthesizer circuitry 806d of the RF circuitry 806 may include a divider, a delay-locked loop (DLL), a multiplexer and a phase accumulator. In some embodiments, the divider may be a dual modulus divider (DMD) and the phase accumulator may be a digital phase accumulator (DPA). In some embodiments, the DMD may be configured to divide the input signal by either N or N+1 (e.g., based on a carry out) to provide a fractional division ratio. In some example embodiments, the DLL may include a set of cascaded, tunable, delay elements, a phase detector, a charge pump and a D-type flip-flop. In these embodiments, the delay elements may be configured to break a VCO period up into Nd equal packets of phase, where Nd is the number of delay elements in the delay line. In this way, the DLL provides negative feedback to help ensure that the total delay through the delay line is one VCO cycle.

[0097] In some embodiments, synthesizer circuitry 806d may be configured to generate a carrier frequency as the output frequency, while in other embodiments, the output frequency may be a multiple of the carrier frequency (e.g., twice the carrier frequency, four times the carrier frequency) and used in conjunction with quadrature generator and divider circuitry to generate multiple signals at the carrier frequency with multiple different phases with respect to each other. In some embodiments, the output frequency may be a LO frequency (fLO). In some embodiments, the RF circuitry 806 may include an IQ/polar converter.

[0098] FEM circuitry 808 may include a receive signal path which may include circuitry configured to operate on RF signals received from one or more antennas 810, amplify the received signals and provide the amplified versions of the received signals to the RF circuitry 806 for further processing. FEM circuitry 808 may also include a transmit signal path which may include circuitry configured to amplify signals for transmission provided by the RF circuitry 806 for transmission by one or more of the one or more antennas 810. In various embodiments, the amplification through the transmit or receive signal paths may be done solely in the RF circuitry 806, solely in the FEM 808, or in both the RF circuitry 806 and the FEM 808.

[0099] In some embodiments, the FEM circuitry 808 may include a TX/RX switch to switch between transmit mode and receive mode operation. The FEM circuitry may include a receive signal path and a transmit signal path. The receive signal path of the FEM circuitry may include an LNA to amplify received RF signals and provide the amplified received RF signals as an output (e.g., to the RF circuitry 806). The transmit signal path of the FEM circuitry 808 may include a power amplifier (PA) to amplify input RF signals (e.g., provided by RF circuitry 806), and one or more filters to generate RF signals for subsequent transmission (e.g., by one or more of the one or more antennas 810).

[00100] In some embodiments, the PMC 812 may manage power provided to the baseband circuitry 804. In particular, the PMC 812 may control power-source selection, voltage scaling, battery charging, or DC-to-DC conversion. The PMC 812 may often be included when the device 800 is capable of being powered by a battery, for example, when the device is included in a UE. The PMC 812 may increase the power conversion efficiency while providing desirable implementation size and heat dissipation characteristics.

[00101] While FIG. 8 shows the PMC 812 coupled only with the baseband circuitry 804. However, in other embodiments, the PMC 8 12 may be additionally or alternatively coupled with, and perform similar power management operations for, other components such as, but not limited to, application circuitry 802, RF circuitry 806, or FEM 808.

[00102] In some embodiments, the PMC 812 may control, or otherwise be part of, various power saving mechanisms of the device 800. For example, if the device 800 is in

an RRC_Connected state, where it is still connected to the RAN node as it expects to receive traffic shortly, then it may enter a state known as Discontinuous Reception Mode (DRX) after a period of inactivity. During this state, the device 800 may power down for brief intervals of time and thus save power.

[00103] If there is no data traffic activity for an extended period of time, then the device 800 may transition off to an RRC_Idle state, where it disconnects from the network and does not perform operations such as channel quality feedback, handover, etc. The device 800 goes into a very low power state and it performs paging where again it periodically wakes up to listen to the network and then powers down again. The device 800 may not receive data in this state, in order to receive data, it can transition back to RRC_Connected state.

[00104] An additional power saving mode may allow a device to be unavailable to the network for periods longer than a paging interval (ranging from seconds to a few hours). During this time, the device is totally unreachable to the network and may power down completely. Any data sent during this time incurs a large delay and it is assumed the delay is acceptable.

[00105] Processors of the application circuitry 802 and processors of the baseband circuitry 804 may be used to execute elements of one or more instances of a protocol stack. For example, processors of the baseband circuitry 804, alone or in combination, may be used execute Layer 3, Layer 2, or Layer 1 functionality, while processors of the application circuitry 804 may utilize data (e.g., packet data) received from these layers and further execute Layer 4 functionality (e.g., transmission communication protocol (TCP) and user datagram protocol (UDP) layers). As referred to herein, Layer 3 may comprise a radio resource control (RRC) layer, described in further detail below. As referred to herein, Layer 2 may comprise a medium access control (MAC) layer, a radio link control (RLC) layer, and a packet data convergence protocol (PDCP) layer, described in further detail below. As referred to herein, Layer 1 may comprise a physical (PHY) layer of a UE/RAN node, described in further detail below.

[00106] FIG. 9 illustrates example interfaces of baseband circuitry in accordance with some embodiments. As discussed above, the baseband circuitry 804 of FIG. 8 may comprise processors 804A-804E and a memory 804G utilized by said processors. Each

of the processors 804A-804E may include a memory interface, 904A-904E, respectively, to send/receive data to/from the memory 804G

[00107] The baseband circuitry 804 may further include one or more interfaces to communicatively couple to other circuitries/devices, such as a memory interface 912 (e.g., an interface to send/receive data to/from memory external to the baseband circuitry 804), an application circuitry interface 914 (e.g., an interface to send/receive data to/from the application circuitry 802 of FIG. 8), an RF circuitry interface 916 (e.g., an interface to send/receive data to/from RF circuitry 806 of FIG. 8), a wireless hardware connectivity interface 918 (e.g., an interface to send/receive data to/from Near Field Communication (NFC) components, Bluetooth® components (e.g., Bluetooth® Low Energy), Wi-Fi® components, and other communication components), and a power management interface 920 (e.g., an interface to send/receive power or control signals to/from the PMC 812.

[00108] FIG. 10 provides an example illustration of the wireless device, such as a user equipment (UE), a mobile station (MS), a mobile wireless device, a mobile communication device, a tablet, a handset, or other type of wireless device. The wireless device can include one or more antennas configured to communicate with a node, macro node, low power node (LPN), or, transmission station, such as a base station (BS), an evolved Node B (eNB), a baseband processing unit (BBU), a remote radio head (RRH), a remote radio equipment (RRE), a relay station (RS), a radio equipment (RE), or other type of wireless wide area network (WWAN) access point. The wireless device can be configured to communicate using at least one wireless communication standard such as, but not limited to, 3GPP LTE, WiMAX, High Speed Packet Access (HSPA), Bluetooth, and WiFi. The wireless device can communicate using separate antennas for each wireless communication standard or shared antennas for multiple wireless communication standards. The wireless device can communicate in a wireless local area network (WLAN), a wireless personal area network (WPAN), and/or a WWAN. The wireless device can also comprise a wireless modem. The wireless modem can comprise, for example, a wireless radio transceiver and baseband circuitry (e.g., a baseband processor). The wireless modem can, in one example, modulate signals that the wireless device transmits via the one or more antennas and demodulate signals that the wireless device receives via the one or more antennas.

[00109] FIG. 10 also provides an illustration of a microphone and one or more speakers that can be used for audio input and output from the wireless device. The display screen can be a liquid crystal display (LCD) screen, or other type of display screen such as an organic light emitting diode (OLED) display. The display screen can be configured as a touch screen. The touch screen can use capacitive, resistive, or another type of touch screen technology. An application processor and a graphics processor can be coupled to internal memory to provide processing and display capabilities. A non-volatile memory port can also be used to provide data input/output options to a user. The non-volatile memory port can also be used to expand the memory capabilities of the wireless device. A keyboard can be integrated with the wireless device or wirelessly connected to the wireless device to provide additional user input. A virtual keyboard can also be provided using the touch screen.

Examples

[00110] The following examples pertain to specific technology embodiments and point out specific features, elements, or actions that can be used or otherwise combined in achieving such embodiments.

[00111] Example 1 includes an apparatus of a user equipment (UE) operable to maintain a plurality of received beams, the apparatus comprising: one or more processors configured to: decode an interference measurement resource (IMR) configuration for the UE that is received from a transmission reception point (TRP); identify a receive (Rx) beam of the plurality of Rx beams that is associated with the IMR configuration; perform an interference measurement and a channel measurement using the identified Rx beam; and encode a measurement report for transmission to the TRP, wherein the measurement report is based on the interference measurement and the channel measurement; and a memory interface configured to send to a memory the IMR configuration.

[00112] Example 2 includes the apparatus of example 1, wherein the one or more processors are further configured to decode a CSI-RS configuration for the UE that is received from the TRP, wherein the CSI-RS configuration includes a UE Rx beam indication associated with each CSI-RS resource configured in the CSI-RS configuration for the UE.

[00113] Example 3 includes the apparatus of example 1 or 2, wherein the one or more processors are further configured to identify the Rx beam that is associated with the IMR configuration by determining a UE Rx beam indication associated with each CSI-RS resource and using a same Rx beam to perform each IMR measurement at the UE.

[00114] Example 4 includes the apparatus of example 3, wherein the UE Rx beam indication comprises $\log_2 N$ bits, wherein N is a number of CSI-RS resources configured for the UE.

[00115] Example 5 includes the apparatus of example 3, wherein the UE Rx beam indication is included in a quasi-co-location (QCL) indicator, wherein the QCL indicator is associated with a non-zero power (NZP) CSI-RS resource, a synchronization signal or a physical broadcast channel (PBCH) block, wherein the QCL indicator corresponds to one or more spatial Rx parameters.

[00116] Example 6 includes the apparatus of example 1, wherein the one or more processors are further configured to identify the Rx beam that is associated with the interference measurement by decoding a UE Rx beam indication that is received in the IMR configuration and is associated with the interference measurement.

[00117] Example 7 includes the apparatus of example 1 or 2, wherein the IMR configuration is received via one or more of downlink control information (DCI) or higher layer signaling.

