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Sun et al.

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(54) **USER EQUIPMENT CAPABILITY SIGNALING ENHANCEMENT**

(71) Applicant: **Apple Inc.**, Cupertino, CA (US)

(72) Inventors: **Haitong Sun**, Cupertino, CA (US); **Hong He**, San Jose, CA (US); **Oghenekome Oteri**, San Diego, CA (US); **Weidong Yang**, San Diego, CA (US); **Chunxuan Ye**, San Diego, CA (US); **Sigen Ye**, Whitehouse Station, NJ (US); **Chunhai Yao**, Beijing (CN); **Wei Zeng**, Saratoga, CA (US); **Dawei Zhang**, Saratoga, CA (US); **Yushu Zhang**, Beijing (CN)

(73) Assignee: **Apple Inc.**, Cupertino, CA (US)

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H04W 76/10	(2018.01)

(52) **U.S. Cl.**

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(58) **Field of Classification Search**

CPC H04L 5/0026; H04L 5/0035; H04W 76/10

(Continued)

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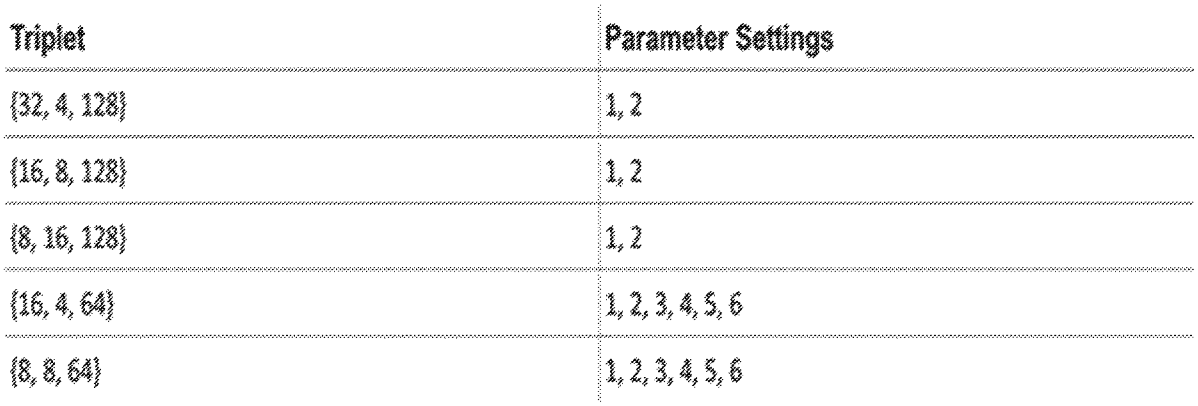
Primary Examiner — Christopher R Crompton

(74) *Attorney, Agent, or Firm* — Kilpatrick Townsend & Stockton LLP

(57) **ABSTRACT**

Embodiments are directed to techniques to implement full power transmission in a user equipment (UE). An embodiment of a user equipment (UE) comprises an antenna array comprising a plurality of antenna elements, and a processor to cause the UE to establish a communication connection with a network entity; cause the UE to transmit, to the network entity, at least one of a channel state information reference signal (CSI-RS) capability indicator, a beam switch timing capability indicator, or a cross carrier scheduling capability indicator.

13 Claims, 12 Drawing Sheets



Triplet	Parameter Settings
{32, 4, 128}	1, 2
{16, 8, 128}	1, 2
{8, 16, 128}	1, 2
{16, 4, 64}	1, 2, 3, 4, 5, 6
{8, 8, 64}	1, 2, 3, 4, 5, 6

(58) **Field of Classification Search**
USPC 370/330
See application file for complete search history.

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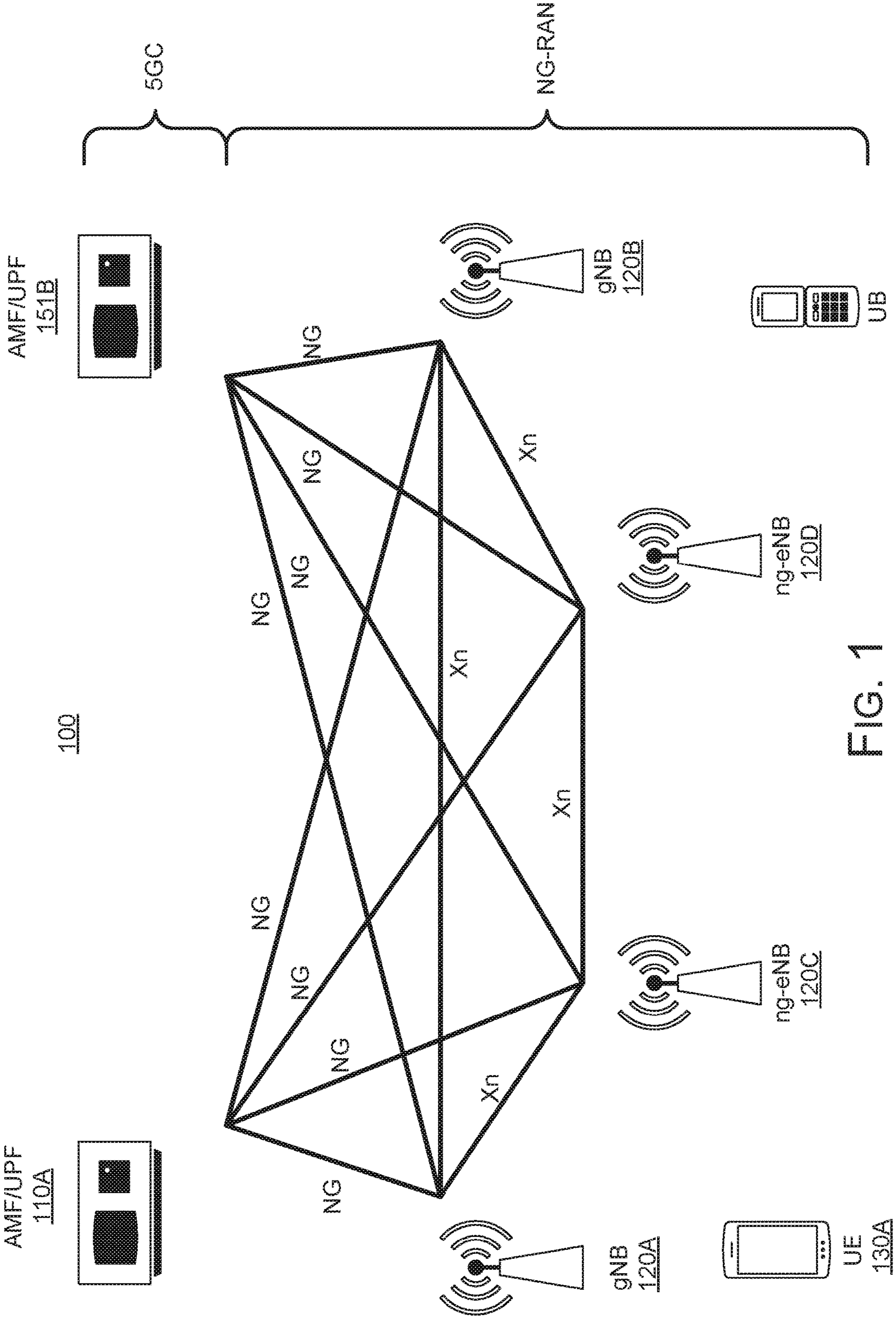
100
5GC
NG-RAN
AMF/UPF
151B
AMF/UPF
110A
gNB
120B
gNB
120A
ng-eNB
120D
ng-eNB
120C
UB
130A
UE
130A
NG
NG
NG
NG
NG
NG
NG
NG
Xn
Xn
Xn
Xn

FIG. 1

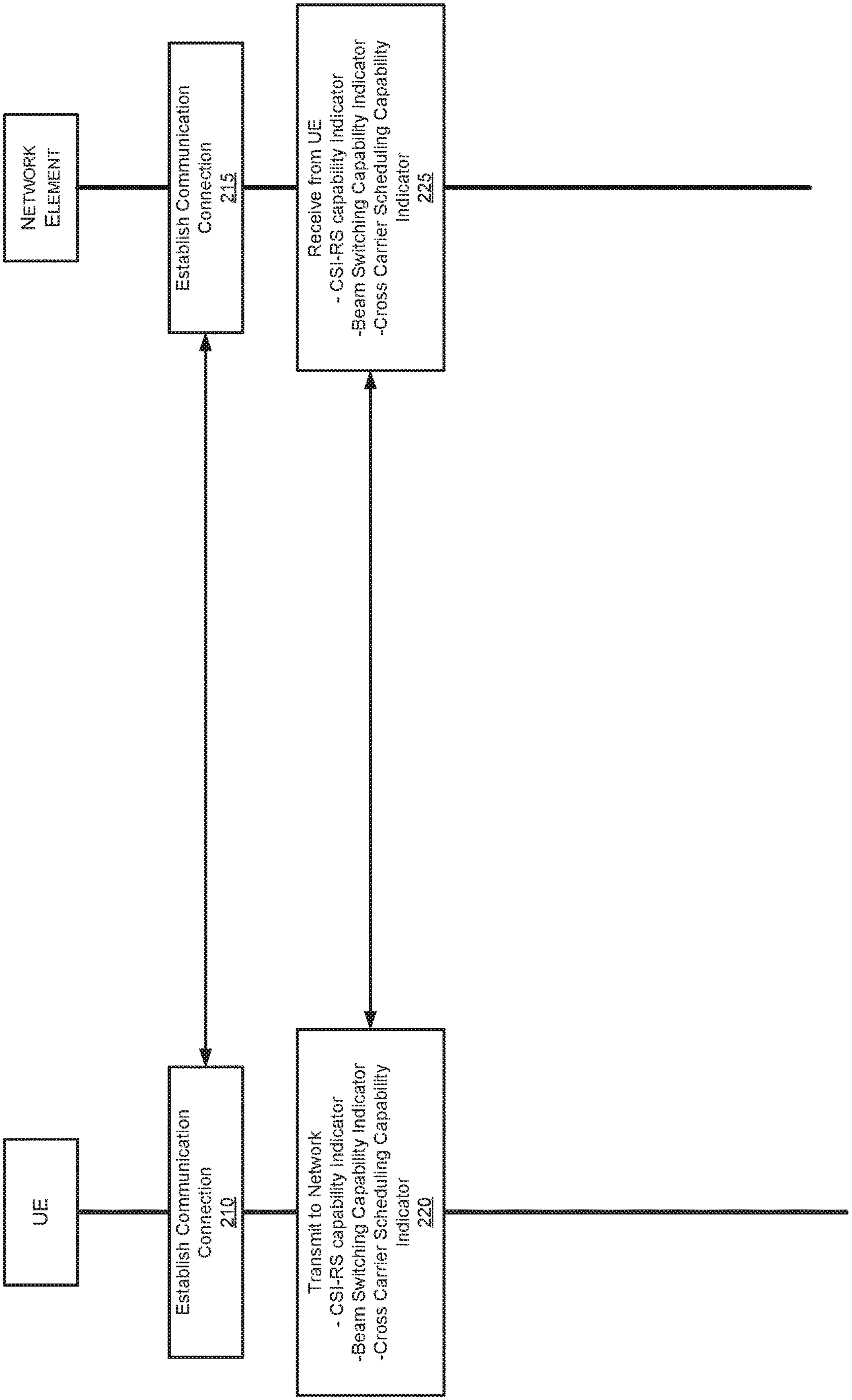
NETWORK ELEMENT
Establish Communication Connection 215
Receive from UE
- CSI-RS capability Indicator
-Beam Switching Capability Indicator
-Cross Carrier Scheduling Capability Indicator
225
UE
Establish Communication Connection 210
Transmit to Network
- CSI-RS capability Indicator
-Beam Switching Capability Indicator
-Cross Carrier Scheduling Capability Indicator
220

FIG. 2

paramCombination-r16	L	p_{υ}		β
		$\upsilon \in \{1,2\}$	$\upsilon \in \{3,4\}$	
1	2	¼	1/8	¼
2	2	¼	1/8	½
3	4	¼	1/8	¼
4	4	¼	1/8	½
5	4	¼	¼	¾
6	4	½	¼	½
7	6	¼	-	½
8	6	¼	-	¾

FIG. 3

Triplet	Parameter Settings
{32, 4, 128}	1, 2
{16, 8, 128}	1, 2
{8, 16, 128}	1, 2
{16, 4, 64}	1, 2, 3, 4, 5, 6
{8, 8, 64}	1, 2, 3, 4, 5, 6

FIG. 4

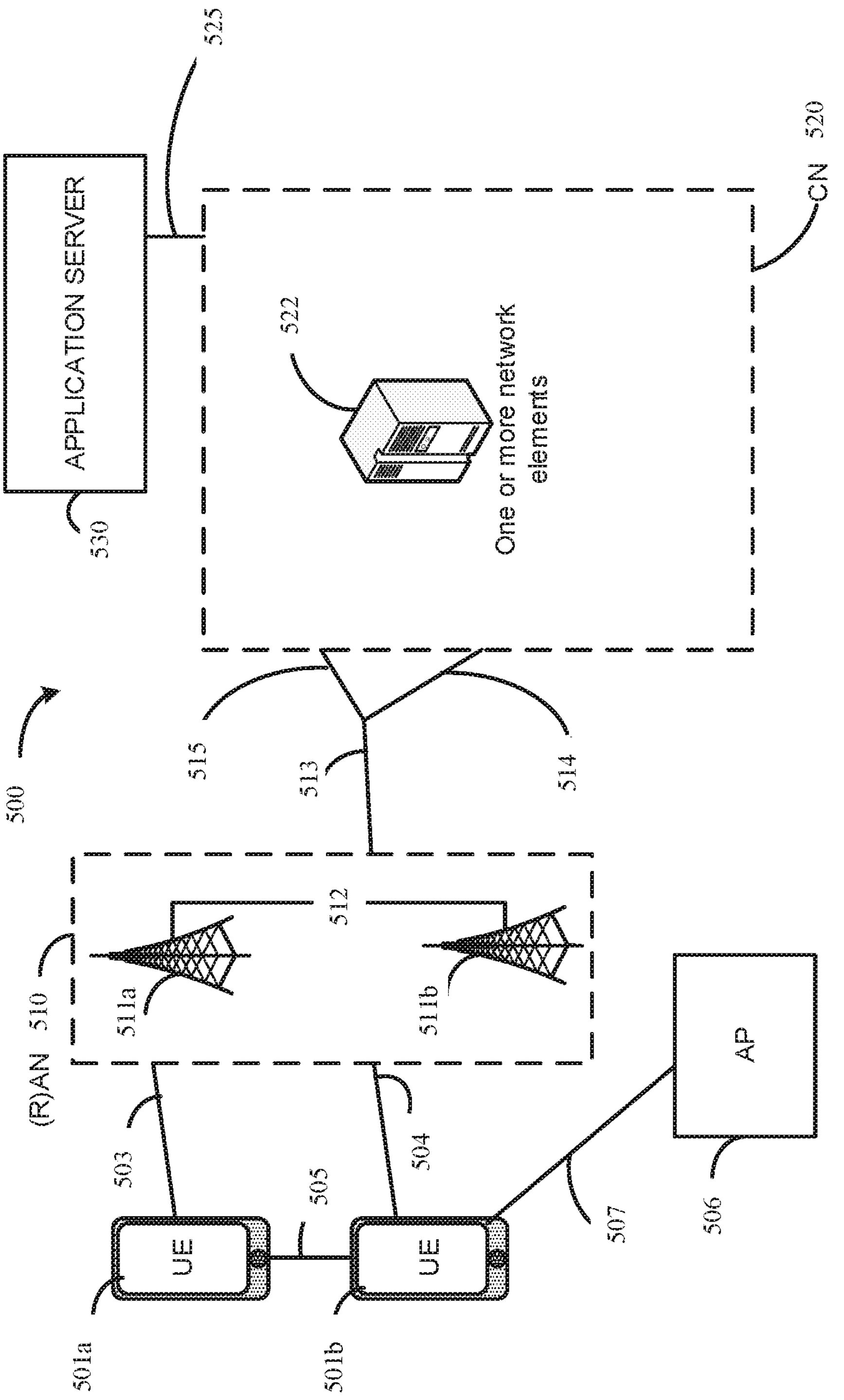
500
APPLICATION SERVER
530
525
CN 520
522
One or more network elements
515
513
514
(R)AN 510
511a
511b
512
503
504
505
UE
UE
501a
501b
AP
506
507