[00118] Example 8 includes the apparatus of example 1 or 2, wherein the measurement report is a channel state information (CSI) report or a reference signal receive power (RSRP) report, wherein the CSI report or RSRP report comprises one or more of: a CSI reference signal (CSI-RS) resource index (CRI); a channel quality indicator (CQI); a precoding matrix indicator (PMI); or a rank indicator (RI).

[00119] Example 9 includes an apparatus of a transmission reception point (TRP) operable to maintain a plurality of received beams, the apparatus comprising: one or more processors configured to: decode a user equipment (UE) capability report received from a UE; identify a number of receive (Rx) beams the UE is capable of maintaining simultaneously; encode an interference measurement resource (IMR) configuration for the UE, wherein each IMR in the IMR configuration is associated with a UE Rx beam

when the number of received beams is greater than one; and decode a measurement report received from the UE, wherein the measurement report is based on an interference measurement and a channel measurement performed at the UE; and a memory interface configured to send to a memory the UE capability report.

[00120] Example 10 includes the apparatus of example 9, wherein the one or more processors are further configured to encode a CSI-RS configuration for the UE, wherein the CSI-RS configuration includes a UE Rx beam indication associated with each CSI-RS resource configured in the CSI-RS configuration for the UE.

[00121] Example 11 includes the apparatus of example 10, wherein the one or more processors are further configured to encode the IMR configuration for the UE, wherein the IMR configuration includes a UE Rx beam indication associated with each IMR in the IMR configuration.

[00122] Example 12 includes the apparatus of example 10, wherein the UE Rx beam indication comprises $\log_2 N$ bits, wherein N is a number of CSI-RS resources configured for the UE.

[00123] Example 13 includes the apparatus of example 9 or 10, wherein the one or more processors are further configured to encode an interference measurement resource (IMR) configuration for the UE, wherein each IMR in the IMR configuration is not associated with a UE Rx beam when the number of received beams is equal to one.

[00124] Example 14 includes the apparatus of example 10, wherein the UE Rx beam indication is included in a quasi-co-location (QCL) indicator wherein the QCL indicator is associated with a non-zero power (NZP) CSI-RS resource, a synchronization signal or a physical broadcast channel (PBCH) block, wherein the QCL indicator corresponds to one or more spatial Rx parameters.

[00125] Example 15 includes the apparatus of example 9 or 10, wherein the one or more processors are further configured to encode the IMR configuration for transmission to the UE using one or more of downlink control information (DCI) or higher layer signaling.

[00126] Example 16 includes apparatus of a user equipment (UE) operable to measure interference using non-zero power (NZP) channel state information reference symbols

(CSI-RS), the apparatus comprising: one or more processors configured to: decode channel state information reference signal (CSI-RS) configuration information received from a transmission reception point (TRP) for the UE; decode CSI-RS configuration information received from the TRP for one or more additional UEs associated with multi-user multiple input multiple output (MU-MIMO) operation or additional UEs associated with one or more neighboring TRPs; estimate a channel, H_i, for an *i*-th UE of the one or more additional UEs; calculate an interference, R_i, for the one or more additional UEs using $R_i = H_i * H_i^H$, wherein $()^H$ is a conjugate transpose operation, and *i* is the *i*-th UE of the one or more additional UEs; encode the interference of the one or more additional UEs in a CSI report for transmission to the TRP; and a memory interface configured to send to a memory the CSI report.

[00127] Example 17 includes the apparatus of example 16, wherein the one or more processors are further configured to decode the interference measurement configuration information comprising which of the one or more additional UEs to calculate the interference for.

[00128] Example 18 includes the apparatus of example 16 or 17, wherein the one or more processors are further configured to decode the interference measurement configuration information comprising selected combinations of the one or more additional UEs to report the interference for.

[00129] Example 19 includes the apparatus of example 18, wherein the one or more processors are further configured to add the interference, R_i, for the selected combinations of the one or more additional UEs and encode the added R_i for transmission to the TRP in the intra-cell interference report or a CSI report.

[00130] Example 20 includes an apparatus of a transmission reception point (TRP) operable to determine intra-cell performance, the apparatus comprising: one or more processors configured to: encode an interference measurement resource (IMR) configuration comprising a channel state information (CSI) reference signal (CSI-RS) configuration information for a user equipment (UE); encode CSI-RS configuration information for one or more additional UEs associated with multi-user multiple input multiple output (MU-MIMO) operation for transmission to the UE, to enable the UE to:

estimate a channel, H_i, for an *i*-th UE of the one or more additional UEs; calculate an interference, R_i, for the one or more additional UEs using $R_i = H_i * H_i^H$, wherein $()^H$ is a conjugate transpose operation, and *i* is the *i*-th UE of the one or more additional UEs; encode the interference of the one or more additional UEs in an intra-cell interference report or a CSI report for transmission to the TRP; and a memory interface configured to send to a memory the CSI report.

[00131] Example 21 includes the apparatus of example 20, wherein the CSI-RS configuration information includes Non-Zero Power (NZP) CSI-RS.

[00132] Example 22 includes an apparatus of a user equipment (UE) operable to maintain a plurality of received beams, the apparatus comprising: one or more processors configured to: decode an interference measurement resource (IMR) configuration for the UE that is received from a transmission reception point (TRP); identify a receive (Rx) beam of the plurality of Rx beams that is associated with the IMR configuration; perform an interference measurement and a channel measurement using the identified Rx beam; and encode a measurement report for transmission to the TRP, wherein the measurement report is based on the interference measurement and the channel measurement; and a memory interface configured to send to a memory the IMR configuration.

[00133] Example 23 includes the apparatus of example 22, wherein the one or more processors are further configured to decode a CSI-RS configuration for the UE that is received from the TRP, wherein the CSI-RS configuration includes a UE Rx beam indication associated with each CSI-RS resource configured in the CSI-RS configuration for the UE.

[00134] Example 24 includes the apparatus of example 23, wherein the one or more processors are further configured to identify the Rx beam that is associated with the IMR configuration by determining a UE Rx beam indication associated with each CSI-RS resource and using a same Rx beam to perform each IMR measurement at the UE.

[00135] Example 25 includes the apparatus of example 24, wherein the UE Rx beam indication comprises $\log_2 N$ bits, wherein N is a number of CSI-RS resources configured for the UE.

[00136] Example 26 includes the apparatus of example 24, wherein the UE Rx beam

indication is included in a quasi-co-location (QCL) indicator, wherein the QCL indicator is associated with a non-zero power (NZP) CSI-RS resource, a synchronization signal or a physical broadcast channel (PBCH) block, wherein the QCL indicator corresponds to one or more spatial Rx parameters.

[00137] Example 27 includes the apparatus of example 22, wherein the one or more processors are further configured to identify the Rx beam that is associated with the interference measurement by decoding a UE Rx beam indication that is received in the IMR configuration and is associated with the interference measurement.

[00138] Example 28 includes the apparatus of example 22, wherein the IMR configuration is received via one or more of downlink control information (DCI) or higher layer signaling.

[00139] Example 29 includes the apparatus of example 22, wherein the measurement report is a channel state information (CSI) report or a reference signal receive power (RSRP) report, wherein the CSI report or RSRP report comprises one or more of: a CSI reference signal (CSI-RS) resource index (CRI); a channel quality indicator (CQI); a precoding matrix indicator (PMI); or a rank indicator (RI).

[00140] Example 30 includes an apparatus of a transmission reception point (TRP) operable to maintain a plurality of received beams, the apparatus comprising: one or more processors configured to: decode a user equipment (UE) capability report received from a UE; identify a number of receive (Rx) beams the UE is capable of maintaining simultaneously; encode an interference measurement resource (IMR) configuration for the UE, wherein each IMR in the IMR configuration is associated with a UE Rx beam when the number of received beams is greater than one; and decode a measurement report received from the UE, wherein the measurement report is based on an interference measurement and a channel measurement performed at the UE; and a memory interface configured to send to a memory the UE capability report.

[00141] Example 31 includes the apparatus of example 30, wherein the one or more processors are further configured to encode a CSI-RS configuration for the UE, wherein the CSI-RS configuration includes a UE Rx beam indication associated with each CSI-RS resource configured in the CSI-RS configuration for the UE.

[00142] Example 32 includes the apparatus of example 31, wherein the one or more processors are further configured to encode the IMR configuration for the UE, wherein the IMR configuration includes a UE Rx beam indication associated with each IMR in the IMR configuration.

[00143] Example 33 includes the apparatus of example 31, wherein the UE Rx beam indication comprises $\log_2 N$ bits, wherein N is a number of CSI-RS resources configured for the UE.

[00144] Example 34 includes the apparatus of example 30, wherein the one or more processors are further configured to encode an interference measurement resource (IMR) configuration for the UE, wherein each IMR in the IMR configuration is not associated with a UE Rx beam when the number of received beams is equal to one.

[00145] Example 35 includes the apparatus of example 31, wherein the UE Rx beam indication is included in a quasi-co-location (QCL) indicator wherein the QCL indicator is associated with a non-zero power (NZP) CSI-RS resource, a synchronization signal or a physical broadcast channel (PBCH) block, wherein the QCL indicator corresponds to one or more spatial Rx parameters.

[00146] Example 36 includes the apparatus of example 30, wherein the one or more processors are further configured to encode the IMR configuration for transmission to the UE using one or more of downlink control information (DCI) or higher layer signaling.

[00147] Example 37 includes an apparatus of a user equipment (UE) operable to measure interference using non-zero power (NZP) channel state information reference symbols (CSI-RS), the apparatus comprising:one or more processors configured to: decode channel state information reference signal (CSI-RS) configuration information received from a transmission reception point (TRP) for the UE; decode CSI-RS configuration information received from the TRP for one or more additional UEs associated with multi-user multiple input multiple output (MU-MIMO) operation or additional UEs associated with one or more neighboring TRPs; estimate a channel, H_i, for an *i*-th UE of the one or more additional UEs; calculate an interference, R_i, for the one or more additional UEs using $R_i = H_i * H_i^H$, wherein $()^H$ is a conjugate transpose operation, and *i* is the *i*-th UE of the one or more additional UEs; encode the

interference of the one or more additional UEs in a CSI report for transmission to the TRP; and a memory interface configured to send to a memory the CSI report.

[00148] Example 38 includes the apparatus of example 37, wherein the one or more processors are further configured to decode the interference measurement configuration information comprising which of the one or more additional UEs to calculate the interference for.

[00149] Example 39 includes the apparatus of example 37, wherein the one or more processors are further configured to decode the interference measurement configuration information comprising selected combinations of the one or more additional UEs to report the interference for.

[00150] Example 40 includes the apparatus of example 39, wherein the one or more processors are further configured to add the interference, R_i, for the selected combinations of the one or more additional UEs and encode the added R_i for transmission to the TRP in the intra-cell interference report or a CSI report.

[00151] Example 41 includes an apparatus of a transmission reception point (TRP) operable to determine intra-cell performance, the apparatus comprising: one or more processors configured to: encode an interference measurement resource (IMR) configuration comprising a channel state information (CSI) reference signal (CSI-RS) configuration information for a user equipment (UE); encode CSI-RS configuration information for one or more additional UEs associated with multi-user multiple input multiple output (MU-MIMO) operation for transmission to the UE, to enable the UE to: estimate a channel, H_i, for an *i*-th UE of the one or more additional UEs; calculate an interference, R_i, for the one or more additional UEs using $R_i = H_i * H_i^H$, wherein $()^H$ is a conjugate transpose operation, and *i* is the *i*-th UE of the one or more additional UEs; encode the interference of the one or more additional UEs in an intra-cell interference report or a CSI report for transmission to the TRP; and a memory interface configured to send to a memory the CSI report.

[00152] Example 42 includes the apparatus of example 41, wherein the CSI-RS configuration information includes Non-Zero Power (NZP) CSI-RS.

[00153] Example 43 includes an apparatus of a user equipment (UE) operable to

maintain a plurality of received beams, the apparatus comprising: one or more processors configured to: decode an interference measurement resource (IMR) configuration for the UE that is received from a transmission reception point (TRP); identify a receive (Rx) beam of the plurality of Rx beams that is associated with the IMR configuration; perform an interference measurement and a channel measurement using the identified Rx beam; and encode a measurement report for transmission to the TRP, wherein the measurement report is based on the interference measurement and the channel measurement; and a memory interface configured to send to a memory the IMR configuration.

[00154] Example 44 includes the apparatus of example 43, wherein the one or more processors are further configured to: decode a CSI-RS configuration for the UE that is received from the TRP, wherein the CSI-RS configuration includes a UE Rx beam indication associated with each CSI-RS resource configured in the CSI-RS configuration for the UE; and identify the Rx beam that is associated with the IMR configuration by determining a UE Rx beam indication associated with each CSI-RS resource and using a same Rx beam to perform each IMR measurement at the UE.

[00155] Example 45 includes the apparatus of example 44, wherein the UE Rx beam indication comprises $\log_2 N$ bits, wherein N is a number of CSI-RS resources configured for the UE and the UE Rx beam indication is included in a quasi-co-location (QCL) indicator, wherein the QCL indicator is associated with a non-zero power (NZP) CSI-RS resource, a synchronization signal or a physical broadcast channel (PBCH) block, wherein the QCL indicator corresponds to one or more spatial Rx parameters.

[00156] Example 46 includes the apparatus of example 43, wherein the one or more processors are further configured to identify the Rx beam that is associated with the interference measurement by decoding a UE Rx beam indication that is received in the IMR configuration and is associated with the interference measurement.

[00157] Example 47 includes the apparatus of example 43 or 44, wherein the IMR configuration is received via one or more of downlink control information (DCI) or higher layer signaling.

[00158] Example 48 includes the apparatus of example 43 or 44, wherein the measurement report is a channel state information (CSI) report or a reference signal

receive power (RSRP) report, wherein the CSI report or RSRP report comprises one or more of: a CSI reference signal (CSI-RS) resource index (CRI); a channel quality indicator (CQI); a precoding matrix indicator (PMI); or a rank indicator (RI).

[00159] Example 49 includes the apparatus of a transmission reception point (TRP) operable to maintain a plurality of received beams, the apparatus comprising: one or more processors configured to: decode a user equipment (UE) capability report received from a UE; identify a number of receive (Rx) beams the UE is capable of maintaining simultaneously; encode an interference measurement resource (IMR) configuration for the UE, wherein each IMR in the IMR configuration is associated with a UE Rx beam when the number of received beams is greater than one; and decode a measurement report received from the UE, wherein the measurement report is based on an interference measurement and a channel measurement performed at the UE; and a memory interface configured to send to a memory the UE capability report.

[00160] Example 50 includes the apparatus of example 49, wherein the one or more processors are further configured to: encode a CSI-RS configuration for the UE, wherein the CSI-RS configuration includes a UE Rx beam indication associated with each CSI-RS resource configured in the CSI-RS configuration for the UE; and encode the IMR configuration for the UE, wherein the IMR configuration includes a UE Rx beam indication associated with each IMR in the IMR configuration, wherein the UE Rx beam indication comprises log2 N bits, wherein N is a number of CSI-RS resources configured for the UE.

[00161] Example 51 includes the apparatus of example 49 or 50, wherein the one or more processors are further configured to: encode an interference measurement resource (IMR) configuration for the UE, wherein each IMR in the IMR configuration is not associated with a UE Rx beam when the number of received beams is equal to one; and encode the IMR configuration for transmission to the UE using one or more of downlink control information (DCI) or higher layer signaling.

[00162] Example 52 includes the apparatus of example 50, wherein the UE Rx beam indication is included in a quasi-co-location (QCL) indicator wherein the QCL indicator is associated with a non-zero power (NZP) CSI-RS resource, a synchronization signal or a physical broadcast channel (PBCH) block, wherein the QCL indicator corresponds to one

or more spatial Rx parameters.

[00163] Example 53 includes an apparatus of a user equipment (UE) operable to measure interference using non-zero power (NZP) channel state information reference symbols (CSI-RS), the apparatus comprising: one or more processors configured to: decode channel state information reference signal (CSI-RS) configuration information received from a transmission reception point (TRP) for the UE; decode CSI-RS configuration information received from the TRP for one or more additional UEs associated with multi-user multiple input multiple output (MU-MIMO) operation or additional UEs associated with one or more neighboring TRPs; estimate a channel, H_i, for an *i*-th UE of the one or more additional UEs; calculate an interference, R_i, for the one or more additional UEs using $R_i = H_i * H_i^H$, wherein $()^H$ is a conjugate transpose operation, and *i* is the *i*-th UE of the one or more additional UEs; encode the interference of the one or more additional UEs in a CSI report for transmission to the TRP; and a memory interface configured to send to a memory the CSI report.

[00164] Example 54 includes the apparatus of example 53, wherein the one or more processors are further configured to: decode the interference measurement configuration information comprising which of the one or more additional UEs to calculate the interference for; and decode the interference measurement configuration information comprising selected combinations of the one or more additional UEs to report the interference for.

[00165] Example 55 includes the apparatus of example 54, wherein the one or more processors are further configured to add the interference, R_i, for the selected combinations of the one or more additional UEs and encode the added R_i for transmission to the TRP in the intra-cell interference report or a CSI report.

[00166] Example 56 includes the apparatus of a transmission reception point (TRP) operable to determine intra-cell performance, the apparatus comprising: one or more processors configured to: encode an interference measurement resource (IMR) configuration comprising a channel state information (CSI) reference signal (CSI-RS) configuration information for a user equipment (UE); encode CSI-RS configuration information for one or more additional UEs associated with multi-user multiple input

multiple output (MU-MIMO) operation for transmission to the UE, to enable the UE to: estimate a channel, H_i, for an *i*-th UE of the one or more additional UEs; calculate an interference, R_i, for the one or more additional UEs using $R_i = H_i * H_i^H$, wherein $()^H$ is a conjugate transpose operation, and *i* is the *i*-th UE of the one or more additional UEs; encode the interference of the one or more additional UEs in an intra-cell interference report or a CSI report for transmission to the TRP; and a memory interface configured to send to a memory the CSI report.

[00167] Example 57 includes the apparatus of example 56, wherein the CSI-RS configuration information includes Non-Zero Power (NZP) CSI-RS.

[00168] Various techniques, or certain aspects or portions thereof, may take the form of program code (i.e., instructions) embodied in tangible media, such as floppy diskettes, compact disc-read-only memory (CD-ROMs), hard drives, non-transitory computer readable storage medium, or any other machine-readable storage medium wherein, when the program code is loaded into and executed by a machine, such as a computer, the machine becomes an apparatus for practicing the various techniques. In the case of program code execution on programmable computers, the computing device may include a processor, a storage medium readable by the processor (including volatile and non-volatile memory and/or storage elements), at least one input device, and at least one output device. The volatile and non-volatile memory and/or storage elements may be a random-access memory (RAM), erasable programmable read only memory (EPROM), flash drive, optical drive, magnetic hard drive, solid state drive, or other medium for storing electronic data. The node and wireless device may also include a transceiver module (i.e., transceiver), a counter module (i.e., counter), a processing module (i.e., processor), and/or a clock module (i.e., clock) or timer module (i.e., timer). In one example, selected components of the transceiver module can be located in a cloud radio access network (C-RAN). One or more programs that may implement or utilize the various techniques described herein may use an application programming interface (API), reusable controls, and the like. Such programs may be implemented in a high level procedural or object oriented programming language to communicate with a computer system. However, the program(s) may be implemented in assembly or machine language, if desired. In any case, the language may be a compiled or interpreted language, and

combined with hardware implementations.

[00169] As used herein, the term "circuitry" may refer to, be part of, or include an Application Specific Integrated Circuit (ASIC), an electronic circuit, a processor (shared, dedicated, or group), and/or memory (shared, dedicated, or group) that execute one or more software or firmware programs, a combinational logic circuit, and/or other suitable hardware components that provide the described functionality. In some embodiments, the circuitry may be implemented in, or functions associated with the circuitry may be implemented by, one or more software or firmware modules. In some embodiments, circuitry may include logic, at least partially operable in hardware.

[00170] It should be understood that many of the functional units described in this specification have been labeled as modules, in order to more particularly emphasize their implementation independence. For example, a module may be implemented as a hardware circuit comprising custom very-large-scale integration (VLSI) circuits or gate arrays, off-the-shelf semiconductors such as logic chips, transistors, or other discrete components. A module may also be implemented in programmable hardware devices such as field programmable gate arrays, programmable array logic, programmable logic devices or the like.