FIG. 5

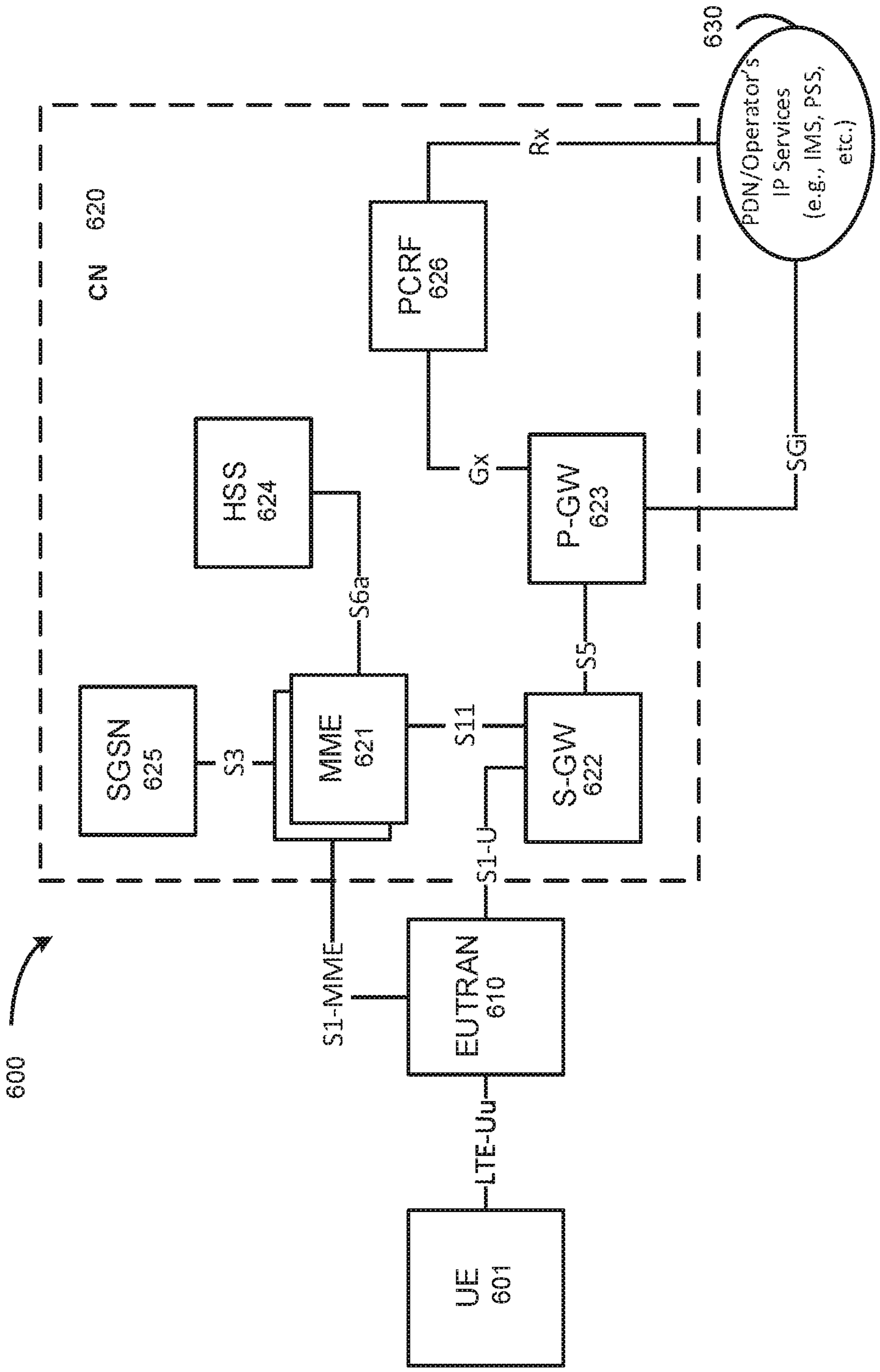
600
UE
601
LTE-Uu
EUTRAN
610
S1-MME
S1-U
CN 620
SGSN
625
S3
MME
621
S11
S-GW
622
S6a
HSS
624
S5
P-GW
623
Gx
PCRF
626
Rx
SGi
630
PDN/Operator's
IP Services
(e.g., IMS, PSS,
etc.)

FIG. 6

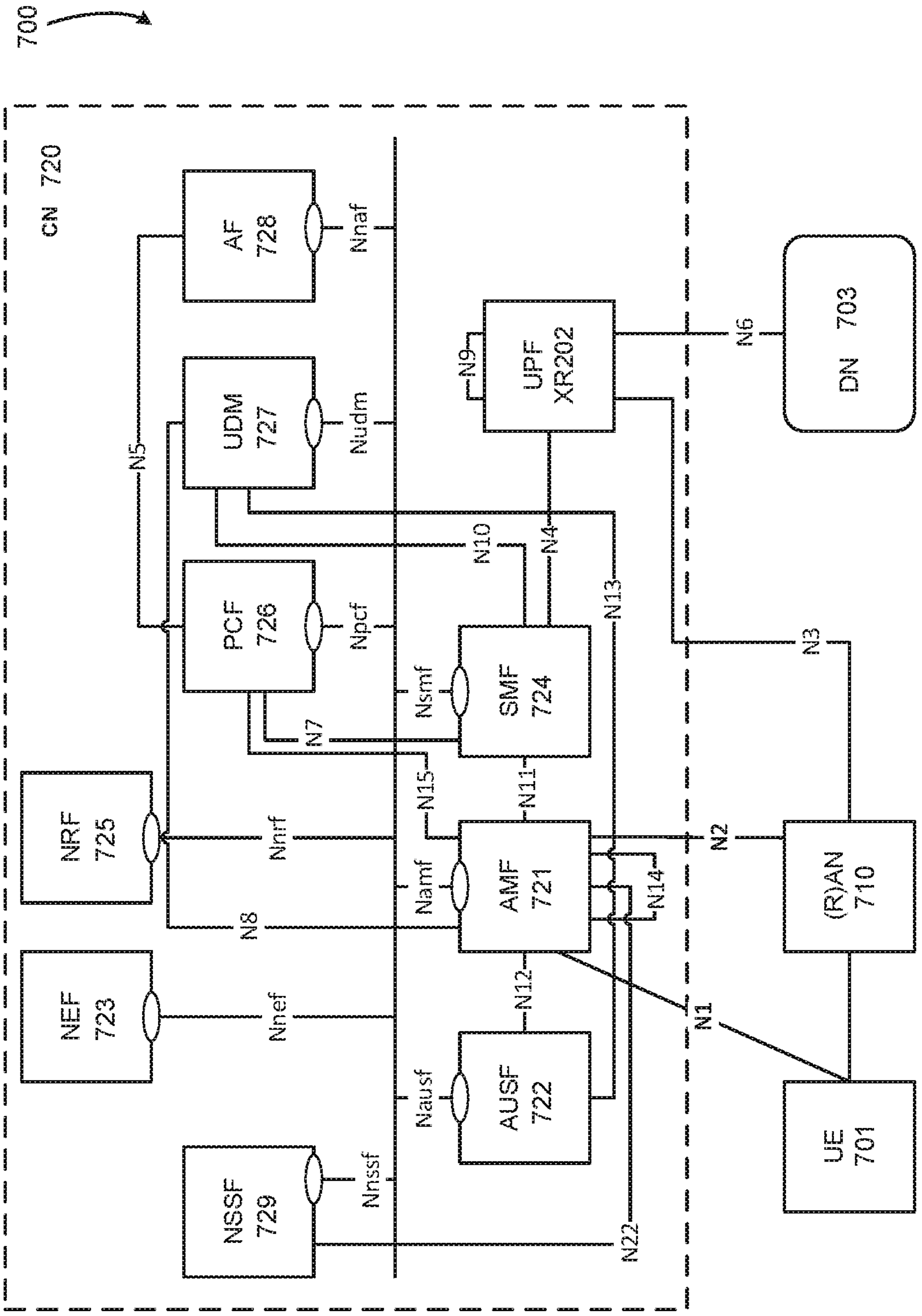
700
CN 720
AF 728
Nnaf
UDM 727
Nudm
PCF 726
Npcf
NRF 725
Nnrf
NEF 723
Nnef
NSSF 729
Nnssf
N5
N8
AMF 721
Namf
AUSF 722
Nausf
SMF 724
Nsmf
UPF XR202
N9
N6
DN 703
N10
N4
N13
N7
N15
N11
N12
N14
N22
N3
N2
N1
(R)AN 710
UE 701

FIG. 7

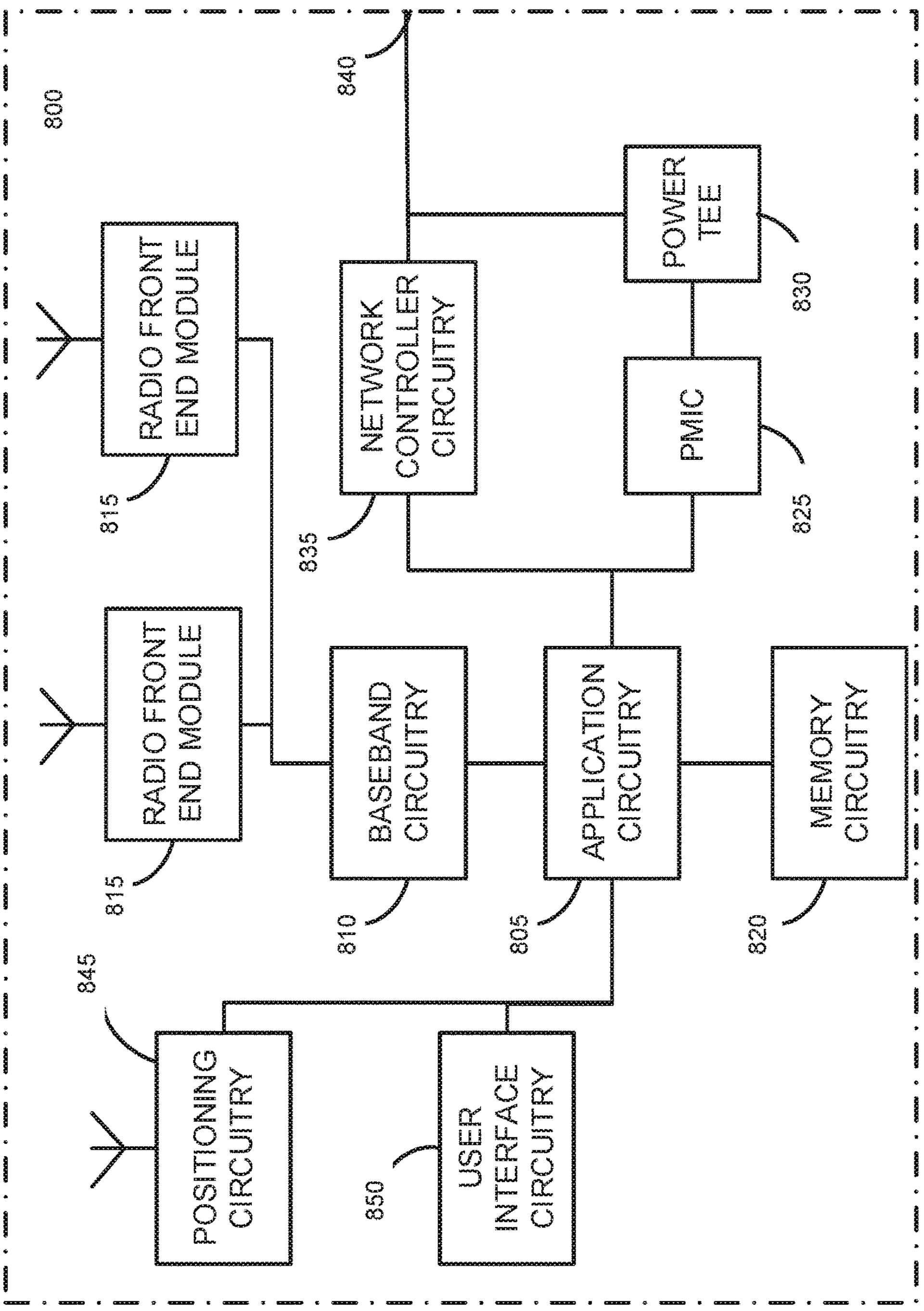
800
840
RADIO FRONT END MODULE
815
RADIO FRONT END MODULE
815
POSITIONING CIRCUITRY
845
NETWORK CONTROLLER CIRCUITRY
835
BASEBAND CIRCUITRY
810
USER INTERFACE CIRCUITRY
850
APPLICATION CIRCUITRY
805
POWER TEE
830
PMIC
825
MEMORY CIRCUITRY
820

FIG. 8

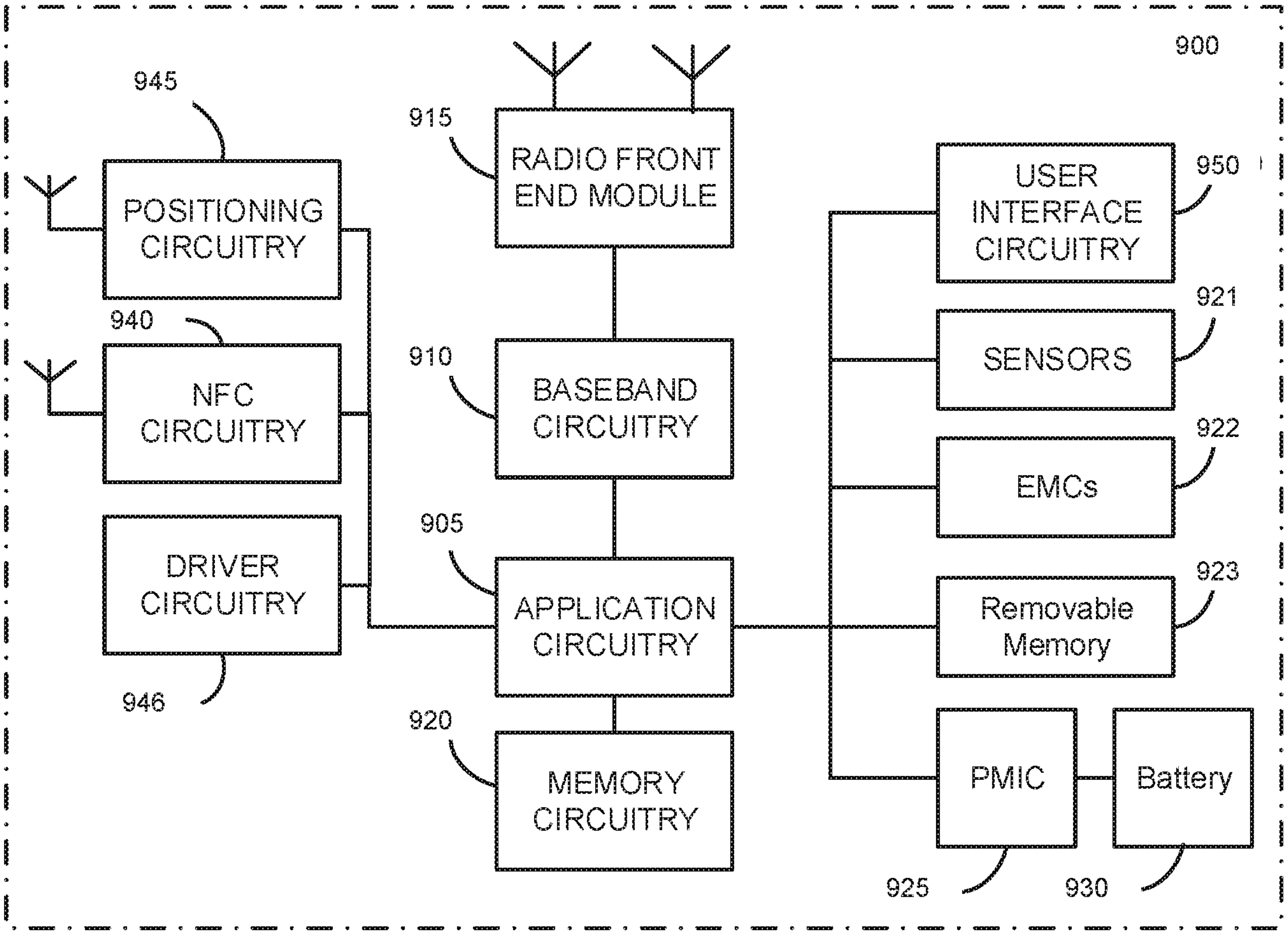
900
945
POSITIONING CIRCUITRY
940
NFC CIRCUITRY
DRIVER CIRCUITRY
946
915
RADIO FRONT END MODULE
910
BASEBAND CIRCUITRY
905
APPLICATION CIRCUITRY
920
MEMORY CIRCUITRY
USER INTERFACE CIRCUITRY
950
SENSORS
921
EMCs
922
Removable Memory
923
PMIC
925
Battery
930

FIG. 9

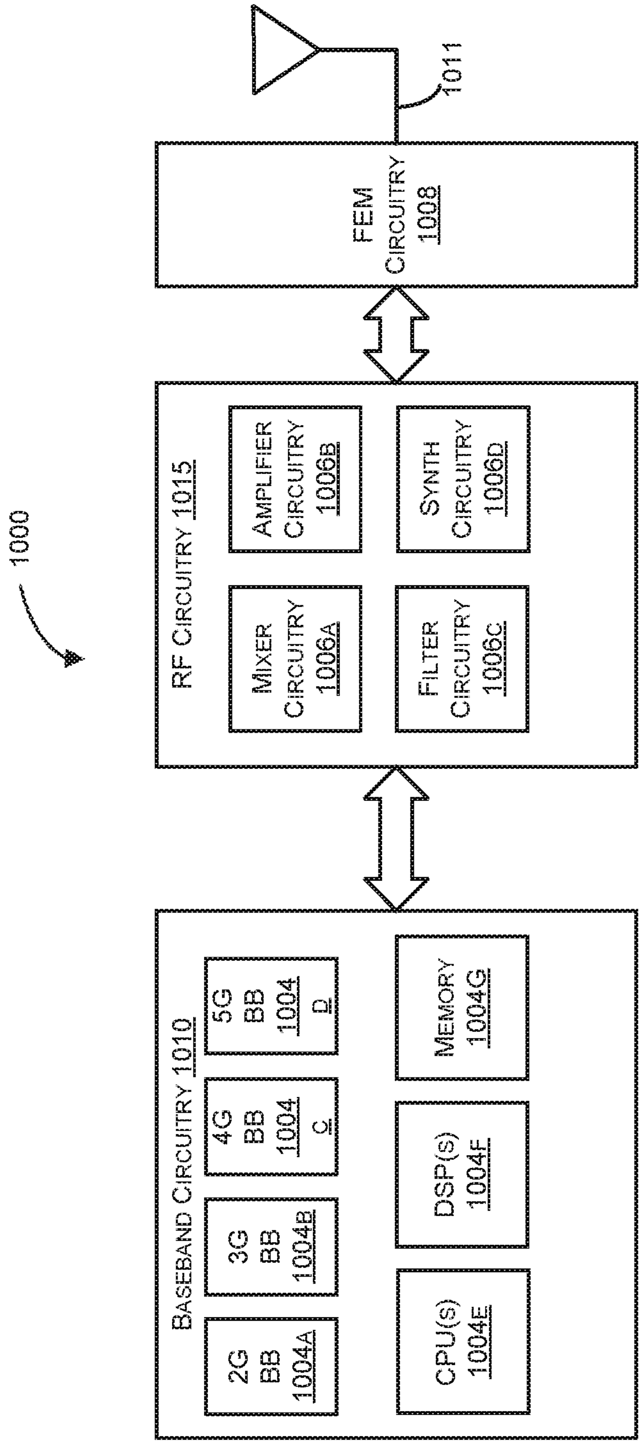
1000
1011
FEM CIRCUITRY 1008
RF CIRCUITRY 1015
MIXER CIRCUITRY 1006A
AMPLIFIER CIRCUITRY 1006B
FILTER CIRCUITRY 1006C
SYNTH CIRCUITRY 1006D
BASEBAND CIRCUITRY 1010
2G BB 1004A
3G BB 1004B
4G BB 1004 C
5G BB 1004 D
CPU(S) 1004E
DSP(S) 1004F
MEMORY 1004G

FIG. 10

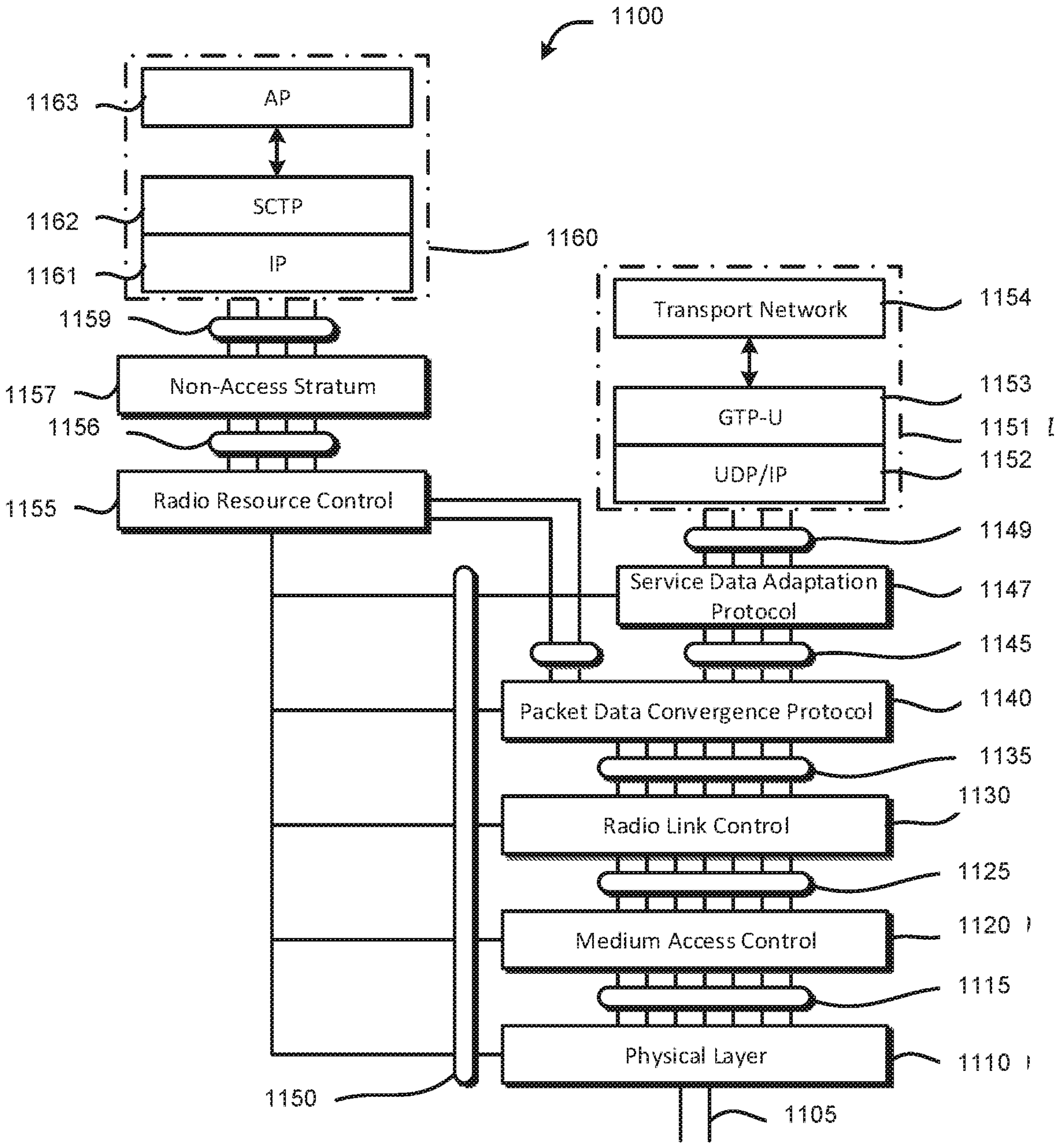
1100
1163
AP
1162
SCTP
1161
IP
1160
1159
1157
Non-Access Stratum
1156
1155
Radio Resource Control
Transport Network
1154
1153
GTP-U
1151
1152
UDP/IP
1149
Service Data Adaptation Protocol
1147
1145
Packet Data Convergence Protocol
1140
1135
1130
Radio Link Control
1125
Medium Access Control
1120
1115
Physical Layer
1110
1150
1105

FIG. 11

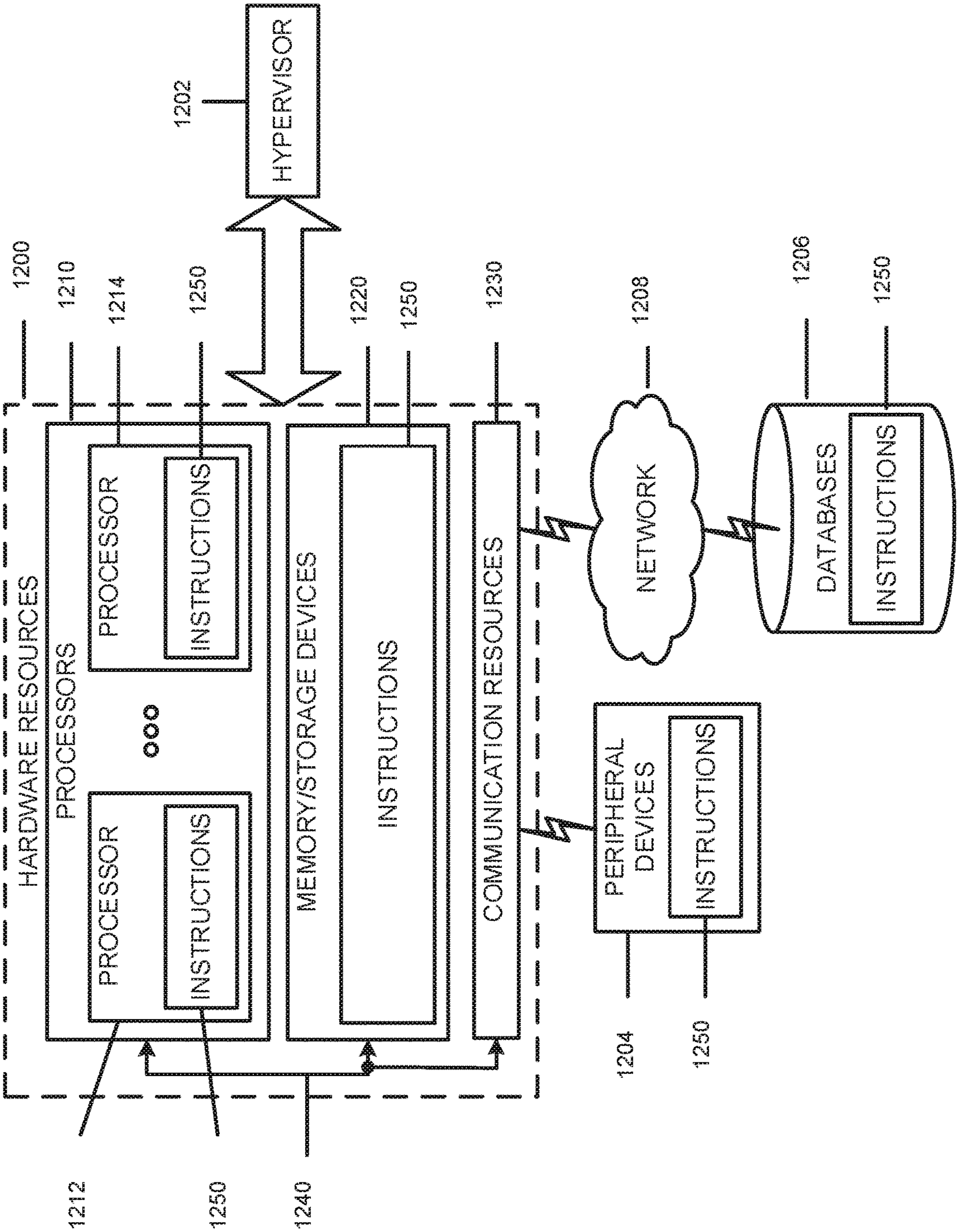
1200
HARDWARE RESOURCES
1210
PROCESSORS
1214
PROCESSOR
1250
INSTRUCTIONS
PROCESSOR
INSTRUCTIONS
1212
1250
1240
1220
MEMORY/STORAGE DEVICES
1250
INSTRUCTIONS
1230
COMMUNICATION RESOURCES
1202
HYPERVISOR
1208
NETWORK
1206
DATABASES
1250
INSTRUCTIONS
PERIPHERAL DEVICES
INSTRUCTIONS
1204
1250

FIG. 12

USER EQUIPMENT CAPABILITY SIGNALING ENHANCEMENT

CROSS-REFERENCE TO RELATED APPLICATION

This application is a 371 U.S. National Phase of PCT International Patent Application No. PCT/CN2020/090575, filed on May 15, 2020; the disclosure of which is incorporated by reference herein in its entirety for all purposes.

FIELD

Various embodiments generally may relate to the field of wireless communications, including techniques to implement user equipment capability signaling enhancement.

BACKGROUND

This section is intended to introduce the reader to various aspects of art that may be related to various aspects of the present disclosure, which are described and/or claimed below. This discussion is believed to be helpful in providing the reader with background information to facilitate a better understanding of the various aspects of the present disclosure. Accordingly, it will be understood that these statements made in this section are not intended to be admissions of prior art.

Various electrical devices use wireless communication systems to exchange data and/or form communication networks. For example, laptops, mobile phones, and other similar devices may have wireless network adaptors that can connect to cellular networks, wireless Ethernet networks, Bluetooth networks, and the like. In some devices, the wireless communication systems may employ multi-input multi-output (MIMO) antenna setups, which may include arrays of discrete antennas, to access a radio frequency (RF) channel. Adroit management of antennas and device configurations may facilitate effective signal transmission and power utilization.

SUMMARY

Embodiments are directed to techniques to implement full power transmission in a user equipment (UE). An embodiment of a user equipment (UE) comprises an antenna array comprising a plurality of antenna elements, and a processor to cause the UE to establish a communication connection with a network entity; cause the UE to transmit, to the network entity, at least one of a channel state information reference signal (CSI-RS) capability indicator, a beam switch timing capability indicator, or a cross carrier scheduling capability indicator.

BRIEF DESCRIPTION OF THE DRAWINGS

The detailed description is provided with reference to the accompanying figures.

FIG. **1** is a high-level schematic, block diagram illustration of various components in a 3GPP NR (e.g., 5G) network environment which may be used to implement user equipment capability signaling enhancement in communication networks in accordance with various examples discussed herein.

FIG. **2** is a schematic illustration of operations in a method of an implementation of user equipment capability signaling enhancement, according to embodiments.

FIG. **3** is a schematic illustration of parameter settings which may be used in an implementation of user equipment capability signaling enhancement, according to embodiments.

FIG. **4** is a schematic illustration of parameter settings which may be used in an implementation of user equipment capability signaling enhancement, according to embodiments.

FIG. **5** is a schematic illustration of a system of a network which may be used in an implementation of user equipment capability signaling enhancement, according to embodiments.

FIG. **6** is a schematic illustration of a system which may be used in an implementation of user equipment capability signaling enhancement, according to embodiments.

FIG. **7** is a schematic illustration of a system which may be used in an implementation of user equipment capability signaling enhancement, according to embodiments.

FIG. **8** is a schematic illustration of infrastructure equipment which may be used in an implementation of user equipment capability signaling enhancement, according to embodiments.

FIG. **9** is a schematic illustration of a platform which may be used in an implementation of user equipment capability signaling enhancement, according to embodiments.

FIG. **10** is a schematic illustration of baseband circuitry which may be used in an implementation of user equipment capability signaling enhancement, according to embodiments.

FIG. **11** is a schematic illustration of various protocol functions which may be used in an implementation of user equipment capability signaling enhancement, according to embodiments.

FIG. **12** is a schematic illustration of components able to read instructions form a machine-readable or computer-readable medium which may be used in an implementation of user equipment capability signaling enhancement, according to embodiments.

DETAILED DESCRIPTION

The following detailed description refers to the accompanying drawings. The same reference numbers may be used in different drawings to identify the same or similar elements. In the following description, for purposes of explanation and not limitation, specific details are set forth such as particular structures, architectures, interfaces, techniques, etc. in order to provide a thorough understanding of the various aspects of various embodiments. However, it will be apparent to those skilled in the art having the benefit of the present disclosure that the various aspects of the various embodiments may be practiced in other examples that depart from these specific details. In certain instances, descriptions of well-known devices, circuits, and methods are omitted so as not to obscure the description of the various embodiments with unnecessary detail. For the purposes of the present document, the phrase “A or B” means (A), (B), or (A and B).

Further, various aspects of examples may be performed using various means, such as integrated semiconductor circuits (“hardware”), computer-readable instructions organized into one or more programs (“software”), or some combination of hardware and software. For the purposes of this disclosure reference to “logic” shall mean either hardware, software, or some combination thereof.

Reference throughout this specification to “one embodiment” or “an embodiment” means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments. Additionally, the word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment described herein as "exemplary" is not to be construed as necessarily preferred or advantageous over other embodiments.

Various operations may be described as multiple discrete operations in turn and in a manner that is most helpful in understanding the claimed subject matter. The order of description, however, should not be construed as to imply that these operations are necessarily order dependent. In particular, these operations need not be performed in the order of presentation. Operations described may be performed in a different order than the described embodiment. Various additional operations may be performed and/or described operations may be omitted in additional embodiments.

Further details and techniques will be described with reference to the network architectures, devices, and method described below with reference to FIGS. **1**-**10**. FIG. **1** is a high-level schematic, block diagram illustration of components in a 3GPP NR (or 5G) network environment **100**, which may be used to implement coordinated IP packet filtering in communication networks in accordance with various examples discussed herein.

Referring to FIG. **1**, in some examples network **100** comprises one or more Access and Mobility Management Function/User Plane Function (AMF/UPF) devices **110**A, **110**B, one or more gNBs **120**A, **120**B, and one or more ng-eNBs **120**C, **120**D. The AMF/UPF devices **110**A, **110**B are communicatively coupled to the gNBs **120**A, **120**B and the ng-eNBs **120**C, **120**D, via NG interfaces. The gNBs **120**A, **120**B and the ng-eNBs **120**C, **120**D are communicatively coupled to one another via Xn interfaces. One or more User Equipment (UE) **130**A, **130**B are capable to establish a communication connection with the one or more gNBs **120**A, **120**B, or the ng-eNBs **120**C, **120**D. Detailed descriptions of wireless networks and UE are provided below.

In some examples the wireless network **100** which may include, or be communicatively coupled to, one or more cellular networks (e.g., 4G standards such as Long Term Evolution or LTE, 5G standards such as New Radio or 5G NR) and/or connectivity networks (e.g., IEEE 802.3 or WiFi, Bluetooth), may be implemented by establishing radio frequency (RF) connections between electronic devices. To establish a wireless RF connection, the UE**130**A, **130**B may include RF communication systems, which may include transmission and reception circuitry coupled to an antenna array comprising one or more antennas. The circuitry may include a transceiver module, which may perform encoding/decoding and modulation/demodulation tasks, as well as digital-to-analog and analog-to-digital conversion. The transceiver module may be coupled to the antenna(s) by a front-end module (FEM) or RF head, which may provide filtering and/or power amplification capabilities to the RF communication system. The RF head circuitry may be coupled to an antenna array. The transceiver circuitry and/or the RF head circuitry may generate RF signals that drive the antenna array and/or decode signals received by the antenna array. Examples of a UE are discussed in greater detail below.

Subject matter described herein relates to capability signal enhancement for user equipment (UE). In some examples, subject matter described herein provides UE capability signaling enhancements in the following areas: (1) multi-user (MU) CSI enhancement capability reporting; (2) Aperiodic (AP) CSI-RS beam switch timing capability reporting; and cross carrier scheduling (CCS) related capability signaling.

FIG. **2** is a schematic illustration of operations in a method of an implementation of user equipment capability signaling enhancement, according to embodiments. In some examples the operations may be implemented between a UE (e.g., UE **130**A, **130**B) and a network element (e.g., gNB **120**A, **120**B or ng-eNB **120**C, **120**D). The operations depicted in FIG. **2** enable a UE to provide enhanced capability signaling for features including multi-user (MU) channel state information (CSI) capabilities, aperiodic channel state information reference signal (AP-CSI-RS) capabilities, and cross carrier scheduling (CCS) capability reporting. The network element may transmit these instructions to the EU, which may use the reporting to configure the EU and one or more network elements.