[00171] Modules may also be implemented in software for execution by various types of processors. An identified module of executable code may, for instance, comprise one or more physical or logical blocks of computer instructions, which may, for instance, be organized as an object, procedure, or function. Nevertheless, the executables of an identified module may not be physically located together, but may comprise disparate instructions stored in different locations which, when joined logically together, comprise the module and achieve the stated purpose for the module.

[00172] Indeed, a module of executable code may be a single instruction, or many instructions, and may even be distributed over several different code segments, among different programs, and across several memory devices. Similarly, operational data may be identified and illustrated herein within modules, and may be embodied in any suitable form and organized within any suitable type of data structure. The operational data may be collected as a single data set, or may be distributed over different locations including over different storage devices, and may exist, at least partially, merely as electronic

signals on a system or network. The modules may be passive or active, including agents operable to perform desired functions.

[00173] Reference throughout this specification to "an example" or “exemplary” means that a particular feature, structure, or characteristic described in connection with the example is included in at least one embodiment of the present technology. Thus, appearances of the phrases "in an example" or the word “exemplary” in various places throughout this specification are not necessarily all referring to the same embodiment.

[00174] As used herein, a plurality of items, structural elements, compositional elements, and/or materials may be presented in a common list for convenience. However, these lists should be construed as though each member of the list is individually identified as a separate and unique member. Thus, no individual member of such list should be construed as a de facto equivalent of any other member of the same list solely based on their presentation in a common group without indications to the contrary. In addition, various embodiments and example of the present technology may be referred to herein along with alternatives for the various components thereof. It is understood that such embodiments, examples, and alternatives are not to be construed as defacto equivalents of one another, but are to be considered as separate and autonomous representations of the present technology.

[00175] Furthermore, the described features, structures, or characteristics may be combined in any suitable manner in one or more embodiments. In the following description, numerous specific details are provided, such as examples of layouts, distances, network examples, etc., to provide a thorough understanding of embodiments of the technology. One skilled in the relevant art will recognize, however, that the technology can be practiced without one or more of the specific details, or with other methods, components, layouts, etc. In other instances, well-known structures, materials, or operations are not shown or described in detail to avoid obscuring aspects of the technology.

While the forgoing examples are illustrative of the principles of the present technology in one or more particular applications, it will be apparent to those of ordinary skill in the art that numerous modifications in form, usage and details of implementation can be made without the exercise of inventive faculty, and without departing from the principles and

concepts of the technology. Accordingly, it is not intended that the technology be limited, except as by the claims set forth below.

CLAIMS

What is claimed is:

1. An apparatus of a user equipment (UE) operable to maintain a plurality of received beams, the apparatus comprising:

one or more processors configured to:

decode an interference measurement resource (IMR) configuration for the UE that is received from a transmission reception point (TRP);

identify a receive (Rx) beam of the plurality of Rx beams that is associated with the IMR configuration;

perform an interference measurement and a channel measurement using the identified Rx beam; and

encode a measurement report for transmission to the TRP, wherein the measurement report is based on the interference measurement and the channel measurement; and

a memory interface configured to send to a memory the IMR configuration.

2. The apparatus of claim 1, wherein the one or more processors are further configured to decode a CSI-RS configuration for the UE that is received from the TRP, wherein the CSI-RS configuration includes a UE Rx beam indication associated with each CSI-RS resource configured in the CSI-RS configuration for the UE.

3. The apparatus of claim 1 or 2, wherein the one or more processors are further configured to identify the Rx beam that is associated with the IMR configuration by determining a UE Rx beam indication associated with each CSI-RS resource and using a same Rx beam to perform each IMR measurement at the UE.

4. The apparatus of claim 3, wherein the UE Rx beam indication comprises $\log_2 N$ bits, wherein N is a number of CSI-RS resources configured for the UE.

5. The apparatus of claim 3, wherein the UE Rx beam indication is included in a quasi-co-location (QCL) indicator, wherein the QCL indicator is associated with a non-zero power (NZP) CSI-RS resource, a synchronization signal or a physical broadcast channel (PBCH) block, wherein the QCL indicator corresponds to one or more spatial Rx parameters.

6. The apparatus of claim 1, wherein the one or more processors are further configured to identify the Rx beam that is associated with the interference measurement by decoding a UE Rx beam indication that is received in the IMR configuration and is associated with the interference measurement.

7. The apparatus of claim 1 or 2, wherein the IMR configuration is received via one or more of downlink control information (DCI) or higher layer signaling.

8. The apparatus of claim 1 or 2, wherein the measurement report is a channel state information (CSI) report or a reference signal receive power (RSRP) report, wherein the CSI report or RSRP report comprises one or more of:

a CSI reference signal (CSI-RS) resource index (CRI);
a channel quality indicator (CQI);
a precoding matrix indicator (PMI); or
a rank indicator (RI).

9. An apparatus of a transmission reception point (TRP) operable to maintain a plurality of received beams, the apparatus comprising:

one or more processors configured to:

decode a user equipment (UE) capability report received from a UE;

identify a number of receive (Rx) beams the UE is capable of maintaining simultaneously;

encode an interference measurement resource (IMR) configuration for the UE, wherein each IMR in the IMR configuration is associated with

a UE Rx beam when the number of received beams is greater than one; and

decode a measurement report received from the UE, wherein the measurement report is based on an interference measurement and a channel measurement performed at the UE; and

a memory interface configured to send to a memory the UE capability report.

10. The apparatus of claim 9, wherein the one or more processors are further configured to encode a CSI-RS configuration for the UE, wherein the CSI-RS configuration includes a UE Rx beam indication associated with each CSI-RS resource configured in the CSI-RS configuration for the UE.

11. The apparatus of claim 10, wherein the one or more processors are further configured to encode the IMR configuration for the UE, wherein the IMR configuration includes a UE Rx beam indication associated with each IMR in the IMR configuration.

12. The apparatus of claim 10, wherein the UE Rx beam indication comprises $\log_2 N$ bits, wherein N is a number of CSI-RS resources configured for the UE.

13. The apparatus of claim 9 or 10, wherein the one or more processors are further configured to encode an interference measurement resource (IMR) configuration for the UE, wherein each IMR in the IMR configuration is not associated with a UE Rx beam when the number of received beams is equal to one.

14. The apparatus of claim 10, wherein the UE Rx beam indication is included in a quasi-co-location (QCL) indicator wherein the QCL indicator is associated with a non-zero power (NZP) CSI-RS resource, a synchronization signal or a physical broadcast channel (PBCH) block, wherein the QCL indicator corresponds to one or more spatial Rx parameters.

15. The apparatus of claim 9 or 10, wherein the one or more processors are further configured to encode the IMR configuration for transmission to the UE using one or more of downlink control information (DCI) or higher layer signaling.

16. An apparatus of a user equipment (UE) operable to measure interference using non-zero power (NZP) channel state information reference symbols (CSI-RS), the apparatus comprising:

one or more processors configured to:

decode channel state information reference signal (CSI-RS) configuration information received from a transmission reception point (TRP) for the UE;

decode CSI-RS configuration information received from the TRP for one or more additional UEs associated with multi-user multiple input multiple output (MU-MIMO) operation or additional UEs associated with one or more neighboring TRPs;

estimate a channel, H_i, for an *i*-th UE of the one or more additional UEs;

calculate an interference, R_i, for the one or more additional UEs using $R_i = H_i \times H_i^H$, wherein $()^H$ is a conjugate transpose operation, and *i* is the *i*-th UE of the one or more additional UEs;

encode the interference of the one or more additional UEs in a CSI report for transmission to the TRP; and

a memory interface configured to send to a memory the CSI report.

17. The apparatus of claim 16, wherein the one or more processors are further configured to decode the interference measurement configuration information comprising which of the one or more additional UEs to calculate the interference for.

18. The apparatus of claim 16 or 17, wherein the one or more processors are further configured to decode the interference measurement configuration information comprising selected combinations of the one or more additional UEs to report the

interference for.

19. The apparatus of claim 18, wherein the one or more processors are further configured to add the interference, R_i, for the selected combinations of the one or more additional UEs and encode the added R_i for transmission to the TRP in the intra-cell interference report or a CSI report.

20. An apparatus of a transmission reception point (TRP) operable to determine intra-cell performance, the apparatus comprising:

one or more processors configured to:

encode an interference measurement resource (IMR) configuration comprising a channel state information (CSI) reference signal (CSI-RS) configuration information for a user equipment (UE);

encode CSI-RS configuration information for one or more additional UEs associated with multi-user multiple input multiple output (MU-MIMO) operation for transmission to the UE, to enable the UE to:

estimate a channel, H_i, for an *i*-th UE of the one or more additional UEs;

calculate an interference, R_i, for the one or more additional UEs using $R_i = H_i * H_i^H$, wherein $()^H$ is a conjugate transpose operation, and *i* is the *i*-th UE of the one or more additional UEs;

encode the interference of the one or more additional UEs in an intra-cell interference report or a CSI report for transmission to the TRP; and

a memory interface configured to send to a memory the CSI report.