Referring to FIG. **2**, at operations **210** and **215** the UE and network element, respectively, establish a communication connection. At operation **220** the UE transmits to the network element a CSI-RS capability indicator, a beam switching capability indicator, and a CCS capability indicator. At operation **225** the network element receives the CSI-RS capability indicator, a beam switching capability indicator, and a CCS capability indicator transmitted by the UE. Subsequently, the network element may use one or more of the CSI-RS capability indicator, beam switching capability indicator, and CCS capability indicator to configure the UE and/or one or more network elements. The various indicators are described in greater detail below:

In a first set of examples, MU-CSI enhancement capability reporting is provided. A UE can indicate to the network entity a list of triplets, (e.g., supportedCSI-RS-ResourceList), for each codebook type used to configure the UE. Each triplet SupportedCSI-RS-Resource contains a set of three parameters: (1) a maximum number of ports per CSI-RS resource, (2) a maximum total number of CSI-RS resources, and (3) a maximum total number of ports, as illustrated below. In some examples, a maximum list of 7 triples can be reported.

```
SupportedCSI-RS-Resource::          =SEQUENCE {
   maxNumberTxPortsPerResource        ENUMERATED {p2, p4, p8, p12, p16, p24, p32},
   maxNumberResourcePerBand           INTEGER (1..64),
   totalNumberTxPortsPerBand          INTEGER (2..256)
}
```

Referring to FIG. **3** and FIG. **4**, in some examples eight different parameter settings are defined for CSI feedback. A UE may be mandated to support parameter settings 1-6, while parameter settings 7 and 8 are optional. In some examples, for each triplet, the UE is allowed to indicate the supported list of parameter settings. Across all the signaled triplets, UE has to indicate parameter setting 1-6 at least once for each parameter setting.

In some examples, for each triplet, the UE indicates a supported maximum number of beams (L), which may be selected form a set of {2, 4, 6}. The UE supports all the parameter settings that contain a number of beams (L) that is less than or equal to the signaled maximum L. For example, referring to FIG. **3**, L=2, in parameter settings 1 and 2, while L=4 in parameter settings 3, 4, 5, and 6, and L=6, in parameter settings 7 and 8.

In some examples the UE indicates the supported list of parameter settings for each maximum number of ports per CSI resource. The number of ports can be selected from the set of ports comprising {p2, p4, p8, p12, p16, p24, p32}.

In some examples the UE indicates the supported maximum number of beams (L) selected from the set of {2, 4, 6} for each maximum number of ports per CSI resource, UE is allowed to indicate. The UE supports all the parameter settings that contains a number of beams (L) that is less than or equal to the signaled maximum number of beams (L). Referring to FIG. **3**, L=2 in parameter settings 1 and 2, L=4, in parameter settings 3, 4, 5, and 6, and L=6 in parameter settings 7 and 8. In some examples the UE reported a list of maximum L, one-to-one mapping to the possible number of ports for CSI-RS resource, where the ports are selected from the list of ports comprising {p2, p4, p8, p12, p16, p24, p32}.

In another example, for triplet related capability reporting, the UE can indicate the triplet per frequency band in the band of frequencies on which the UE transmits and/or receives, and/or can report the triplet per Band Combinations (BC). In another example the UE can indicate a separate list of triplets for each codebook type, which can be indicated by the UE using a parameter of R=1 to indicate one PMI sub-band for each CSI sub-band, or R=2 to indicate two PMI sub-bands per CSI sub-band. For each triplet for which the UE indicates it can support two PMI sub-bands per CSI sub-band (i.e., R=2), the UE also has to support one PMI sub-band for each CSI sub-band (i.e., R=1) for the same triplet.

In another example, for the list of triplets that UE reports it can support one PMI sub-band for each CSI sub-band (i.e., R=1), the UE may transmit a bitmap to indicate whether UE supports the corresponding triplet for two PMI sub-bands per CSI sub-band (i.e., R=2). In some examples the indicator may reside in a specific bit in bitmap. For example, if the indicator in the n^{th} bit of the bitmap is set to a value of 1, it means UE also supports two PMI sub-bands per CSI sub-band (i.e., R=2) for the n^{th} triplet reported in the triplet list. By contrast, if the indicator in the n^{th} bit of the bitmap is set to a value of 0, it means UE does not support two PMI sub-bands per CSI sub-band (i.e., R=2) for the n^{th} triplet reported in the triplet list.

In a second set of examples, AP-CSI-RS beam switch timing capability reporting is provided. In some existing protocols, a UE can report the following capability:

```
beamSwitchTiming    SEQUENCE{
   scs-60kHz         ENUMERATED{sym 14, sym28, sy48, sym224, sym336}OPTIONAL,
   scs-120kHz        ENUMERATED{sym 14, sym28, sy48, sym224, sym336}OPTIONAL,
}                                                                   OPTIONAL
```

When a non-zero power (NZP) CSI-RS resource is configured with repetition on, e.g., for a receive (Rx) beam sweep, the UE requires reported 224 symbols or 336 symbols for the AP-CSI-RS. For all the other NZP-CSI-RS resources, the assumes that UE requires 48 symbols.

In one example, the UE can indicate separate beamSwitchTiming values based upon an operating mode of the UE. For example, a UE can indicate a first beamSwitchTiming value when operating in compliance with a first set of protocols (e.g., Release 15 NR), and a second value when operating in compliance with a second set of protocols (e.g., Release 16 NR). The second value should be larger or equal to the first value.

In another example, when a UE indicates a beamSwitchTiming value of either 224 symbols or 336 symbols, and when NZP-CSI-RS resource is configured with repetition on, (e.g., for Rx beam sweep), the UE requires reported 224 symbols or 336 symbols for the AP-CSI-RS. For all the other NZP-CSI-RS resources, the network assumes that UE requires capability as indicated by the first beamSwitchTiming value, which can be less than 48 symbols. If the UE does not transmit a beamSwitchTiming indicator, then a value of either 336 symbols or value 48 symbols shall be assumed.

In a third set of examples, a UE report can transmit one or more indicators to report cross-carrier scheduling (CCS) related capabilities. In some examples the indicators may have different resolutions to provide different degrees of flexibility in the reporting capabilities. In a first resolution the indicator may include a first sub-carrier spacing (SCS) indicator that indicates whether a first subcarrier spacing value associated with a first carrier and a second subcarrier spacing value associated with a second sub-carrier are equal.

In a second resolution the indicator may include a first sub-carrier spacing (SCS) indicator that indicates whether a first subcarrier spacing value associated with a first carrier and a second subcarrier spacing value associated with a second sub-carrier are equal and a second SCS indicator that is set to a first value to indicate that a small SCS cell is to schedule a large SCS cell or to a second value to indicate that a large SCS cell is to schedule a small SCS cell.

In a third resolution, the cross-carrier scheduling capability indicator comprises a frequency range (FR) indicator that may be set to one of a first value to indicate that a FR1 cell is to schedule a FR1 cell, a second value to indicate that a FR1 cell is to schedule a FR2 cell, a third value to indicate that a FR2 cell is to schedule a FR1 cell. Or a fourth value to indicate that a FR2 cell is to schedule a FR2 cell.

In a fourth resolution, the cross-carrier scheduling capability indicator enables cross carrier scheduling between frequency ranges including 15 kHz, 30 kHz, 60 kHz used for FR1, 60 kHz used for FR2 and 120 KHz.

In another example, for CCS with different numerology, a UE may indicate the physical downlink control channel (PDCCH) monitoring related capability. In one example, the cross-carrier scheduling capability indicator comprises a physical downlink control channel (PDCCH) monitoring indicator that may be set to one of a first value to indicate that a PDCCH monitoring is to be performed at the beginning of a slot, a second value to indicate that PDCCH monitoring may be performed at any time. For example, the indicator may be set to a first value to indicate basic PDCCH minoring which implements single PDCCH monitoring occasion at the beginning of a slot. The indicator may be set to a second value to indicate a span-based PDCCH monitoring occasion (e.g., pdcch-

MonitoringAnyOccasions=withDCI-gap). The indicator may be set to a third value to indicate a span-based PDCCH monitoring occasion (e.g., pdcch-MonitoringAny Occasions WithSpanGap=set1, set2, set3), where set1=(7, 3), set2=(4, 3) and (7, 3), and set3=(2, 2) and (4, 3) and (7, 3).

In another example, the cross-carrier scheduling capability indicator comprises a downlink (DL) unicast downlink control information (DCI) indicator that indicates a number of DCI the UE can decode during PDCCH monitoring. For CCS with different numerology, for each PDCCH minoring related capability, the UE may indicate a number of unicast DCI the UE can decode in each monitoring occasion. It can be separately indicated as number of DL unicast DCI and number of UL unicast DL. It can be indicated as total unicast number of DCI including DL unicast DCI and UL unicast DL. It can be indicated a list of combinations of {number of DL unicast DCI, number of UL unicast DCI}.

Systems and Implementations

FIG. **5** illustrates an example architecture of a system **500** of a network, in accordance with various embodiments. The following description is provided for an example system **500** that operates in conjunction with the LTE system standards and 5G or NR system standards as provided by 3GPP technical specifications. However, the example embodiments are not limited in this regard and the described embodiments may apply to other networks that benefit from the principles described herein, such as future 3GPP systems (e.g., Sixth Generation (6G)) systems, IEEE 802.16 protocols (e.g., WMAN, WiMAX, etc.), or the like.

As shown by FIG. **5**, the system **500** includes UE **501***a* and UE **501***b* (collectively referred to as “UEs **501**” or “UE **501**”). In this example, UEs **501** 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 consumer electronics devices, cellular phones, smartphones, feature phones, tablet computers, wearable computer devices, personal digital assistants (PDAs), pagers, wireless handsets, desktop computers, laptop computers, in-vehicle infotainment (IVI), in-car entertainment (ICE) devices, an Instrument Cluster (IC), head-up display (HUD) devices, onboard diagnostic (OBD) devices, dashtop mobile equipment (DME), mobile data terminals (MDTs), Electronic Engine Management System (EEMS), electronic/engine control units (ECUs), electronic/engine control modules (ECMs), embedded systems, microcontrollers, control modules, engine management systems (EMS), networked or “smart” appliances, MTC devices, M2M, IoT devices, and/or the like.

In some embodiments, any of the UEs **501** may be IoT UEs, which may comprise a network access layer designed for low-power IoT applications utilizing short-lived UE connections. An IoT UE can utilize technologies such as M2M or MTC for exchanging data with an MTC server or device via a PLMN, ProSe or 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. In some of these embodiments, the UEs **501** may be NB-IOT UEs **501**. NB-IOT provides access to network services using physical layer optimized for very low power consumption (e.g., full carrier BW is 180 kHz, subcarrier spacing can be 3.75 kHz or 15 kHz). A number of E-UTRA functions are not used for NB-IOT and need not be supported by RAN nodes **511** and UEs **501** only using NB-IOT. Examples of such E-UTRA functions may include inter-RAT mobility, handover, measurement reports, public warning functions, GBR, CSG, support of HeNBs, relaying, carrier aggregation, dual connectivity. NAICS, MBMS, real-time services, interference avoidance for in-device coexistence, RAN assisted WLAN interworking, sidelink communication/discovery, MDT, emergency call, CS fallback, self-configuration/self-optimization, among others. For NB-IOT operation, a UE **501** operates in the DL using 12 sub-carriers with a sub-carrier BW of 15 kHz, and in the UL using a single sub-carrier with a sub-carrier BW of either 3.75 kHz or 15 kHz or alternatively 3, 6 or 12 sub-carriers with a sub-carrier BW of 15 kHz.

In various embodiments, the UEs **501** may be MF UEs **501**. MF UEs **501** are LTE-based UEs **501** that operate (exclusively) in unlicensed spectrum. This unlicensed spectrum is defined in MF specifications provided by the MulteFire Forum, and may include, for example. 1.9 GHZ (Japan). 3.5 GHZ, and 5 GHZ. MulteFire is tightly aligned with 3GPP standards and builds on elements of the 3GPP specifications for LAA/eLAA, augmenting standard LTE to operate in global unlicensed spectrum. In some embodiments. LBT may be implemented to coexist with other unlicensed spectrum networks, such as WiFi, other LAA networks, or the like. In various embodiments, some or all UEs **501** may be NB-IOT UEs **501** that operate according to MF. In such embodiments, these UEs **501** may be referred to as “MF NB-IOT UEs **501**.” however, the term “NB-IOT UE **501**” may refer to an “MF UE **501**” or an “MF and NB-IoT UE **501**” unless stated otherwise. Thus, the terms “NB-IOT UE **501**.” “MF UE **501**.” and “MF NB-IOT UE **501**” may be used interchangeably throughout the present disclosure.

The UEs **501** may be configured to connect, for example, communicatively couple, with an or RAN **510**. In embodiments, the RAN **510** may be an NG RAN or a 5G RAN, an E-UTRAN, an MF RAN, or a legacy RAN, such as a UTRAN or GERAN. As used herein, the term “NG RAN” or the like may refer to a RAN **510** that operates in an NR or 5G system **500**, the term “E-UTRAN” or the like may refer to a RAN **510** that operates in an LTE or 4G system **500**, and the term “MF RAN” or the like refers to a RAN **510** that operates in an MF system **100**. The UEs **501** utilize connections (or channels) **503** and **504**, respectively, each of which comprises a physical communications interface or layer (discussed in further detail below). The connections **103** and **104** may include several different physical DL channels and several different physical UL channels. As examples, the physical DL channels include the PDSCH, PMCH, PDCCH, EPDCCH, MPDCCH, R-PDCCH, SPDCCH, PBCH, PCFICH, PHICH, NPBCH, NPDCCH, NPDSCH, and/or any other physical DL channels mentioned herein. As examples, the physical UL channels include the PRACH, PUSCH, PUCCH, SPUCCH, NPRACH, NPUSCH, and/or any other physical UL channels mentioned herein.

In this example, the connections **503** and **504** are illustrated as an air interface to enable communicative coupling, and can be consistent with cellular communications protocols, such as a GSM protocol, a CDMA network protocol, a PTT protocol, a POC protocol, a UMTS protocol, a 3GPP LTE protocol, a 5G protocol, a NR protocol, and/or any of the other communications protocols discussed herein. In embodiments, the UEs **501** may directly exchange communication data via a ProSe interface **505**. The ProSe interface **505** may alternatively be referred to as a SL interface **505** and may comprise one or more physical and/or logical channels, including but not limited to the PSCCH, PSSCH, PSDCH, and PSBCH.

The UE **501***b* is shown to be configured to access an AP **506** (also referred to as "WLAN node **506**," "WLAN **506**," "WLAN Termination **506**," "WT **506**" or the like) via connection **507**. The connection **507** can comprise a local wireless connection, such as a connection consistent with any IEEE 802.11 protocol, wherein the AP **506** would comprise a wireless fidelity (Wi-Fi®) router. In this example, the AP **506** is shown to be connected to the Internet without connecting to the core network of the wireless system (described in further detail below). In various embodiments, the UE **501***b*, RAN **510**, and AP **506** may be configured to utilize LWA operation and/or LWIP operation. The LWA operation may involve the UE **501***b* in RRC_CONNECTED being configured by a RAN node **511***a-b* to utilize radio resources of LTE and WLAN. LWIP operation may involve the UE **501***b* using WLAN radio resources (e.g., connection **507**) via IPsec protocol tunneling to authenticate and encrypt packets (e.g., IP packets) sent over the connection **507**. IPsec tunneling may include encapsulating the entirety of original IP packets and adding a new packet header, thereby protecting the original header of the IP packets.

The RAN **510** can include one or more AN nodes or RAN nodes **511***a* and **511***b* (collectively referred to as "RAN nodes **511**" or "RAN node **511**") that enable the connections **503** and **504**. As used herein, the terms "access node," "access point," or the like may describe equipment that provides the radio baseband functions for data and/or voice connectivity between a network and one or more users. These access nodes can be referred to as BS, gNBs, RAN nodes, eNBs, NodeBs, RSUs, MF-APs, TRxPs or TRPs, 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). As used herein, the term "NG RAN node" or the like may refer to a RAN node **511** that operates in an NR or 5G system **500** (e.g., a gNB), and the term "E-UTRAN node" or the like may refer to a RAN node **511** that operates in an LTE or 4G system **500** (e.g., an eNB). According to various embodiments, the RAN nodes **511** may be implemented as one or more of a dedicated physical device such as a macrocell base station, and/or a low power (LP) base station for providing femtocells, picocells or other like cells having smaller coverage areas, smaller user capacity, or higher BW compared to macrocells.

In some embodiments, all or parts of the RAN nodes **511** may be implemented as one or more software entities running on server computers as part of a virtual network, which may be referred to as a CRAN and/or a virtual baseband unit pool (vBBUP). In these embodiments, the CRAN or vBBUP may implement a RAN function split, such as a PDCP split wherein RRC and PDCP layers are operated by the CRAN/vBBUP and other L2 protocol entities are operated by individual RAN nodes **511**; a MAC/PHY split wherein RRC, PDCP, RLC, and MAC layers are operated by the CRAN/vBBUP and the PHY layer is operated by individual RAN nodes **511**; or a "lower PHY" split wherein RRC, PDCP, RLC, MAC layers and upper portions of the PHY layer are operated by the CRAN/vBBUP and lower portions of the PHY layer are operated by individual RAN nodes **511**. This virtualized framework allows the freed-up processor cores of the RAN nodes **511** to perform other virtualized applications. In some implementations, an individual RAN node **511** may represent individual gNB-DUs that are connected to a gNB-CU via individual F1 interfaces (not shown by FIG. **5**). In these implementations, the gNB-DUs may include one or more remote radio heads or RFEMs (see e.g., FIG. **8**), and the gNB-CU may be operated by a server that is located in the RAN **510** (not shown) or by a server pool in a similar manner as the CRAN/vBBUP. Additionally or alternatively, one or more of the RAN nodes **511** may be next generation eNBs (ng-eNBs), which are RAN nodes that provide E-UTRA user plane and control plane protocol terminations toward the UEs **501**, and are connected to a 5GC (e.g., CN **720** of FIG. **7**) via an NG interface (discussed infra). In MF implementations, the MF-APs **511** are entities that provide MulteFire radio services and may be similar to eNBs **511** in an 3GPP architecture. Each MF-AP **511** includes or provides one or more MF cells.

In V2X scenarios one or more of the RAN nodes **511** may be or act as RSUs. The term "Road Side Unit" or "RSU" may refer to any transportation infrastructure entity used for V2X communications. An RSU may be implemented in or by a suitable RAN node or a stationary (or relatively stationary) UE, where an RSU implemented in or by a UE may be referred to as a "UE-type RSU," an RSU implemented in or by an eNB may be referred to as an "eNB-type RSU," an RSU implemented in or by a gNB may be referred to as a "gNB-type RSU," and the like. In one example, an RSU is a computing device coupled with radio frequency circuitry located on a roadside that provides connectivity support to passing vehicle UEs **501** (vUEs **501**). The RSU may also include internal data storage circuitry to store intersection map geometry, traffic statistics, media, as well as applications/software to sense and control ongoing vehicular and pedestrian traffic. The RSU may operate on the 5.9 GHz Direct Short Range Communications (DSRC) band to provide very low latency communications required for high speed events, such as crash avoidance, traffic warnings, and the like. Additionally or alternatively, the RSU may operate on the cellular V2X band to provide the aforementioned low latency communications, as well as other cellular communications services. Additionally or alternatively, the RSU may operate as a Wi-Fi hotspot (2.4 GHz band) and/or provide connectivity to one or more cellular networks to provide uplink and downlink communications. The computing device(s) and some or all of the radiofrequency circuitry of the RSU may be packaged in a weatherproof enclosure suitable for outdoor installation and may include a network interface controller to provide a wired connection (e.g., Ethernet) to a traffic signal controller and/or a backhaul network.

Any of the RAN nodes **511** can terminate the air interface protocol and can be the first point of contact for the UEs **501**. In some embodiments, any of the RAN nodes **511** can fulfill various logical functions for the RAN **510** 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.

In embodiments, the UEs **501** can be configured to communicate using OFDM communication signals with each other or with any of the RAN nodes **511** over a multicarrier communication channel in accordance with various communication techniques, such as, but not limited to, an OFDMA communication technique (e.g., for downlink communications) or a 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.

Downlink and uplink transmissions may be organized into frames with 10 ms durations, where each frame includes ten 1 ms subframes. A slot duration is 14 symbols with Normal CP and 12 symbols with Extended CP, and scales in time as a function of the used sub-carrier spacing so that there is always an integer number of slots in a subframe. In LTE implementations, a DL resource grid can be used for DL transmissions from any of the RAN nodes **511** to the UEs **501**, while UL transmissions from the UEs **501** to RAN nodes **511** can utilize a suitable UL resource grid in a similar manner. These resource grids may refer to time-frequency grids and indicate physical resource in the DL or UL in each slot. Each column and each row of the DL resource grid corresponds to one OFDM symbol and one OFDM subcarrier, respectively, and each column and each row of the UL resource grid corresponds to one SC-FDMA symbol and one SC-FDMA subcarrier, respectively. The duration of the resource grid in the time domain corresponds to one slot in a radio frame. The resource grids comprise a number of RBs, which describe the mapping of certain physical channels to REs. In the frequency domain, this may represent the smallest quantity of resources that currently can be allocated. Each RB comprises a collection of REs. An RE is the smallest time-frequency unit in a resource grid. Each RE is uniquely identified by the index pair (k,l) in a slot where $k=0, \ldots, N_{RB}^{DL}N_{sc}^{RB}-1$, and $l=0, \ldots, N_{symb}^{DL}-1$ are the indices in the frequency and time domains, respectively. RE (k,l) on antenna port p corresponds to the complex value $\alpha_{k,l}^{(p)}$. An antenna port is defined such that the channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed. There is one resource grid per antenna port. The set of antenna ports supported depends on the reference signal configuration in the cell, and these aspects are discussed in more detail in 3GPP TS 36.211.

In NR/5G implementations, DL and UL transmissions are organized into frames with 10 ms durations each of which includes ten 1 ms subframes. The number of consecutive OFDM symbols per subframe is $N_{symb}^{subframe,\mu}=N_{symb}^{slot}N_{slot}^{subframe,\mu}$. Each frame is divided into two equally-sized half-frames of five subframes each with half-frame 0 comprising subframes 0-4 and half-frame 1 comprising subframes 5-9. There is one set of frames in the UL and one set of frames in the DL on a carrier. Uplink frame number i for transmission from the UE shall start $T_{TA}=(N_{TA}+N_{TA,offset})T_c$ before the start of the corresponding downlink frame at the UE where $N_{TA,offset}$ is given by 3GPP TS 38.213. For subcarrier spacing configuration μ, slots are numbered $n_s^{\mu}\in\{0, \ldots, N_{slot}^{subframe,\mu}-1\}$ in increasing order within a subframe and $n_{s,f}^{\mu}\in\{0, \ldots, N_{slot}^{frame,\mu}-1\}$ in increasing order within a frame. There are N_{symb}^{slot} consecutive OFDM symbols in a slot where N_{symb}^{slot} depends on the cyclic prefix as given by tables 4.3.2-1 and 4.3.2-2 of 3GPP TS 38.211. The start of slot n_s^{μ} in a subframe is aligned in time with the start of OFDM symbol $n_s^{\mu}N_{symb}^{slot}$ in the same subframe. OFDM symbols in a slot can be classified as 'downlink', 'flexible', or 'uplink', where downlink transmissions only occur in 'downlink' or 'flexible' symbols and the UEs **501** only transmit in 'uplink' or 'flexible' symbols.

For each numerology and carrier, a resource grid of $N_{grid,x}^{size,\mu}N_{sc}^{RB}$ subcarriers and $N_{symb}^{subframe,\mu}$ OFDM symbols is defined, starting at common RB $N_{grid}^{start,\mu}$ indicated by higher-layer signaling. There is one set of resource grids per transmission direction (i.e., uplink or downlink) with the subscript x set to DL for downlink and x set to UL for uplink. There is one resource grid for a given antenna port p, subcarrier spacing configuration μ, and transmission direction (i.e., downlink or uplink).

An RB is defined as $N_{sc}^{RB}=12$ consecutive subcarriers in the frequency domain. Common RBs are numbered from 0 and upwards in the frequency domain for subcarrier spacing configuration μ. The center of subcarrier 0 of common resource block 0 for subcarrier spacing configuration μ coincides with 'point A'. The relation between the common resource block number n_{CRB}^{μ} in the frequency domain and resource elements (k,l) for subcarrier spacing configuration μ is given by

$$n_{CRB}^{\mu}=\left\lfloor\frac{k}{N_{sc}^{RB}}\right\rfloor$$

where k is defined relative to point A such that k=0 corresponds to the subcarrier centered around point A. Point A serves as a common reference point for resource block grids and is obtained from offsetToPointA for a PCell downlink where ofsetToPointA represents the frequency offset between point A and the lowest subcarrier of the lowest resource block, which has the subcarrier spacing provided by the higher-layer parameter subCarrierSpacingCommon and overlaps with the SS/PBCH block used by the UE for initial cell selection, expressed in units of resource blocks assuming 15 kHz subcarrier spacing for FR1 and 60 kHz subcarrier spacing for FR2; and absoluteFrequencyPointA for all other cases where absoluteFrequencyPointA represents the frequency-location of point A expressed as in ARFCN.

A PRB for subcarrier configuration p are defined within a BWP and numbered from 0 to $N_{BWP,i}^{size,\mu}-1$ where i is the number of the BWP. The relation between the physical resource block n_{PRB}^{n} in BWPi and the common RB n_{CRB}^{μ} is given by $n_{CRB}^{\mu}=n_{PRB}^{\mu}+N_{BWP,i}^{start,\mu}$ where $N_{BWP,i}^{start,\mu}$ is the common RB where BWP starts relative to common RB 0. VRBs are defined within a BWP and numbered from 0 to $N_{BWP,i}^{size}-1$ where i is the number of the BWP.

Each element in the resource grid for antenna port p and subcarrier spacing configuration μ is called an RE and is uniquely identified by $(k,l)_{p,\mu}$ where k is the index in the frequency domain and l refers to the symbol position in the time domain relative to some reference point. Resource element $(k,l)_{p,\mu}$ corresponds to a physical resource and the complex value $\alpha_{k,l}^{(p,\mu)}$. An antenna port is defined such that the channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed. Two antenna ports are said to be quasi co-located if the large-scale properties of the channel over which a symbol on one antenna port is conveyed can be inferred from the channel over which a symbol on the other antenna port is conveyed. The large-scale properties include one or more of delay spread, Doppler spread, Doppler shift, average gain, average delay, and spatial Rx parameters.

A BWP is a subset of contiguous common resource blocks defined in subclause 4.4.4.3 of 3GPP TS 38.211 for a given numerology μ_i in BWP i on a given carrier. The starting position $N_{BWP,i}^{start,\mu}$ and the number of resource blocks $N_{BWP,i}^{size,\mu}$ in a BWP shall fulfil $N_{grid,x}^{start,\mu}\leq N_{BWP,i}^{start,\mu}<N_{grid,x}^{start,\mu}+N_{grid,x}^{start,\mu}$ and

$N_{grid,x}^{start,\mu} < N_{BWP,i}^{start,\mu} + N_{BWP,i}^{size,\mu} \leq N_{grid,x}^{start,\mu} + N_{grid,x}^{size,\mu}$, respectively. Configuration of a BWP is described in clause **12** of 3GPP TS 38.213. The UEs **501** can be configured with up to four BWPs in the DL with a single DL BWP being active at a given time. The UEs **501** are not expected to receive PDSCH, PDCCH, or CSI-RS (except for RRM) outside an active BWP. The UEs **501** can be configured with up to four BWPs in the UL with a single UL BWP being active at a given time. If a UE **501** is configured with a supplementary UL, the UE **501** can be configured with up to four additional BWPs in the supplementary UL with a single supplementary UL BWP being active at a given time. The UEs **501** do not transmit PUSCH or PUCCH outside an active BWP, and for an active cell, the UEs do not transmit SRS outside an active BWP.

An NB is defined as six non-overlapping consecutive PRBs in the frequency domain. The total number of DL NBs in the DL transmission BW configured in the cell is given by

$$N_{NB}^{DL} = \left\lfloor \frac{N_{RB}^{DL}}{6} \right\rfloor.$$

The NBs are numbered $n_{NB}=0, \ldots, N_{NB}^{DL}-1$ in order of increasing PRB number where narrowband n_{NB} is comprises PRB indices:

$$\begin{cases} 6n_{NB} + i_0 + i & \text{if } N_{RB}^{UL} \bmod 2 = 0 \\ 6n_{NB} + i_0 + i & \text{if } N_{RB}^{UL} \bmod 2 = 1 \text{ and } n_{NB} < N_{NB}^{UL}/2, \\ 6n_{NB} + i_0 + i + 1 & \text{if } N_{RB}^{UL} \bmod 2 = 1 \text{ and } n_{NB} \geq N_{NB}^{UL}/2 \end{cases}$$

$$i = 0, 1, \ldots, 5 \text{ where}$$

$$i_0 = \left\lfloor \frac{N_{RB}^{UL}}{2} \right\rfloor - \frac{6N_{NB}^{UL}}{2}.$$

If $N_{NB}^{UL} \geq 4$, a wideband is defined as four non-overlapping narrowbands in the frequency domain. The total number of uplink widebands in the uplink transmission bandwidth configured in the cell is given by

$$N_{WB}^{UL} = \left\lfloor \frac{N_{NB}^{UL}}{4} \right\rfloor$$

and the widebands are numbered $n_{WB}=0, \ldots, N_{WB}^{UL}-1$ in order of increasing narrowband number where wideband n_{WB} is composed of narrowband indices $4n_{WB}+i$ where $i=0, 1, \ldots, 3$. If $N_{NB}^{UL}<4$, then $N_{WB}^{UL}=1$ and the single wideband is composed of the N_{NB}^{UL} non-overlapping narrowband(s).

There are several different physical channels and physical signals that are conveyed using RBs and/or individual REs. A physical channel corresponds to a set of REs carrying information originating from higher layers. Physical UL channels may include PUSCH, PUCCH, PRACH, and/or any other physical UL channel(s) discussed herein, and physical DL channels may include PDSCH, PBCH, PDCCH, and/or any other physical DL channel(s) discussed herein. A physical signal is used by the physical layer (e.g., PHY **1110** of FIG. **11**) but does not carry information originating from higher layers. Physical UL signals may include DMRS, PTRS, SRS, and/or any other physical UL signal(s) discussed herein, and physical DL signals may include DMRS, PTRS, CSI-RS, PSS, SSS, and/or any other physical DL signal(s) discussed herein.

The PDSCH carries user data and higher-layer signaling to the UEs **501**. Typically, DL scheduling (assigning control and shared channel resource blocks to the UE **501** within a cell) may be performed at any of the RAN nodes **511** based on channel quality information fed back from any of the UEs **501**. The downlink resource assignment information may be sent on the PDCCH used for (e.g., assigned to) each of the UEs **501**. The PDCCH uses CCEs to convey control information (e.g., DCI), and a set of CCEs may be referred to a "control region." Control channels are formed by aggregation of one or more CCEs, where different code rates for the control channels are realized by aggregating different numbers of CCEs. The CCEs are numbered from 0 to $N_{CCE,k}-1$, where $N_{CCE,k}-1$ is the number of CCEs in the control region of subframe k. Before being mapped to REs, 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 REs known as REGs. Four QPSK symbols may be mapped to each REG. The PDCCH can be transmitted using one or more CCEs, depending on the size of the DCI and the channel condition. There can be four or more different PDCCH formats defined with different numbers of CCEs (e.g., aggregation level, L=1, 2, 4, or 8 in LTE and L=1, 2, 4, 8, or 16 in NR). The UE **501** monitors a set of PDCCH candidates on one or more activated serving cells as configured by higher layer signaling for control information (e.g., DCI), where monitoring implies attempting to decode each of the PDCCHs (or PDCCH candidates) in the set according to all the monitored DCI formats (e.g., DCI formats 0 through 6-2 as discussed in section 5.3.3 of 3GPP TS 38.212, DCI formats 0_0 through 2_3 as discussed in section 7.3 of 3GPP TS 38.212, or the like). The UEs **501** monitor (or attempt to decode) respective sets of PDCCH candidates in one or more configured monitoring occasions according to the corresponding search space configurations. A DCI transports DL, UL, or SL scheduling information, requests for aperiodic CQI reports, LAA common information, notifications of MCCH change, UL power control commands for one cell and/or one RNTI, notification of a group of UEs **501** of a slot format, notification of a group of UEs of the PRB(s) and OFDM symbol(s) where UE may assume no transmission is intended for the UE, TPC commands for PUCCH and PUSCH, and/or TPC commands for PUCCH and PUSCH. The DCI coding steps are discussed in 3GPP TS 38.212.

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 EPDCCH that uses PDSCH resources for control information transmission. The EPDCCH may be transmitted using one or more ECCEs. Similar to above, each ECCE may correspond to nine sets of four physical resource elements known as an EREGs. An ECCE may have other numbers of EREGs in some situations.

As alluded to previously, the PDCCH can be used to schedule DL transmissions on PDSCH and UL transmissions on PUSCH, wherein the DCI on PDCCH includes, inter alia, downlink assignments containing at least modulation and coding format, resource allocation, and HARQ information related to DL-SCH; and/or uplink scheduling grants containing at least modulation and coding format, resource allocation, and HARQ information related to UL-

SCH. In addition to scheduling, the PDCCH can be used to for activation and deactivation of configured PUSCH transmission(s) with configured grant; activation and deactivation of PDSCH semi-persistent transmission; notifying one or more UEs **501** of a slot format; notifying one or more UEs **501** of the PRB(s) and OFDM symbol(s) where a UE **501** may assume no transmission is intended for the UE; transmission of TPC commands for PUCCH and PUSCH; transmission of one or more TPC commands for SRS transmissions by one or more UEs **501**; switching an active BWP for a UE **501**; and initiating a random access procedure.

In NR implementations, the UEs **501** monitor (or attempt to decode) respective sets of PDCCH candidates in one or more configured monitoring occasions in one or more configured CORESETs according to the corresponding search space configurations. A CORESET may include a set of PRBs with a time duration of 1 to 3 OFDM symbols. A CORESET may additionally or alternatively include $N_{RB}^{CORESET}$ RBs in the frequency domain and $N_{symb}^{CORESET} \in \{1,2,3\}$ symbols in the time domain. A CORESET includes six REGs numbered in increasing order in a time-first manner, wherein an REG equals one RB during one OFDM symbol. The UEs **501** can be configured with multiple CORESETS where each CORESET is associated with one CCE-to-REG mapping only. Interleaved and non-interleaved CCE-to-REG mapping are supported in a CORESET. Each REG carrying a PDCCH carries its own DMRS.

According to various embodiments, the UEs **501** and the RAN nodes **511** communicate data (for example, transmit and receive) data over a licensed medium (also referred to as the "licensed spectrum" and/or the "licensed band") and an unlicensed shared medium (also referred to as the "unlicensed spectrum" and/or the "unlicensed band"). The licensed spectrum may include channels that operate in the frequency range of approximately 400 MHz to approximately 3.8 GHz, whereas the unlicensed spectrum may include the 5 GHz band.

To operate in the unlicensed spectrum, the UEs **501** and the RAN nodes **511** may operate using LAA, eLAA, and/or feLAA mechanisms. In these implementations, the UEs **501** and the RAN nodes **511** may perform one or more known medium-sensing operations and/or carrier-sensing operations in order to determine whether one or more channels in the unlicensed spectrum is unavailable or otherwise occupied prior to transmitting in the unlicensed spectrum. The medium/carrier sensing operations may be performed according to a listen-before-talk (LBT) protocol.