21. The apparatus of claim 19, wherein the CSI-RS configuration information includes Non-Zero Power (NZP) CSI-RS.

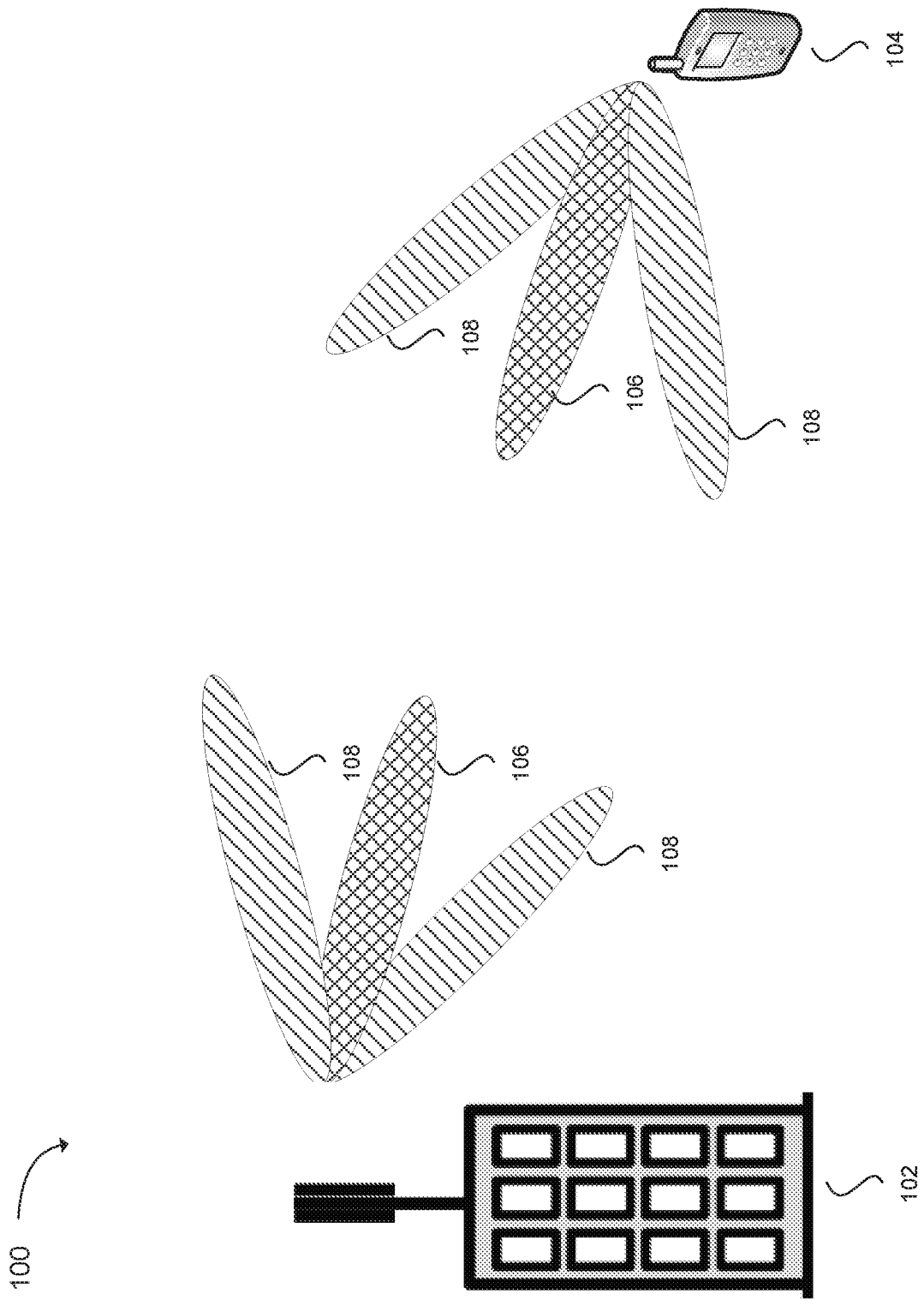


FIG. 1

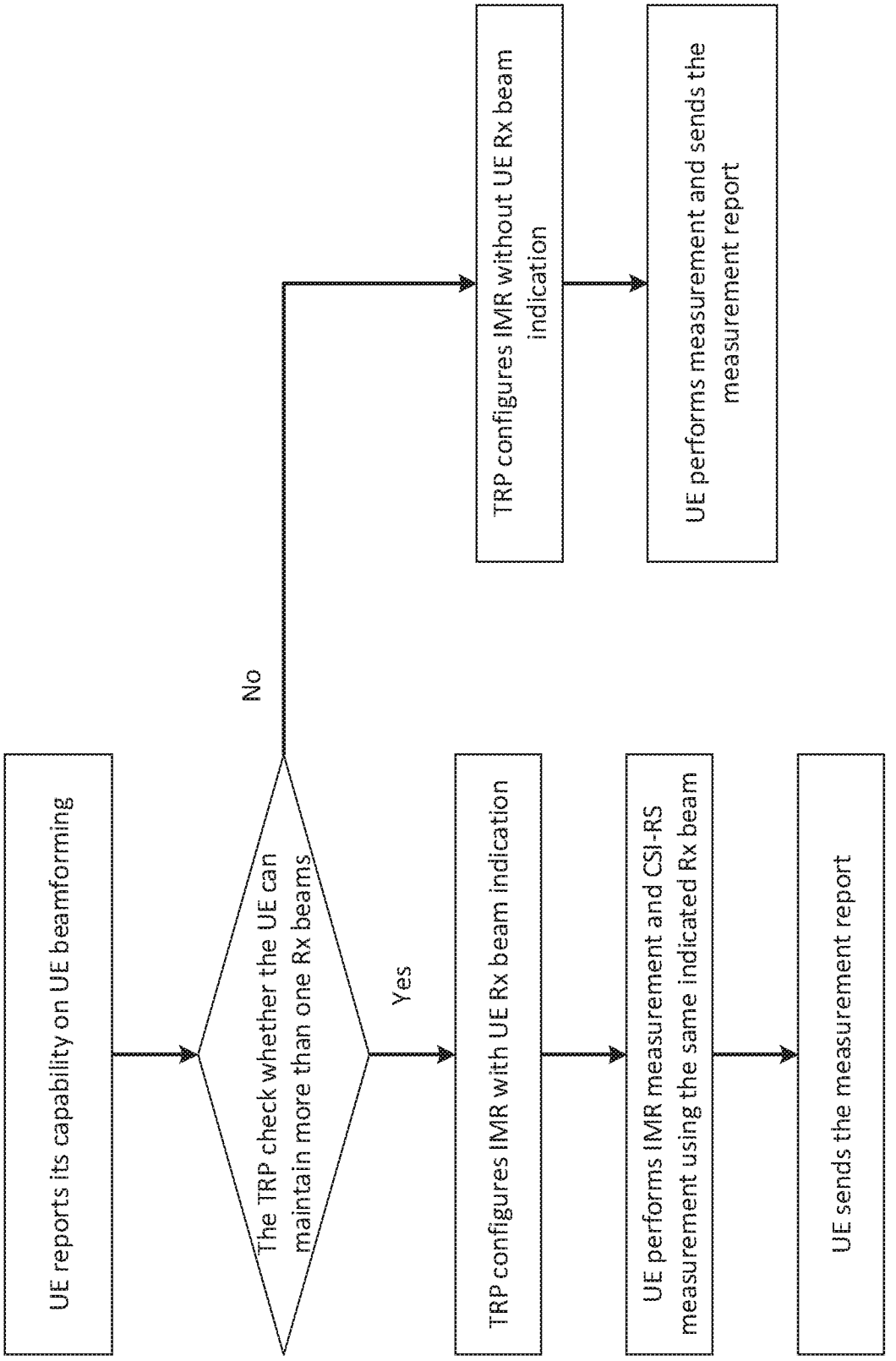

UE reports its capability on UE beamforming
The TRP check whether the UE can maintain more than one Rx beams
No
Yes
TRP configures IMR without UE Rx beam indication
UE performs measurement and sends the measurement report
TRP configures IMR with UE Rx beam indication
UE performs IMR measurement and CSI-RS measurement using the same indicated Rx beam
UE sends the measurement report

FIG. 2

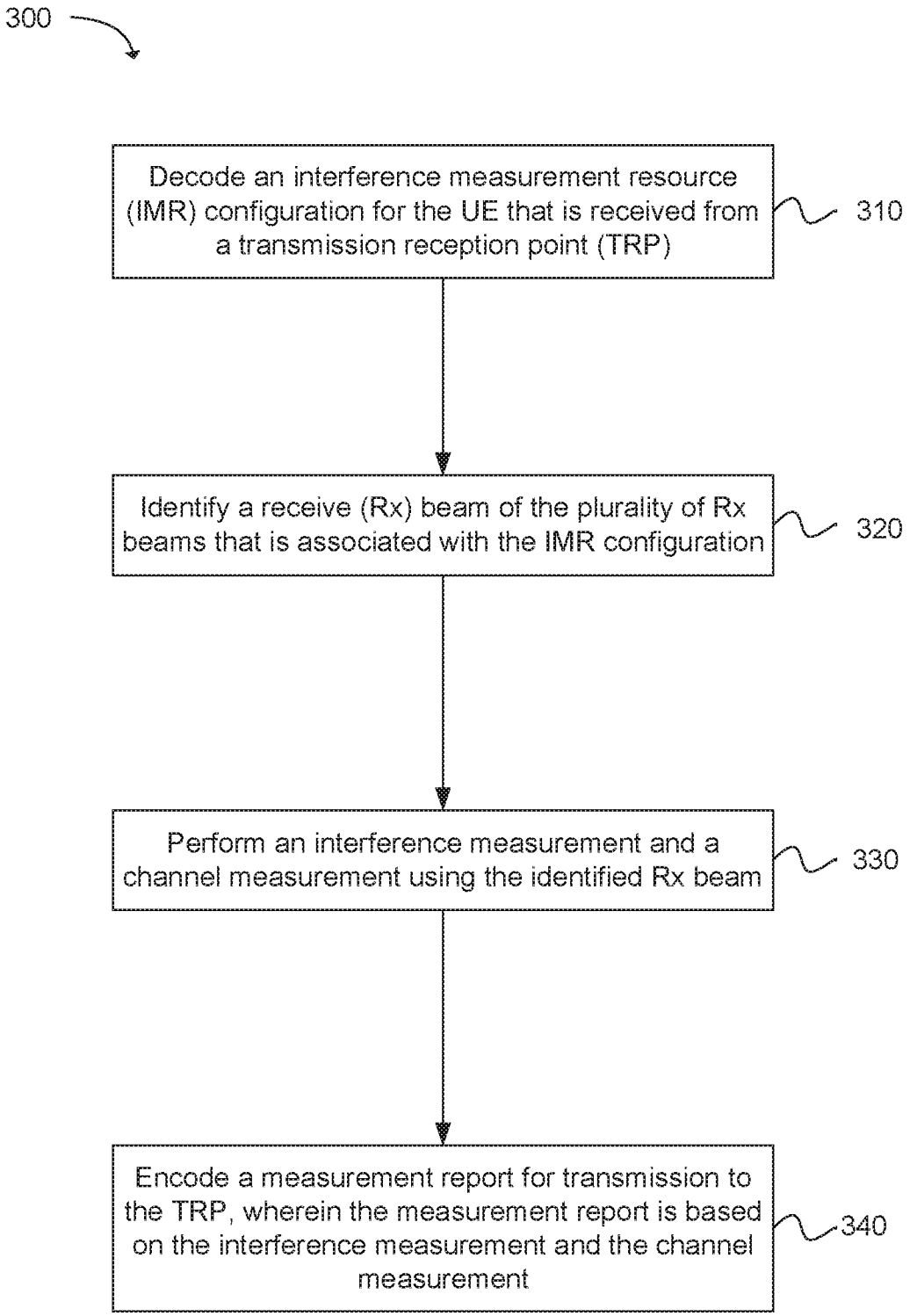

300
Decode an interference measurement resource (IMR) configuration for the UE that is received from a transmission reception point (TRP)
310
Identify a receive (Rx) beam of the plurality of Rx beams that is associated with the IMR configuration
320
Perform an interference measurement and a channel measurement using the identified Rx beam
330
Encode a measurement report for transmission to the TRP, wherein the measurement report is based on the interference measurement and the channel measurement
340