LBT is a mechanism whereby equipment (for example, UEs **501** RAN nodes **511**, etc.) senses a medium (for example, a channel or carrier frequency) and transmits when the medium is sensed to be idle (or when a specific channel in the medium is sensed to be unoccupied). The medium sensing operation may include CCA, which utilizes at least ED to determine the presence or absence of other signals on a channel in order to determine if a channel is occupied or clear. This LBT mechanism allows cellular/LAA networks to coexist with incumbent systems in the unlicensed spectrum and with other LAA networks. ED may include sensing RF energy across an intended transmission band for a period of time and comparing the sensed RF energy to a predefined or configured threshold.

Typically, the incumbent systems in the 5 GHz band are WLANs based on IEEE 802.11 technologies. WLAN employs a contention-based channel access mechanism, called CSMA/CA. Here, when a WLAN node (e.g., a mobile station (MS) such as UE **501**, AP **506**, or the like) intends to transmit, the WLAN node may first perform CCA before transmission. Additionally, a backoff mechanism is used to avoid collisions in situations where more than one WLAN node senses the channel as idle and transmits at the same time. The backoff mechanism may be a counter that is drawn randomly within the CWS, which is increased exponentially upon the occurrence of collision and reset to a minimum value when the transmission succeeds. The LBT mechanism designed for LAA is somewhat similar to the CSMA/CA of WLAN. In some implementations, the LBT procedure for DL or UL transmission bursts including PDSCH or PUSCH transmissions, respectively, may have an LAA contention window that is variable in length between X and Y ECCA slots, where X and Y are minimum and maximum values for the CWSs for LAA. In one example, the minimum CWS for an LAA transmission may be 9 microseconds (μs); however, the size of the CWS and a MCOT (for example, a transmission burst) may be based on governmental regulatory requirements.

The LAA mechanisms are built upon CA technologies of LTE-Advanced systems. In CA, each aggregated carrier is referred to as a CC. A CC may have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz and a maximum of five CCs can be aggregated, and therefore, a maximum aggregated bandwidth is 100 MHz. In FDD systems, the number of aggregated carriers can be different for DL and UL, where the number of UL CCs is equal to or lower than the number of DL component carriers. In some cases, individual CCs can have a different bandwidth than other CCs. In TDD systems, the number of CCs as well as the BWs of each CC is usually the same for DL and UL.

CA also comprises individual serving cells to provide individual CCs. The coverage of the serving cells may differ, for example, because CCs on different frequency bands will experience different pathloss. A primary service cell or PCell may provide a PCC for both UL and DL and may handle RRC and NAS related activities. The other serving cells are referred to as SCells, and each SCell may provide an individual SCC for both UL and DL. The SCCs may be added and removed as required, while changing the PCC may require the UE **501** to undergo a handover. In LAA, eLAA, and feLAA, some or all of the SCells may operate in the unlicensed spectrum (referred to as "LAA SCells"), and the LAA SCells are assisted by a PCell operating in the licensed spectrum. When a UE is configured with more than one LAA SCell, the UE may receive UL grants on the configured LAA SCells indicating different PUSCH starting positions within a same subframe.

The RAN nodes **511** may be configured to communicate with one another via interface **512**. In embodiments where the system **500** is an LTE system (e.g., when CN **520** is an EPC **620** as in FIG. **6**), the interface **512** may be an X2 interface **512**. The X2 interface may be defined between two or more RAN nodes **511** (e.g., two or more eNBs and the like) that connect to EPC **520**, and/or between two eNBs connecting to EPC **520**. In some implementations, the X2 interface may include an X2 user plane interface (X2-U) and an X2 control plane interface (X2-C). The X2-U may provide flow control mechanisms for user data packets transferred over the X2 interface and may be used to communicate information about the delivery of user data between eNBs. For example, the X2-U may provide specific sequence number information for user data transferred from a MeNB to an SeNB; information about successful in sequence delivery of PDCP PDUs to a UE **501** from an SeNB for user data; information of PDCP PDUs that were not delivered to a UE **501**; information about a current minimum desired buffer size at the SeNB for transmitting to the UE user data; and the like. The X2-C may provide intra-LTE access mobility functionality, including context transfers from source to target eNBs, user plane transport control, etc.; load management functionality; as well as inter-cell interference coordination functionality. In embodiments where the system **100** is an MF system (e.g., when CN **520** is an NHCN **520**), the interface **512** may be an X2 interface **512**. The X2 interface may be defined between two or more RAN nodes **511** (e.g., two or more MF-APs and the like) that connect to NHCN **520**, and/or between two MF-APs connecting to NHCN **520**. In these embodiments, the X2 interface may operate in a same or similar manner as discussed previously.

In embodiments where the system **500** is a 5G or NR system (e.g., when CN **520** is an 5GC **720** as in FIG. **7**), the interface **512** may be an Xn interface **512**. The Xn interface is defined between two or more RAN nodes **511** (e.g., two or more gNBs and the like) that connect to 5GC **520**, between a RAN node **511** (e.g., a gNB) connecting to 5GC **520** and an eNB, and/or between two eNBs connecting to 5GC **520**. In some implementations, the Xn interface may include an Xn user plane (Xn-U) interface and an Xn control plane (Xn-C) interface. The Xn-U may provide non-guaranteed delivery of user plane PDUs and support/provide data forwarding and flow control functionality. The Xn-C may provide management and error handling functionality, functionality to manage the Xn-C interface; mobility support for UE **501** in a connected mode (e.g., CM-CONNECTED) including functionality to manage the UE mobility for connected mode between one or more RAN nodes **511**. The mobility support may include context transfer from an old (source) serving RAN node **511** to new (target) serving RAN node **511**; and control of user plane tunnels between old (source) serving RAN node **511** to new (target) serving RAN node **511**. A protocol stack of the Xn-U may include a transport network layer built on Internet Protocol (IP) transport layer, and a GTP-U layer on top of a UDP and/or IP layer(s) to carry user plane PDUs. The Xn-C protocol stack may include an application layer signaling protocol (referred to as Xn Application Protocol (Xn-AP)) and a transport network layer that is built on SCTP. The SCTP may be on top of an IP layer, and may provide the guaranteed delivery of application layer messages. In the transport IP layer, point-to-point transmission is used to deliver the signaling PDUs. In other implementations, the Xn-U protocol stack and/or the Xn-C protocol stack may be same or similar to the user plane and/or control plane protocol stack(s) shown and described herein.

The RAN **510** is shown to be communicatively coupled to a core network—in this embodiment, CN **520**. The CN **520** may comprise a plurality of network elements **522**, which are configured to offer various data and telecommunications services to customers/subscribers (e.g., users of UEs **501**) who are connected to the CN **520** via the RAN **510**. The components of the CN **520** may be implemented in one physical node or separate physical nodes including components to read and execute instructions from a machine-readable or computer-readable medium (e.g., a non-transitory machine-readable storage medium). In some embodiments, NFV may be utilized to virtualize any or all of the above-described network node functions via executable instructions stored in one or more computer-readable storage mediums (described in further detail below). A logical instantiation of the CN **520** may be referred to as a network slice, and a logical instantiation of a portion of the CN **520** may be referred to as a network sub-slice. NFV architectures and infrastructures may be used to virtualize one or more network functions, alternatively performed by proprietary hardware, onto physical resources comprising a combination of industry-standard server hardware, storage hardware, or switches. In other words, NFV systems can be used to execute virtual or reconfigurable implementations of one or more EPC components/functions.

Generally, the application server **530** may be an element offering applications that use IP bearer resources with the core network (e.g., UMTS PS domain, LTE PS data services, etc.). The application server **530** can also be configured to support one or more communication services (e.g., VoIP sessions, PIT sessions, group communication sessions, social networking services, etc.) for the UEs **501** via the EPC **520**.

In embodiments, the CN **520** may be a 5GC (referred to as "5GC **520**" or the like), and the RAN **510** may be connected with the CN **520** via an NG interface **513**. In embodiments, the NG interface **513** may be split into two parts, an NG user plane (NG-U) interface **514**, which carries traffic data between the RAN nodes **511** and a UPF, and the S1 control plane (NG-C) interface **515**, which is a signaling interface between the RAN nodes **511** and AMFs. Embodiments where the CN **520** is a 5GC **520** are discussed in more detail with regard to FIG. **7**.

In embodiments, the CN **520** may be a 5G CN (referred to as "5GC **520**" or the like), while in other embodiments, the CN **520** may be an EPC). Where CN **520** is an EPC (referred to as "EPC **520**" or the like), the RAN **510** may be connected with the CN **520** via an S1 interface **513**. In embodiments, the S1 interface **513** may be split into two parts, an S1 user plane (S1-U) interface **514**, which carries traffic data between the RAN nodes **511** and the S-GW, and the S1-MME interface **515**, which is a signaling interface between the RAN nodes **511** and MMEs.

In embodiments where the CN **520** is an MF NHCN **520**, the one or more network elements **522** may include or operate one or more NH-MMEs, local AAA proxies, NH-GWs, and/or other like MF NHCN elements. The NH-MME provides similar functionality as an MME in EPC **520**. A local AAA proxy is an AAA proxy that is part of an NHN that provides AAA functionalities required for interworking with PSP AAA and 3GPP AAAs. A PSP AAA is an AAA server (or pool of servers) using non-USIM credentials that is associated with a PSP, and may be either internal or external to the NHN, and the 3GPP AAA is discussed in more detail in 3GPP TS 23.402. The NH-GW provides similar functionality as a combined S-GW/P-GW for non-EPC routed PDN connections. For EPC Routed PDN connections, the NHN-GW provides similar functionality as the S-GW discussed previously in interactions with the MF-APs over the S1 interface **513** and is similar to the TWAG in interactions with the PLMN PDN-GWs over the S2a interface. In some embodiments, the MF APs **511** may connect with the EPC **520** discussed previously. Additionally, the RAN **510** (referred to as an "MF RAN **510**" or the like) may be connected with the NHCN **520** via an S1 interface **513**. In these embodiments, the S1 interface **513** may be split into two parts, the S1-U interface **514** that carries traffic data between the RAN nodes **511** (e.g., the "MF-APs **511**") and the NH-GW, and the S1-MME-N interface **515**, which is a signaling interface between the RAN nodes **511** and NH-MMEs. The S1-U interface **514** and the S1-MME-N interface **515** have the same or similar functionality as the S1-U interface **514** and the S1-MME interface **515** of the EPC **520** discussed herein.

FIG. **6** illustrates an example architecture of a system **600** including a first CN **620**, in accordance with various embodiments. In this example, system **600** may implement the LTE standard wherein the CN **620** is an EPC **620** that corresponds with CN **520** of FIG. **5**. Additionally, the UE **601** may be the same or similar as the UEs **501** of FIG. **5**, and the E-UTRAN **610** may be a RAN that is the same or similar to the RAN **510** of FIG. **5**, and which may include RAN nodes **511** discussed previously. The CN **620** may comprise MMEs **621**, an S-GW **622**, a P-GW **623**, a HSS **624**, and a SGSN **625**.

The MMEs **621** may be similar in function to the control plane of legacy SGSN, and may implement MM functions to keep track of the current location of a UE **601**. The MMEs **621** may perform various MM procedures to manage mobility aspects in access such as gateway selection and tracking area list management. MM (also referred to as "EPS MM" or "EMM" in E-UTRAN systems) may refer to all applicable procedures, methods, data storage, etc. that are used to maintain knowledge about a present location of the UE **601**, provide user identity confidentiality, and/or perform other like services to users/subscribers. Each UE **601** and the MME **621** may include an MM or EMM sublayer, and an MM context may be established in the UE **601** and the MME **621** when an attach procedure is successfully completed. The MM context may be a data structure or database object that stores MM-related information of the UE **601**. The MMEs **621** may be coupled with the HSS **624** via an S6a reference point, coupled with the SGSN **625** via an S3 reference point, and coupled with the S-GW **622** via an S11 reference point.

The SGSN **625** may be a node that serves the UE **601** by tracking the location of an individual UE **601** and performing security functions. In addition, the SGSN **625** may perform Inter-EPC node signaling for mobility between 2G/3G and E-UTRAN 3GPP access networks; PDN and S-GW selection as specified by the MMEs **621**; handling of UE **601** time zone functions as specified by the MMEs **621**; and MME selection for handovers to E-UTRAN 3GPP access network. The S3 reference point between the MMEs **621** and the SGSN **625** may enable user and bearer information exchange for inter-3GPP access network mobility in idle and/or active states.

The HSS **624** may comprise a database for network users, including subscription-related information to support the network entities' handling of communication sessions. The EPC **620** may comprise one or several HSSs **624**, depending on the number of mobile subscribers, on the capacity of the equipment, on the organization of the network, etc. For example, the HSS **624** can provide support for routing/roaming, authentication, authorization, naming/addressing resolution, location dependencies, etc. An S6a reference point between the HSS **624** and the MMEs **621** may enable transfer of subscription and authentication data for authenticating/authorizing user access to the EPC **620** between HSS **624** and the MMEs **621**.

The S-GW **622** may terminate the S1 interface **513** ("S1-U" in FIG. **6**) toward the RAN **610**, and routes data packets between the RAN **610** and the EPC **620**. In addition, the S-GW **622** 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. The S1 reference point between the S-GW **622** and the MMEs **621** may provide a control plane between the MMEs **621** and the S-GW **622**. The S-GW **622** may be coupled with the P-GW **623** via an S5 reference point.

The P-GW **623** may terminate an SGi interface toward a PDN **630**. The P-GW **623** may route data packets between the EPC **620** and external networks such as a network including the application server **530** (alternatively referred to as an "AF") via an IP interface **525** (see e.g., FIG. **5**). In embodiments, the P-GW **623** may be communicatively coupled to an application server (application server **530** of FIG. **5** or PDN **630** in FIG. **6**) via an IP communications interface **525** (see, e.g., FIG. **5**). The S5 reference point between the P-GW **623** and the S-GW **622** may provide user plane tunneling and tunnel management between the P-GW **623** and the S-GW **622**. The S5 reference point may also be used for S-GW **622** relocation due to UE **601** mobility and if the S-GW **622** needs to connect to a non-collocated P-GW **623** for the required PDN connectivity. The P-GW **623** may further include a node for policy enforcement and charging data collection (e.g., PCEF (not shown)). Additionally, the SGi reference point between the P-GW **623** and the packet data network (PDN) **630** may be an operator external public, a private PDN, or an intra operator packet data network, for example, for provision of IMS services. The P-GW **623** may be coupled with a PCRF **626** via a Gx reference point.

PCRF **626** is the policy and charging control element of the EPC **620**. In a non-roaming scenario, there may be a single PCRF **626** in the Home Public Land Mobile Network (HPLMN) associated with a UE **601**'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 **601**'s IP-CAN session, a Home PCRF (H-PCRF) within an HPLMN and a Visited PCRF (V-PCRF) within a Visited Public Land Mobile Network (VPLMN). The PCRF **626** may be communicatively coupled to the application server **630** via the P-GW **623**. The application server **630** may signal the PCRF **626** to indicate a new service flow and select the appropriate QoS and charging parameters. The PCRF **626** may provision this rule into a PCEF (not shown) with the appropriate TFT and QCI, which commences the QoS and charging as specified by the application server **630**. The Gx reference point between the PCRF **626** and the P-GW **623** may allow for the transfer of QoS policy and charging rules from the PCRF **626** to PCEF in the P-GW **623**. An Rx reference point may reside between the PDN **630** (or "AF **630**") and the PCRF **626**.

FIG. **7** illustrates an architecture of a system **700** including a second CN **720** in accordance with various embodiments. The system **700** is shown to include a UE **701**, which may be the same or similar to the UEs **501** and UE **601** discussed previously; a (R)AN **710**, which may be the same or similar to the RAN **510** and RAN **610** discussed previously, and which may include RAN nodes **511** discussed previously; and a DN **703**, which may be, for example, operator services, Internet access or 3rd party services; and a 5GC **720**. The 5GC **720** may include an AUSF **722**; an AMF **721**; a SMF **724**; a NEF **723**; a PCF **726**; a NRF **725**; a UDM **727**; an AF **728**; a UPF **702**; and a NSSF **729**.

The UPF **702** may act as an anchor point for intra-RAT and inter-RAT mobility, an external PDU session point of interconnect to DN **703**, and a branching point to support multi-homed PDU session. The UPF **702** may also perform packet routing and forwarding, perform packet inspection, enforce the user plane part of policy rules, lawfully intercept packets (UP collection), perform traffic usage reporting, perform QoS handling for a user plane (e.g., packet filtering, gating, UL/DL rate enforcement), perform Uplink Traffic verification (e.g., SDF to QoS flow mapping), transport level packet marking in the uplink and downlink, and perform downlink packet buffering and downlink data notification triggering. UPF **702** may include an uplink classifier to support routing traffic flows to a data network. The DN **703** may represent various network operator services, Internet access, or third-party services. DN **703** may include, or be similar to, application server **530** discussed previously. The UPF **702** may interact with the SMF **724** via an N4 reference point between the SMF **724** and the UPF **702**.

The AUSF **722** may store data for authentication of UE **701** and handle authentication-related functionality. The AUSF **722** may facilitate a common authentication framework for various access types. The AUSF **722** may communicate with the AMF **721** via an N12 reference point between the AMF **721** and the AUSF **722**; and may communicate with the UDM **727** via an N13 reference point between the UDM **727** and the AUSF **722**. Additionally, the AUSF **722** may exhibit an Nausf service-based interface.

The AMF **721** may be responsible for registration management (e.g., for registering UE **701**, etc.), connection management, reachability management, mobility management, and lawful interception of AMF-related events, and access authentication and authorization. The AMF **721** may be a termination point for the N 1l reference point between the AMF **721** and the SMF **724**. The AMF **721** may provide transport for SM messages between the UE **701** and the SMF **724**, and act as a transparent proxy for routing SM messages. AMF **721** may also provide transport for SMS messages between UE **701** and an SMSF (not shown by FIG. **7**). AMF **721** may act as SEAF, which may include interaction with the AUSF **722** and the UE **701**, receipt of an intermediate key that was established as a result of the UE **701** authentication process. Where USIM based authentication is used, the AMF **721** may retrieve the security material from the AUSF **722**. AMF **721** may also include a SCM function, which receives a key from the SEA that it uses to derive access-network specific keys. Furthermore, AMF **721** may be a termination point of a RAN CP interface, which may include or be an N2 reference point between the (R)AN **710** and the AMF **721**; and the AMF **721** may be a termination point of NAS (N1) signalling, and perform NAS ciphering and integrity protection.

AMF **721** may also support NAS signalling with a UE **701** over an N3 IWF interface. The N3IWF may be used to provide access to untrusted entities. N3IWF may be a termination point for the N2 interface between the (R)AN **710** and the AMF **721** for the control plane, and may be a termination point for the N3 reference point between the (R)AN **710** and the UPF **702** for the user plane. As such, the AMF **721** may handle N2 signalling from the SMF **724** and the AMF **721** for PDU sessions and QoS, encapsulate/de-encapsulate packets for IPSec and N3 tunnelling, mark N3 user-plane packets in the uplink, and enforce QoS corresponding to N3 packet marking taking into account QoS requirements associated with such marking received over N2. N3IWF may also relay uplink and downlink control-plane NAS signalling between the UE **701** and AMF **721** via an N1 reference point between the UE **701** and the AMF **721**, and relay uplink and downlink user-plane packets between the UE **701** and UPF **702**. The N3IWF also provides mechanisms for IPsec tunnel establishment with the UE **701**. The AMF **721** may exhibit an Namf service-based interface, and may be a termination point for an N14 reference point between two AMFs **721** and an N17 reference point between the AMF **721** and a 5G-EIR (not shown by FIG. **7**).

The UE **701** may need to register with the AMF **721** in order to receive network services. RM is used to register or deregister the UE **701** with the network (e.g., AMF **721**), and establish a UE context in the network (e.g., AMF **721**). The UE **701** may operate in an RM-REGISTERED state or an RM-DEREGISTERED state. In the RM-DEREGISTERED state, the UE **701** is not registered with the network, and the UE context in AMF **721** holds no valid location or routing information for the UE **701** so the UE **701** is not reachable by the AMF **721**. In the RM-REGISTERED state, the UE **701** is registered with the network, and the UE context in AMF **721** may hold a valid location or routing information for the UE **701** so the UE **701** is reachable by the AMF **721**. In the RM-REGISTERED state, the UE **701** may perform mobility Registration Update procedures, perform periodic Registration Update procedures triggered by expiration of the periodic update timer (e.g., to notify the network that the UE **701** is still active), and perform a Registration Update procedure to update UE capability information or to re-negotiate protocol parameters with the network, among others.

The AMF **721** may store one or more RM contexts for the UE **701**, where each RM context is associated with a specific access to the network. The RM context may be a data structure, database object, etc. that indicates or stores, inter alia, a registration state per access type and the periodic update timer. The AMF **721** may also store a 5GC MM context that may be the same or similar to the (E)MM context discussed previously. In various embodiments, the AMF **721** may store a CE mode B Restriction parameter of the UE **701** in an associated MM context or RM context. The AMF **721** may also derive the value, when needed, from the UE's usage setting parameter already stored in the UE context (and/or MM/RM context).

CM may be used to establish and release a signaling connection between the UE **701** and the AMF **721** over the N1 interface. The signaling connection is used to enable NAS signaling exchange between the UE **701** and the CN **720**, and comprises both the signaling connection between the UE and the AN (e.g., RRC connection or UE-N3IWF connection for non-3GPP access) and the N2 connection for the UE **701** between the AN (e.g., RAN **710**) and the AMF **721**. The UE **701** may operate in one of two CM states, CM-IDLE mode or CM-CONNECTED mode. When the UE **701** is operating in the CM-IDLE state/mode, the UE **701** may have no NAS signaling connection established with the AMF **721** over the N1 interface, and there may be (R)AN **710** signaling connection (e.g., N2 and/or N3 connections) for the UE **701**. When the UE **701** is operating in the CM-CONNECTED state/mode, the UE **701** may have an established NAS signaling connection with the AMF **721** over the N1 interface, and there may be a (R)AN **710** signaling connection (e.g., N2 and/or N3 connections) for the UE **701**. Establishment of an N2 connection between the (R)AN **710** and the AMF **721** may cause the UE **701** to transition from CM-IDLE mode to CM-CONNECTED mode, and the UE **701** may transition from the CM-CONNECTED mode to the CM-IDLE mode when N2 signaling between the (R)AN **710** and the AMF **721** is released.

The SMF **724** may be responsible for SM (e.g., session establishment, modify and release, including tunnel maintain between UPF and AN node); UE IP address allocation and management (including optional authorization); selection and control of UP function; configuring traffic steering at UPF to route traffic to proper destination; termination of interfaces toward policy control functions; controlling part of policy enforcement and QoS; lawful intercept (for SM events and interface to LI system); termination of SM parts of NAS messages; downlink data notification; initiating AN specific SM information, sent via AMF over N2 to AN; and determining SSC mode of a session. SM may refer to management of a PDU session, and a PDU session or "session" may refer to a PDU connectivity service that provides or enables the exchange of PDUs between a UE **701** and a data network (DN) **703** identified by a Data Network Name (DNN). PDU sessions may be established upon UE **701** request, modified upon UE **701** and 5GC **720** request, and released upon UE **701** and 5GC **720** request using NAS SM signaling exchanged over the N1 reference point between the UE **701** and the SMF **724**. Upon request from an application server, the 5GC **720** may trigger a specific application in the UE **701**. In response to receipt of the trigger message, the UE **701** may pass the trigger message (or relevant parts/information of the trigger message) to one or more identified applications in the UE **701**. The identified application(s) in the UE **701** may establish a PDU session to a specific DNN. The SMF **724** may check whether the UE **701** requests are compliant with user subscription information associated with the UE **701**. In this regard, the SMF **724** may retrieve and/or request to receive update notifications on SMF **724** level subscription data from the UDM **727**.

The SMF **724** may include the following roaming functionality: handling local enforcement to apply QoS SLAs (VPLMN); charging data collection and charging interface (VPLMN); lawful intercept (in VPLMN for SM events and interface to LI system); and support for interaction with external DN for transport of signalling for PDU session authorization/authentication by external DN. An N16 reference point between two SMFs **724** may be included in the system **700**, which may be between another SMF **724** in a visited network and the SMF **724** in the home network in roaming scenarios. Additionally, the SMF **724** may exhibit the Nsmf service-based interface.

The NEF **723** may provide means for securely exposing the services and capabilities provided by 3GPP network functions for third party, internal exposure/re-exposure, Application Functions (e.g., AF **728**), edge computing or fog computing systems, etc. In such embodiments, the NEF **723** may authenticate, authorize, and/or throttle the AFs. NEF **723** may also translate information exchanged with the AF **728** and information exchanged with internal network functions. For example, the NEF **723** may translate between an AF-Service-Identifier and an internal 5GC information. NEF **723** may also receive information from other network functions (NFs) based on exposed capabilities of other network functions. This information may be stored at the NEF **723** as structured data, or at a data storage NF using standardized interfaces. The stored information can then be re-exposed by the NEF **723** to other NFs and AFs, and/or used for other purposes such as analytics. Additionally, the NEF **723** may exhibit an Nnef service-based interface.

The NRF **725** may support service discovery functions, receive NF discovery requests from NF instances, and provide the information of the discovered NF instances to the NF instances. NRF **725** also maintains information of available NF instances and their supported services. As used herein, the terms "instantiate," "instantiation," and the like may refer to the creation of an instance, and an "instance" may refer to a concrete occurrence of an object, which may occur, for example, during execution of program code. Additionally, the NRF **725** may exhibit the Nnrf service-based interface.

The PCF **726** may provide policy rules to control plane function(s) to enforce them, and may also support unified policy framework to govern network behaviour. The PCF **726** may also implement an FE to access subscription information relevant for policy decisions in a UDR of the UDM **727**. The PCF **726** may communicate with the AMF **721** via an N15 reference point between the PCF **726** and the AMF **721**, which may include a PCF **726** in a visited network and the AMF **721** in case of roaming scenarios. The PCF **726** may communicate with the AF **728** via an N5 reference point between the PCF **726** and the AF **728**; and with the SMF **724** via an N7 reference point between the PCF **726** and the SMF **724**. The system **700** and/or CN **720** may also include an N24 reference point between the PCF **726** (in the home network) and a PCF **726** in a visited network. Additionally, the PCF **726** may exhibit an Npcf service-based interface.

The UDM **727** may handle subscription-related information to support the network entities' handling of communication sessions, and may store subscription data of UE **701**. For example, subscription data may be communicated between the UDM **727** and the AMF **721** via an N8 reference point between the UDM **727** and the AMF. The UDM **727** may include two parts, an application FE and a UDR (the FE and UDR are not shown by FIG. **7**). The UDR may store subscription data and policy data for the UDM **727** and the PCF **726**, and/or structured data for exposure and application data (including PFDs for application detection, application request information for multiple UEs **701**) for the NEF **723**. The Nudr service-based interface may be exhibited by the UDR **221** to allow the UDM **727**, PCF **726**, and NEF **723** to access a particular set of the stored data, as well as to read, update (e.g., add, modify), delete, and subscribe to notification of relevant data changes in the UDR. The UDM may include a UDM-FE, which is in charge of processing credentials, location management, subscription management and so on. Several different front ends may serve the same user in different transactions. The UDM-FE accesses subscription information stored in the UDR and performs authentication credential processing, user identification handling, access authorization, registration/mobility management, and subscription management. The UDR may interact with the SMF **724** via an N10 reference point between the UDM **727** and the SMF **724**. UDM **727** may also support SMS management, wherein an SMS-FE implements the similar application logic as discussed previously. Additionally, the UDM **727** may exhibit the Nudm service-based interface.

The AF **728** may provide application influence on traffic routing, provide access to the NCE, and interact with the policy framework for policy control. The NCE may be a mechanism that allows the 5GC **720** and AF **728** to provide information to each other via NEF **723**, which may be used for edge computing implementations. In such implementations, the network operator and third-party services may be hosted close to the UE **701** access point of attachment to achieve an efficient service delivery through the reduced end-to-end latency and load on the transport network. For edge computing implementations, the 5GC may select a UPF **702** close to the UE **701** and execute traffic steering from the UPF **702** to DN **703** via the N6 interface. This may be based on the UE subscription data, UE location, and information provided by the AF **728**. In this way, the AF **728** may influence UPF (re)selection and traffic routing. Based on operator deployment, when AF **728** is considered to be a trusted entity, the network operator may permit AF **728** to interact directly with relevant NFs. Additionally, the AF **728** may exhibit an Naf service-based interface.

The NSSF **729** may select a set of network slice instances serving the UE **701**. The NSSF **729** may also determine allowed NSSAI and the mapping to the subscribed S-NS-

SAIs, if needed. The NSSF **729** may also determine the AMF set to be used to serve the UE **701**, or a list of candidate AMF(s) **721** based on a suitable configuration and possibly by querying the NRF **725**. The selection of a set of network slice instances for the UE **701** may be triggered by the AMF **721** with which the UE **701** is registered by interacting with the NSSF **729**, which may lead to a change of AMF **721**. The NSSF **729** may interact with the AMF **721** via an N22 reference point between AMF **721** and NSSF **729**; and may communicate with another NSSF **729** in a visited network via an N31 reference point (not shown by FIG. **7**). Additionally, the NSSF **729** may exhibit an Nnssf service-based interface.

As discussed previously, the CN **720** may include an SMSF, which may be responsible for SMS subscription checking and verification, and relaying SM messages to/from the UE **701** to/from other entities, such as an SMS-GMSC/IWMSC/SMS-router. The SMS may also interact with AMF **721** and UDM **727** for a notification procedure that the UE **701** is available for SMS transfer (e.g., set a UE not reachable flag, and notifying UDM **727** when UE **701** is available for SMS).

The CN **520** may also include other elements that are not shown by FIG. **7**, such as a Data Storage system/architecture, a 5G-EIR, a SEPP, and the like. The Data Storage system may include a SDSF, an UDSF, and/or the like. Any NF may store and retrieve unstructured data into/from the UDSF (e.g., UE contexts), via N18 reference point between any NF and the UDSF (not shown by FIG. **7**). Individual NFs may share a UDSF for storing their respective unstructured data or individual NFs may each have their own UDSF located at or near the individual NFs. Additionally, the UDSF may exhibit an Nudsf service-based interface (not shown by FIG. **7**). The 5G-EIR may be an NF that checks the status of PEI for determining whether particular equipment/entities are blacklisted from the network; and the SEPP may be a non-transparent proxy that performs topology hiding, message filtering, and policing on inter-PLMN control plane interfaces.

Additionally, there may be many more reference points and/or service-based interfaces between the NF services in the NFs; however, these interfaces and reference points have been omitted from FIG. **7** for clarity. In one example, the CN **720** may include an Nx interface, which is an inter-CN interface between the MME (e.g., MME **621**) and the AMF **721** in order to enable interworking between CN **720** and CN **620**. Other example interfaces/reference points may include an N5g-EIR service-based interface exhibited by a 5G-EIR, an N27 reference point between the NRF in the visited network and the NRF in the home network; and an N31 reference point between the NSSF in the visited network and the NSSF in the home network.

FIG. **8** illustrates an example of infrastructure equipment **800** in accordance with various embodiments. The infrastructure equipment **800** (or "system **800**") may be implemented as a base station, radio head, RAN node such as the RAN nodes **511** and/or AP **506** shown and described previously, application server(s) **530**, and/or any other element/device discussed herein. In other examples, the system **800** could be implemented in or by a UE.

The system **800** includes application circuitry **805**, baseband circuitry **810**, one or more radio front end modules (RFEMs) **815**, memory circuitry **820**, power management integrated circuitry (PMIC) **825**, power tee circuitry **830**, network controller circuitry **835**, network interface connector **840**, satellite positioning circuitry **845**, and user interface **850**. 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. For example, said circuitries may be separately included in more than one device for CRAN, vBBU, or other like implementations.

Application circuitry **805** includes circuitry such as, but not limited to one or more processors (or processor cores), cache memory, and one or more of low drop-out voltage regulators (LDOs), interrupt controllers, serial interfaces such as SPI, I^2C or universal programmable serial interface module, real time clock (RTC), timer-counters including interval and watchdog timers, general purpose input/output (I/O or IO), memory card controllers such as Secure Digital (SD) MultiMediaCard (MMC) or similar, Universal Serial Bus (USB) interfaces, Mobile Industry Processor Interface (MIPI) interfaces and Joint Test Access Group (JTAG) test access ports. The processors (or cores) of the application circuitry **805** may be coupled with or may include memory/storage elements and may be configured to execute instructions stored in the memory/storage to enable various applications or operating systems to run on the system **800**. In some implementations, the memory/storage elements may be on-chip memory circuitry, which may include any suitable volatile and/or non-volatile memory, such as DRAM, SRAM, EPROM, EEPROM, Flash memory, solid-state memory, and/or any other type of memory device technology, such as those discussed herein.

The processor(s) of application circuitry **805** may include, for example, one or more processor cores (CPUs), one or more application processors, one or more graphics processing units (GPUs), one or more reduced instruction set computing (RISC) processors, one or more Acorn RISC Machine (ARM) processors, one or more complex instruction set computing (CISC) processors, one or more digital signal processors (DSP), one or more FPGAs, one or more PLDs, one or more ASICs, one or more microprocessors or controllers, or any suitable combination thereof. In some embodiments, the application circuitry **805** may comprise, or may be, a special-purpose processor/controller to operate according to the various embodiments herein. As examples, the processor(s) of application circuitry **805** may include one or more Intel Pentium®, Core®, or Xeon® processor(s); Advanced Micro Devices (AMD) Ryzen® processor(s), Accelerated Processing Units (APUs), or Epyc® processors; ARM-based processor(s) licensed from ARM Holdings, Ltd. such as the ARM Cortex-A family of processors and the ThunderX2® provided by Cavium™, Inc.; a MIPS-based design from MIPS Technologies, Inc. such as MIPS Warrior P-class processors; and/or the like. In some embodiments, the system **800** may not utilize application circuitry **805**, and instead may include a special-purpose processor/controller to process IP data received from an EPC or 5GC, for example.

In some implementations, the application circuitry **805** may include one or more hardware accelerators, which may be microprocessors, programmable processing devices, or the like. The one or more hardware accelerators may include, for example, computer vision (CV) and/or deep learning (DL) accelerators. As examples, the programmable processing devices may be one or more a field-programmable devices (FPDs) such as field-programmable gate arrays (FPGAs) and the like; programmable logic devices (PLDs) such as complex PLDs (CPLDs), high-capacity PLDs (HCPLDs), and the like; ASICs such as structured ASICs and the like; programmable SoCs (PSoCs); and the like. In such implementations, the circuitry of application circuitry **805** may comprise logic blocks or logic fabric, and other interconnected resources that may be programmed to perform various functions, such as the procedures, methods, functions, etc. of the various embodiments discussed herein. In such embodiments, the circuitry of application circuitry **805** may include memory cells (e.g., erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), flash memory, static memory (e.g., static random access memory (SRAM), anti-fuses, etc.)) used to store logic blocks, logic fabric, data, etc. in look-up-tables (LUTs) and the like.