FIG. 3

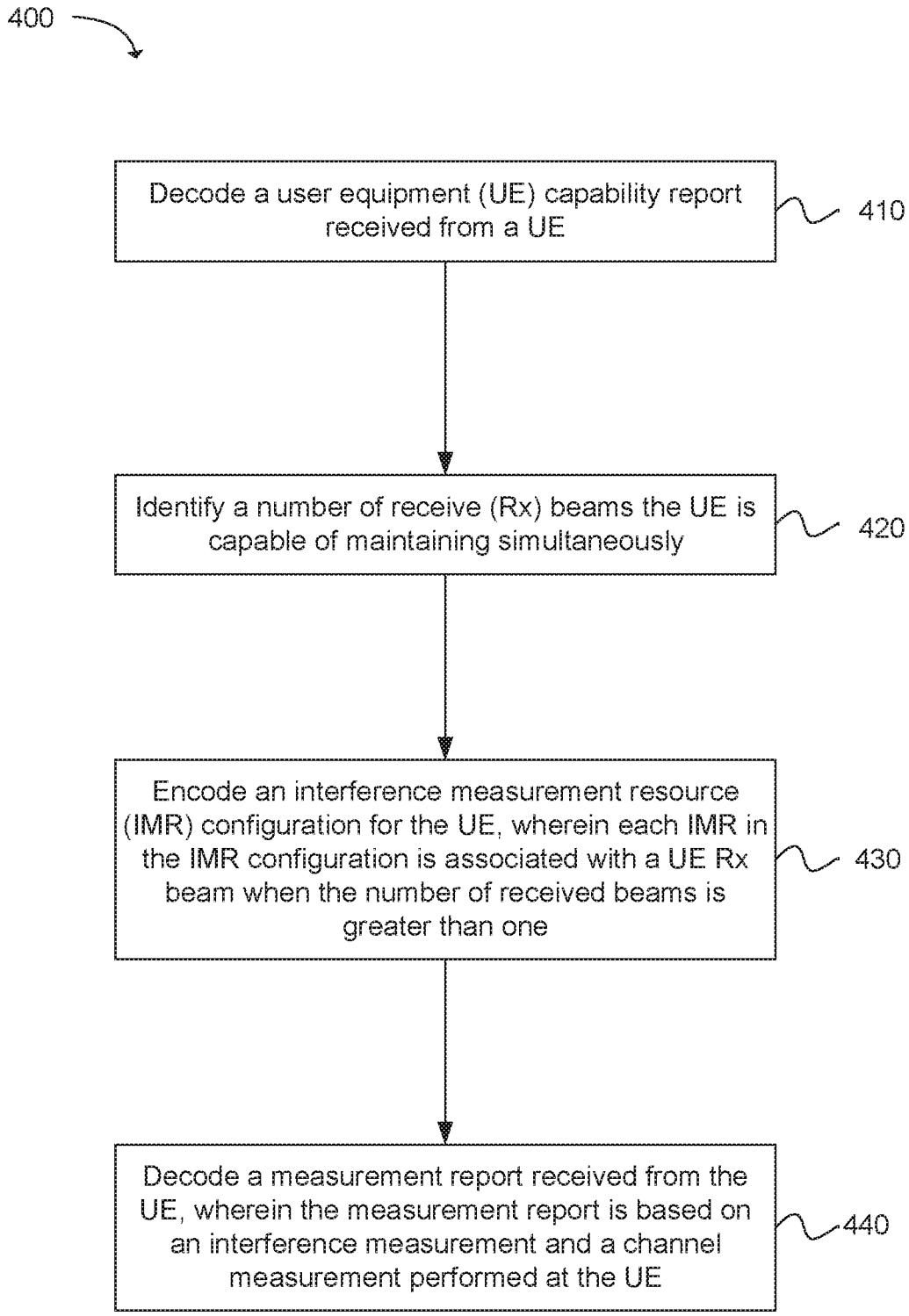

400
Decode a user equipment (UE) capability report received from a UE
410
Identify a number of receive (Rx) beams the UE is capable of maintaining simultaneously
420
Encode an interference measurement resource (IMR) configuration for the UE, wherein each IMR in the IMR configuration is associated with a UE Rx beam when the number of received beams is greater than one
430
Decode a measurement report received from the UE, wherein the measurement report is based on an interference measurement and a channel measurement performed at the UE
440

FIG. 4

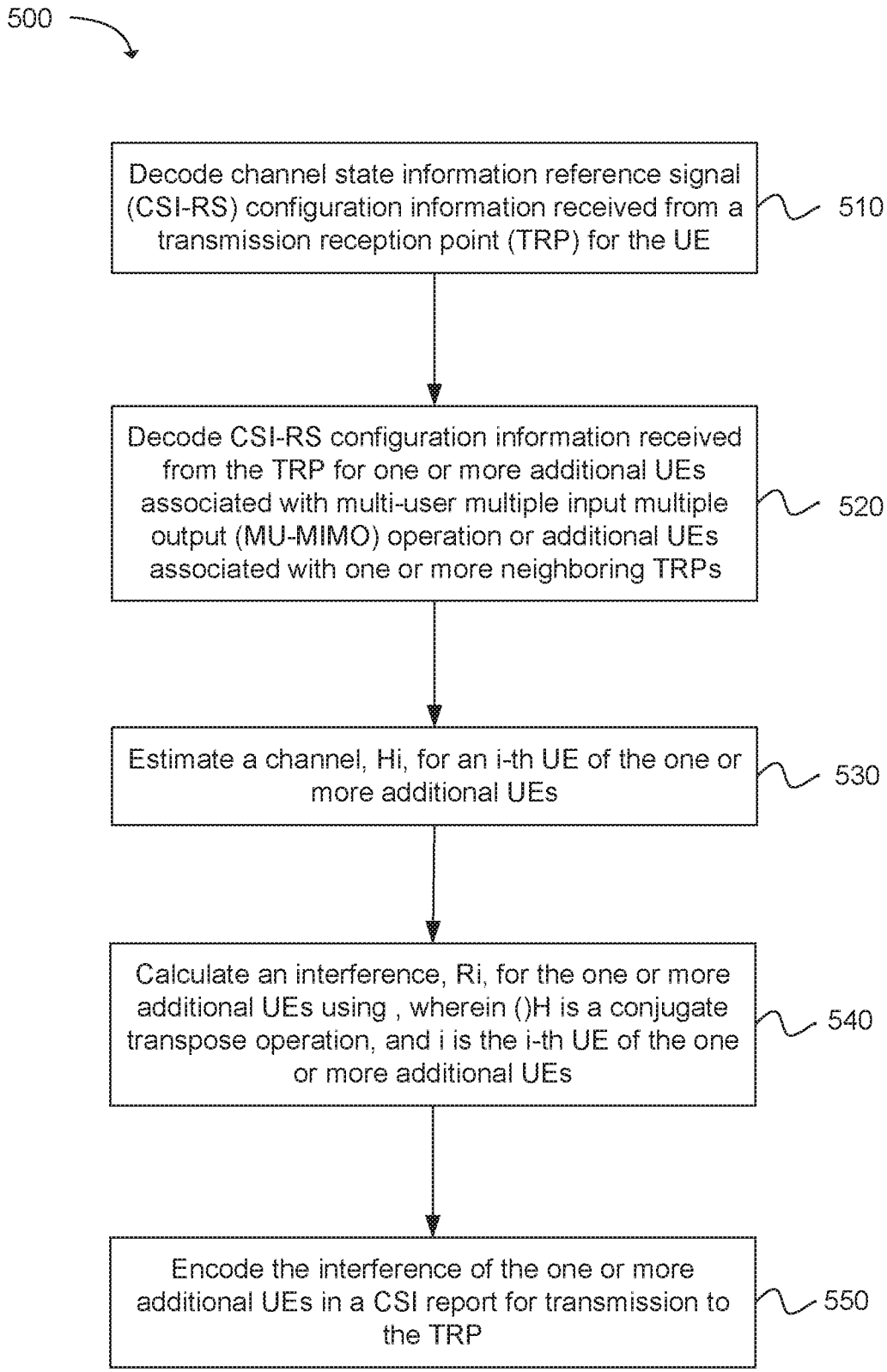

500
Decode channel state information reference signal (CSI-RS) configuration information received from a transmission reception point (TRP) for the UE
510
Decode CSI-RS configuration information received from the TRP for one or more additional UEs associated with multi-user multiple input multiple output (MU-MIMO) operation or additional UEs associated with one or more neighboring TRPs
520
Estimate a channel, Hi, for an i-th UE of the one or more additional UEs
530
Calculate an interference, Ri, for the one or more additional UEs using , wherein ()H is a conjugate transpose operation, and i is the i-th UE of the one or more additional UEs
540
Encode the interference of the one or more additional UEs in a CSI report for transmission to the TRP
550

FIG. 5

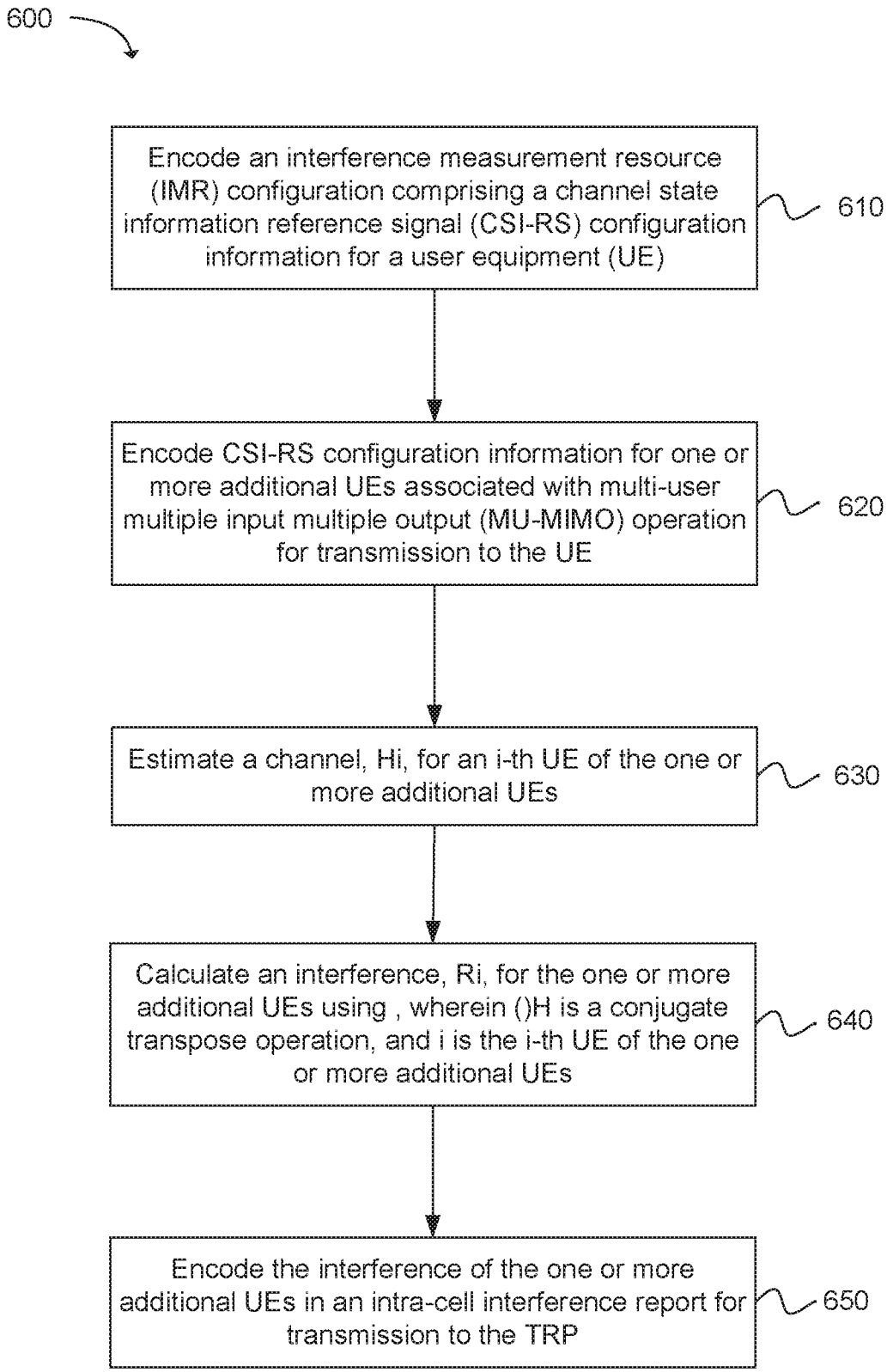

600
Encode an interference measurement resource (IMR) configuration comprising a channel state information reference signal (CSI-RS) configuration information for a user equipment (UE)
610
Encode CSI-RS configuration information for one or more additional UEs associated with multi-user multiple input multiple output (MU-MIMO) operation for transmission to the UE
620
Estimate a channel, Hi, for an i-th UE of the one or more additional UEs
630
Calculate an interference, Ri, for the one or more additional UEs using , wherein ()H is a conjugate transpose operation, and i is the i-th UE of the one or more additional UEs
640
Encode the interference of the one or more additional UEs in an intra-cell interference report for transmission to the TRP
650

FIG. 6

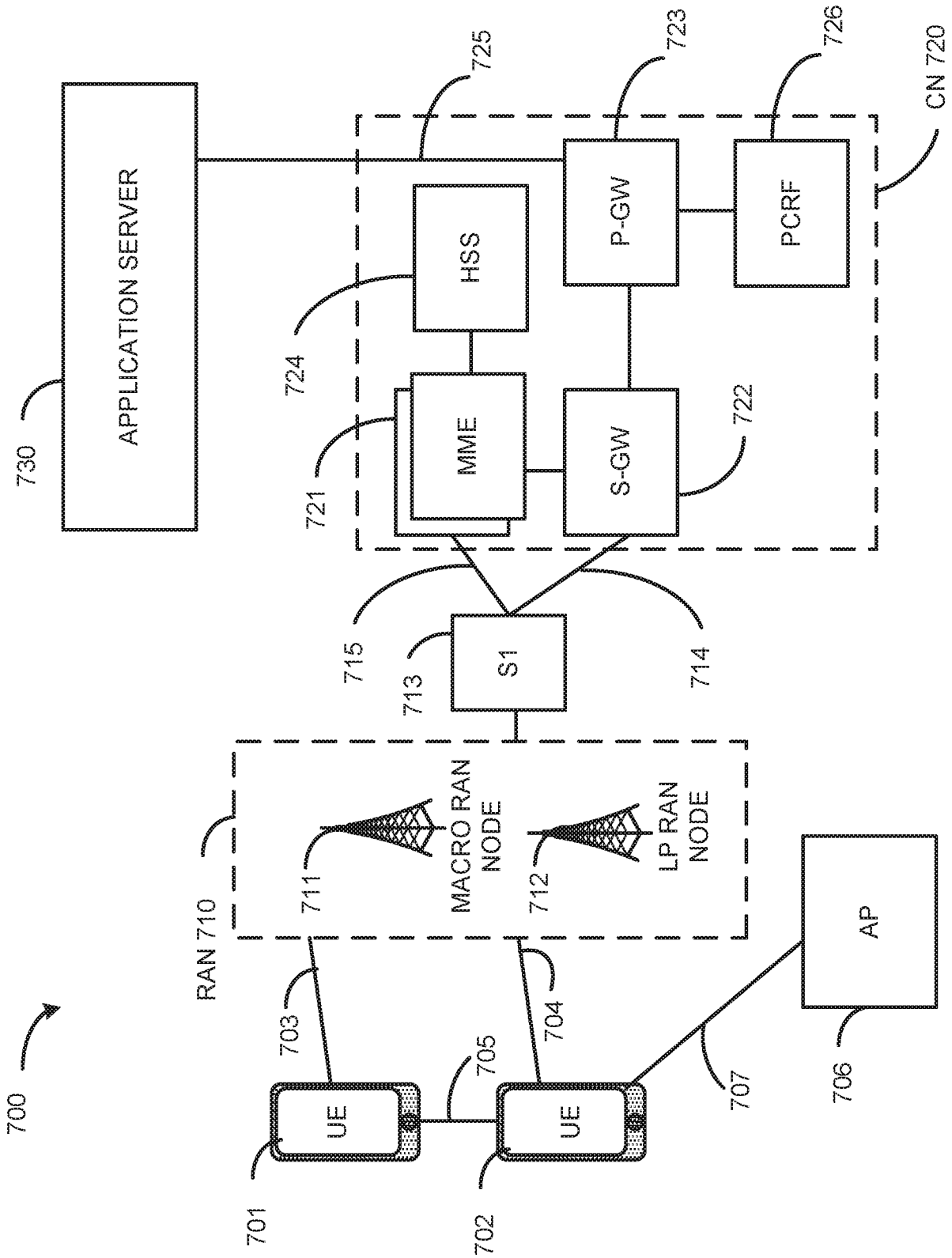

700
APPLICATION SERVER
730
725
723
726
CN 720
HSS
P-GW
PCRF
724
MME
S-GW
721
722
715
713
S1
714
RAN 710
MACRO RAN NODE
LP RAN NODE
711
712
AP
703
704
705
707
706
UE
UE
701
702

FIG. 7

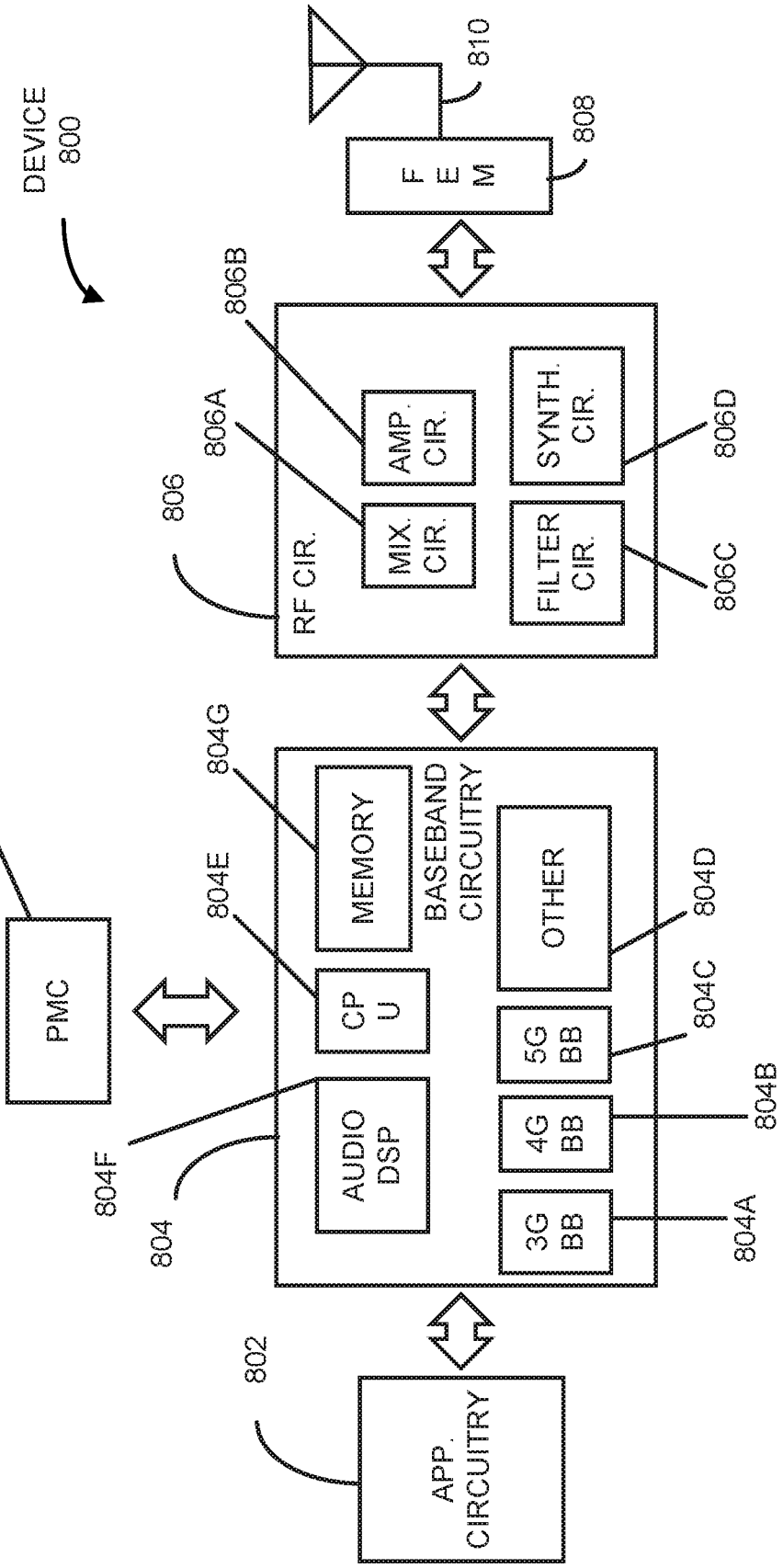

DEVICE
800
810
808
F E M
806B
806A
806
AMP. CIR.
MIX. CIR.
RF CIR.
SYNTH. CIR.
FILTER CIR.
806D
806C
804G
812
MEMORY
BASEBAND CIRCUITRY
804E
OTHER
804D
PMC
CP U
5G BB
804C
4G BB
804B
AUDIO DSP
804F
804
3G BB
804A
802
APP. CIRCUITRY

FIG. 8

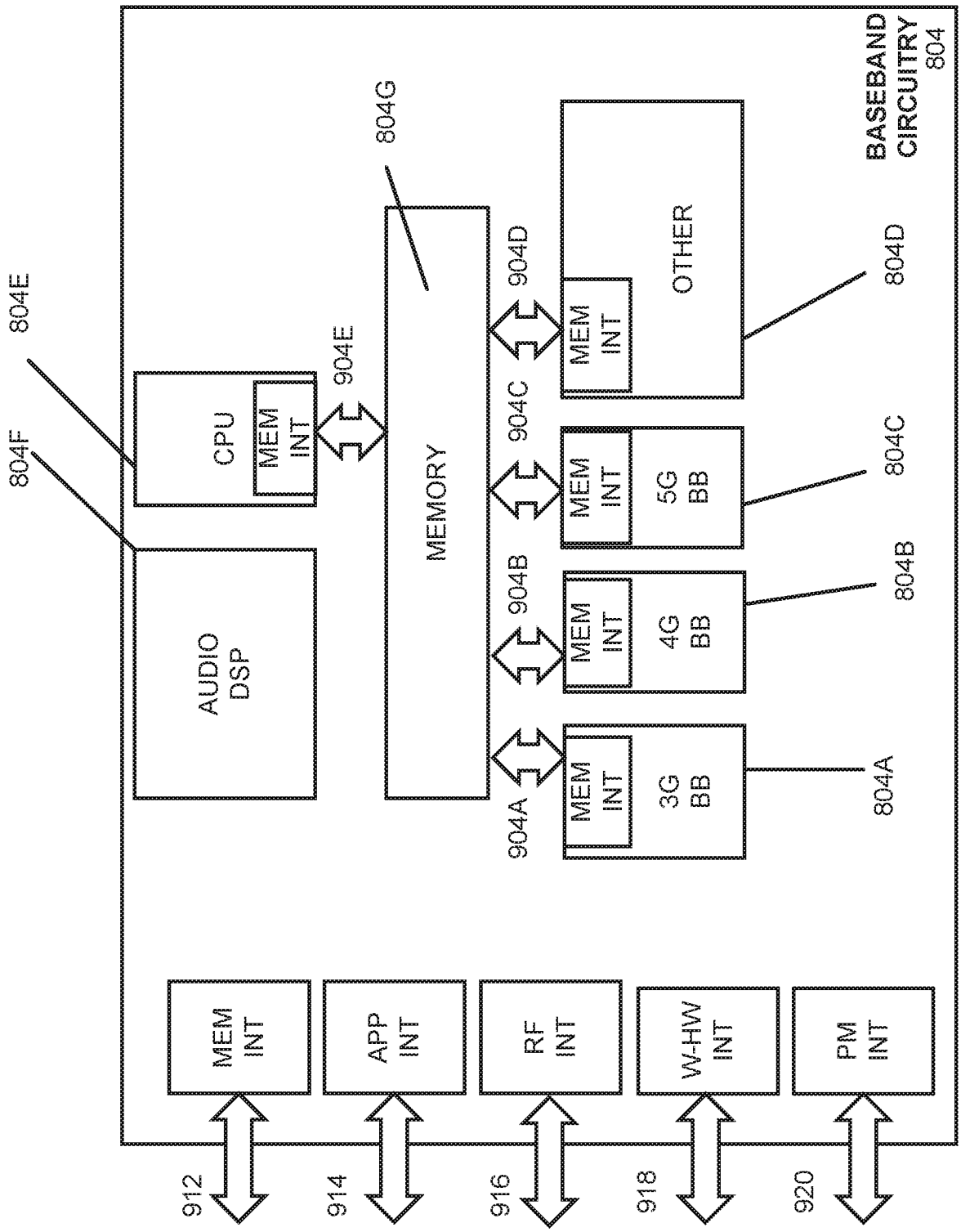

BASEBAND CIRCUITRY
804
804G
804E
804F
CPU
MEM INT
904E
MEMORY
904D
MEM INT
OTHER
804D
904C
MEM INT
5G BB
804C
AUDIO DSP
904B
MEM INT
4G BB
804B
904A
MEM INT
3G BB
804A
MEM INT
APP INT
RF INT
W-HW INT
PM INT
912
914
916
918
920

FIG. 9

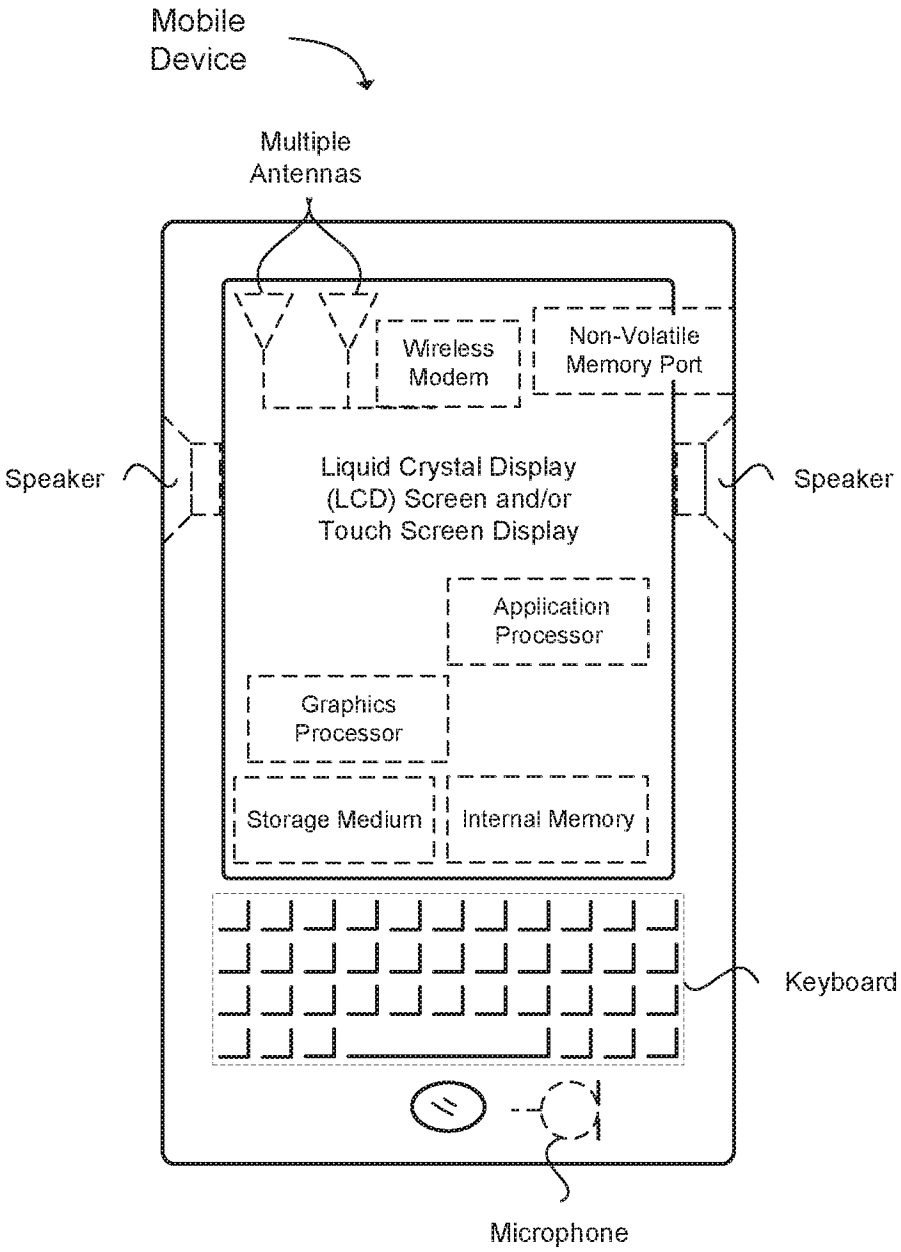

Mobile Device
Multiple Antennas
Wireless Modem
Non-Volatile Memory Port
Speaker
Liquid Crystal Display (LCD) Screen and/or Touch Screen Display
Speaker
Application Processor
Graphics Processor
Storage Medium
Internal Memory
Keyboard
Microphone

FIG. 10