The baseband circuitry **810** may be implemented, for example, as a solder-down substrate including one or more integrated circuits, a single packaged integrated circuit soldered to a main circuit board or a multi-chip module containing two or more integrated circuits. The various hardware electronic elements of baseband circuitry **810** are discussed infra with regard to FIG. **10**.

User interface circuitry **850** may include one or more user interfaces designed to enable user interaction with the system **800** or peripheral component interfaces designed to enable peripheral component interaction with the system **800**. User interfaces may include, but are not limited to, one or more physical or virtual buttons (e.g., a reset button), one or more indicators (e.g., light emitting diodes (LEDs)), a physical keyboard or keypad, a mouse, a touchpad, a touchscreen, speakers or other audio emitting devices, microphones, a printer, a scanner, a headset, a display screen or display device, etc. Peripheral component interfaces may include, but are not limited to, a nonvolatile memory port, a universal serial bus (USB) port, an audio jack, a power supply interface, etc.

The radio front end modules (RFEMs) **815** may comprise a millimeter wave (mmWave) RFEM and one or more sub-mmWave radio frequency integrated circuits (RFICs). In some implementations, the one or more sub-mmWave RFICs may be physically separated from the mmWave RFEM. The RFICs may include connections to one or more antennas or antenna arrays (see e.g., antenna array **10111** of FIG. **10** infra), and the RFEM may be connected to multiple antennas. In alternative implementations, both mmWave and sub-mmWave radio functions may be implemented in the same physical RFEM **815**, which incorporates both mmWave antennas and sub-mmWave.

The memory circuitry **820** may include one or more of volatile memory including dynamic random access memory (DRAM) and/or synchronous dynamic random access memory (SDRAM), and nonvolatile memory (NVM) including high-speed electrically erasable memory (commonly referred to as Flash memory), phase change random access memory (PRAM), magnetoresistive random access memory (MRAM), etc., and may incorporate the three-dimensional (3D) cross-point (XPOINT) memories from Intel® and Micron®. Memory circuitry **820** may be implemented as one or more of solder down packaged integrated circuits, socketed memory modules and plug-in memory cards.

The PMIC **825** may include voltage regulators, surge protectors, power alarm detection circuitry, and one or more backup power sources such as a battery or capacitor. The power alarm detection circuitry may detect one or more of brown out (under-voltage) and surge (over-voltage) conditions. The power tee circuitry **830** may provide for electrical power drawn from a network cable to provide both power supply and data connectivity to the infrastructure equipment **800** using a single cable.

The network controller circuitry **835** may provide connectivity to a network using a standard network interface protocol such as Ethernet, Ethernet over GRE Tunnels, Ethernet over Multiprotocol Label Switching (MPLS), or some other suitable protocol. Network connectivity may be provided to/from the infrastructure equipment **800** via network interface connector **840** using a physical connection, which may be electrical (commonly referred to as a "copper interconnect"), optical, or wireless. The network controller circuitry **835** may include one or more dedicated processors and/or FPGAs to communicate using one or more of the aforementioned protocols. In some implementations, the network controller circuitry **835** may include multiple controllers to provide connectivity to other networks using the same or different protocols.

The positioning circuitry **845** includes circuitry to receive and decode signals transmitted/broadcasted by a positioning network of a global navigation satellite system (GNSS). Examples of navigation satellite constellations (or GNSS) include United States' Global Positioning System (GPS), Russia's Global Navigation System (GLONASS), the European Union's Galileo system, China's BeiDou Navigation Satellite System, a regional navigation system or GNSS augmentation system (e.g., Navigation with Indian Constellation (NAVIC), Japan's Quasi-Zenith Satellite System (QZSS), France's Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS), etc.), or the like. The positioning circuitry **845** comprises various hardware elements (e.g., including hardware devices such as switches, filters, amplifiers, antenna elements, and the like to facilitate OTA communications) to communicate with components of a positioning network, such as navigation satellite constellation nodes. In some embodiments, the positioning circuitry **845** may include a Micro-Technology for Positioning, Navigation, and Timing (Micro-PNT) IC that uses a master timing clock to perform position tracking/estimation without GNSS assistance. The positioning circuitry **845** may also be part of, or interact with, the baseband circuitry **810** and/or RFEMs **815** to communicate with the nodes and components of the positioning network. The positioning circuitry **845** may also provide position data and/or time data to the application circuitry **805**, which may use the data to synchronize operations with various infrastructure (e.g., RAN nodes **511**, etc.), or the like.

The components shown by FIG. **8** may communicate with one another using interface circuitry, which may include any number of bus and/or interconnect (IX) technologies such as industry standard architecture (ISA), extended ISA (EISA), peripheral component interconnect (PCI), peripheral component interconnect extended (PCIx), PCI express (PCIe), or any number of other technologies. The bus/IX may be a proprietary bus, for example, used in a SoC based system. Other bus/IX systems may be included, such as an I^2C interface, an SPI interface, point to point interfaces, and a power bus, among others.

FIG. **9** illustrates an example of a platform **900** (or "device **900**") in accordance with various embodiments. In embodiments, the computer platform **900** may be suitable for use as UEs **501**, **601**, **701**, application servers **530**, and/or any other element/device discussed herein. The platform **900** may include any combinations of the components shown in the example. The components of platform **900** may be implemented as integrated circuits (ICs), portions thereof, discrete electronic devices, or other modules, logic, hardware, software, firmware, or a combination thereof adapted in the computer platform **900**, or as components otherwise incorporated within a chassis of a larger system. The block diagram of FIG. **9** is intended to show a high level view of components of the computer platform **900**. However, some of the components shown may be omitted, additional components may be present, and different arrangement of the components shown may occur in other implementations.

Application circuitry **905** includes circuitry such as, but not limited to one or more processors (or processor cores), cache memory, and one or more of LDOs, interrupt controllers, serial interfaces such as SPI, I^2C or universal programmable serial interface module, RTC, timer-counters including interval and watchdog timers, general purpose I/O, memory card controllers such as SD MMC or similar, USB interfaces, MIPI interfaces, and JTAG test access ports. The processors (or cores) of the application circuitry **905** may be coupled with or may include memory/storage elements and may be configured to execute instructions stored in the memory/storage to enable various applications or operating systems to run on the system **900**. In some implementations, the memory/storage elements may be on-chip memory circuitry, which may include any suitable volatile and/or non-volatile memory, such as DRAM, SRAM, EPROM, EEPROM, Flash memory, solid-state memory, and/or any other type of memory device technology, such as those discussed herein.

The processor(s) of application circuitry **805** may include, for example, one or more processor cores, one or more application processors, one or more GPUs, one or more RISC processors, one or more ARM processors, one or more CISC processors, one or more DSP, one or more FPGAs, one or more PLDs, one or more ASICs, one or more microprocessors or controllers, a multithreaded processor, an ultra-low voltage processor, an embedded processor, some other known processing element, or any suitable combination thereof. In some embodiments, the application circuitry **805** may comprise, or may be, a special-purpose processor/controller to operate according to the various embodiments herein.

As examples, the processor(s) of application circuitry **905** may include an Intel® Architecture Core™ based processor, such as a Quark™, an Atom™, an i3, an i5, an i7, or an MCU-class processor, or another such processor available from Intel® Corporation, Santa Clara, CA. The processors of the application circuitry **905** may also be one or more of Advanced Micro Devices (AMD) Ryzen® processor(s) or Accelerated Processing Units (APUs); A5-A9 processor(s) from Apple® Inc., Snapdragon™ processor(s) from Qualcomm® Technologies, Inc., Texas Instruments, Inc.® Open Multimedia Applications Platform (OMAP)™ processor(s); a MIPS-based design from MIPS Technologies, Inc. such as MIPS Warrior M-class, Warrior I-class, and Warrior P-class processors; an ARM-based design licensed from ARM Holdings, Ltd., such as the ARM Cortex-A, Cortex-R, and Cortex-M family of processors; or the like. In some implementations, the application circuitry **905** may be a part of a system on a chip (SoC) in which the application circuitry **905** and other components are formed into a single integrated circuit, or a single package, such as the Edison™ or Galileo™ SoC boards from Intel® Corporation.

Additionally or alternatively, application circuitry **905** may include circuitry such as, but not limited to, one or more a field-programmable devices (FPDs) such as FPGAs and the like; programmable logic devices (PLDs) such as complex PLDs (CPLDs), high-capacity PLDs (HCPLDs), and the like; ASICs such as structured ASICs and the like; programmable SoCs (PSoCs); and the like. In such embodiments, the circuitry of application circuitry **905** may comprise logic blocks or logic fabric, and other interconnected resources that may be programmed to perform various functions, such as the procedures, methods, functions, etc. of the various embodiments discussed herein. In such embodiments, the circuitry of application circuitry **905** may include memory cells (e.g., erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), flash memory, static memory (e.g., static random access memory (SRAM), anti-fuses, etc.)) used to store logic blocks, logic fabric, data, etc. in look-up tables (LUTs) and the like.

The baseband circuitry **910** may be implemented, for example, as a solder-down substrate including one or more integrated circuits, a single packaged integrated circuit soldered to a main circuit board or a multi-chip module containing two or more integrated circuits. The various hardware electronic elements of baseband circuitry **910** are discussed infra with regard to FIG. **10**.

The RFEMs **915** may comprise a millimeter wave (mmWave) RFEM and one or more sub-mmWave radio frequency integrated circuits (RFICs). In some implementations, the one or more sub-mmWave RFICs may be physically separated from the mmWave RFEM. The RFICs may include connections to one or more antennas or antenna arrays (see e.g., antenna array **1011** of FIG. **10** infra), and the RFEM may be connected to multiple antennas. In alternative implementations, both mmWave and sub-mmWave radio functions may be implemented in the same physical RFEM **915**, which incorporates both mmWave antennas and sub-mmWave.

The memory circuitry **920** may include any number and type of memory devices used to provide for a given amount of system memory. As examples, the memory circuitry **920** may include one or more of volatile memory including random access memory (RAM), dynamic RAM (DRAM) and/or synchronous dynamic RAM (SDRAM), and nonvolatile memory (NVM) including high-speed electrically erasable memory (commonly referred to as Flash memory), phase change random access memory (PRAM), magnetoresistive random access memory (MRAM), etc. The memory circuitry **920** may be developed in accordance with a Joint Electron Devices Engineering Council (JEDEC) low power double data rate (LPDDR)-based design, such as LPDDR2, LPDDR3, LPDDR4, or the like. Memory circuitry **920** may be implemented as one or more of solder down packaged integrated circuits, single die package (SDP), dual die package (DDP) or quad die package (Q17P), socketed memory modules, dual inline memory modules (DIMMs) including microDIMMs or MiniDIMMs, and/or soldered onto a motherboard via a ball grid array (BGA). In low power implementations, the memory circuitry **920** may be on-die memory or registers associated with the application circuitry **905**. To provide for persistent storage of information such as data, applications, operating systems and so forth, memory circuitry **920** may include one or more mass storage devices, which may include, inter alia, a solid state disk drive (SSDD), hard disk drive (HDD), a micro HDD, resistance change memories, phase change memories, holographic memories, or chemical memories, among others. For example, the computer platform **900** may incorporate the three-dimensional (3D) cross-point (XPOINT) memories from Intel® and Micron®.

Removable memory circuitry **923** may include devices, circuitry, enclosures/housings, ports or receptacles, etc. used to couple portable data storage devices with the platform **900**. These portable data storage devices may be used for mass storage purposes, and may include, for example, flash memory cards (e.g., Secure Digital (SD) cards, microSD cards, xD picture cards, and the like), and USB flash drives, optical discs, external HDDs, and the like.

The platform **900** may also include interface circuitry (not shown) that is used to connect external devices with the platform **900**. The external devices connected to the platform **900** via the interface circuitry include sensor circuitry **921** and electro-mechanical components (EMCs) **922**, as well as removable memory devices coupled to removable memory circuitry **923**.

The sensor circuitry **921** include devices, modules, or subsystems whose purpose is to detect events or changes in its environment and send the information (sensor data) about the detected events to some other a device, module, subsystem, etc. Examples of such sensors include, inter alia, inertia measurement units (IMUs) comprising accelerometers, gyroscopes, and/or magnetometers; microelectromechanical systems (MEMS) or nanoelectromechanical systems (NEMS) comprising 3-axis accelerometers, 3-axis gyroscopes, and/or magnetometers; level sensors; flow sensors; temperature sensors (e.g., thermistors); pressure sensors; barometric pressure sensors; gravimeters; altimeters; image capture devices (e.g., cameras or lensless apertures); light detection and ranging (LiDAR) sensors; proximity sensors (e.g., infrared radiation detector and the like), depth sensors, ambient light sensors, ultrasonic transceivers; microphones or other like audio capture devices; etc.

EMCs **922** include devices, modules, or subsystems whose purpose is to enable platform **900** to change its state, position, and/or orientation, or move or control a mechanism or (sub)system. Additionally, EMCs **922** may be configured to generate and send messages/signalling to other components of the platform **900** to indicate a current state of the EMCs **922**. Examples of the EMCs **922** include one or more power switches, relays including electromechanical relays (EMRs) and/or solid state relays (SSRs), actuators (e.g., valve actuators, etc.), an audible sound generator, a visual warning device, motors (e.g., DC motors, stepper motors, etc.), wheels, thrusters, propellers, claws, clamps, hooks, and/or other like electro-mechanical components. In embodiments, platform **900** is configured to operate one or more EMCs **922** based on one or more captured events and/or instructions or control signals received from a service provider and/or various clients.

In some implementations, the interface circuitry may connect the platform **900** with positioning circuitry **945**. The positioning circuitry **945** includes circuitry to receive and decode signals transmitted/broadcasted by a positioning network of a GNSS. Examples of navigation satellite constellations (or GNSS) include United States' GPS, Russia's GLONASS, the European Union's Galileo system, China's BeiDou Navigation Satellite System, a regional navigation system or GNSS augmentation system (e.g., NAVIC), Japan's QZSS, France's DORIS, etc.), or the like. The positioning circuitry **945** comprises various hardware elements (e.g., including hardware devices such as switches, filters, amplifiers, antenna elements, and the like to facilitate OTA communications) to communicate with components of a positioning network, such as navigation satellite constellation nodes. In some embodiments, the positioning circuitry **945** may include a Micro-PNT IC that uses a master timing clock to perform position tracking/estimation without GNSS assistance. The positioning circuitry **945** may also be part of, or interact with, the baseband circuitry **810** and/or RFEMs **915** to communicate with the nodes and components of the positioning network. The positioning circuitry **945** may also provide position data and/or time data to the application circuitry **905**, which may use the data to synchronize operations with various infrastructure (e.g., radio base stations), for turn-by-turn navigation applications, or the like

In some implementations, the interface circuitry may connect the platform **900** with Near-Field Communication (NFC) circuitry **940**. NFC circuitry **940** is configured to provide contactless, short-range communications based on radio frequency identification (RFID) standards, wherein magnetic field induction is used to enable communication between NFC circuitry **940** and NFC-enabled devices external to the platform **900** (e.g., an "NFC touchpoint"). NFC circuitry **940** comprises an NFC controller coupled with an antenna element and a processor coupled with the NFC controller. The NFC controller may be a chip/IC providing NFC functionalities to the NFC circuitry **940** by executing NFC controller firmware and an NFC stack. The NFC stack may be executed by the processor to control the NFC controller, and the NFC controller firmware may be executed by the NFC controller to control the antenna element to emit short-range RF signals. The RF signals may power a passive NFC tag (e.g., a microchip embedded in a sticker or wristband) to transmit stored data to the NFC circuitry **940**, or initiate data transfer between the NFC circuitry **940** and another active NFC device (e.g., a smartphone or an NFC-enabled POS terminal) that is proximate to the platform **900**.

The driver circuitry **946** may include software and hardware elements that operate to control particular devices that are embedded in the platform **900**, attached to the platform **900**, or otherwise communicatively coupled with the platform **900**. The driver circuitry **946** may include individual drivers allowing other components of the platform **900** to interact with or control various input/output (I/O) devices that may be present within, or connected to, the platform **900**. For example, driver circuitry **946** may include a display driver to control and allow access to a display device, a touchscreen driver to control and allow access to a touchscreen interface of the platform **900**, sensor drivers to obtain sensor readings of sensor circuitry **921** and control and allow access to sensor circuitry **921**, EMC drivers to obtain actuator positions of the EMCs **922** and/or control and allow access to the EMCs **922**, a camera driver to control and allow access to an embedded image capture device, audio drivers to control and allow access to one or more audio devices.

The power management integrated circuitry (PMIC) **925** (also referred to as "power management circuitry **925**") may manage power provided to various components of the platform **900**. In particular, with respect to the baseband circuitry **910**, the PMIC **925** may control power-source selection, voltage scaling, battery charging, or DC-to-DC conversion. The PMIC **925** may often be included when the platform **900** is capable of being powered by a battery **930**, for example, when the device is included in a UE **501**, **601**, **701**.

In some embodiments, the PMIC **925** may control, or otherwise be part of, various power saving mechanisms of the platform **900**. For example, if the platform **900** 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 platform **900** may power down for brief intervals of time and thus save power. If there is no data traffic activity for an extended period of time, then the platform **900** 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 platform **900** 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 platform **900** may not receive data in this state; in order to receive data, it must transition back to RRC_Connected state. 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.

A battery **930** may power the platform **900**, although in some examples the platform **900** may be mounted deployed in a fixed location, and may have a power supply coupled to an electrical grid. The battery **930** may be a lithium-ion battery, a metal-air battery, such as a zinc-air battery, an aluminum-air battery, a lithium-air battery, and the like. In some implementations, such as in V2X applications, the battery **930** may be a typical lead-acid automotive battery.

In some implementations, the battery **930** may be a "smart battery," which includes or is coupled with a Battery Management System (BMS) or battery monitoring integrated circuitry. The BMS may be included in the platform **900** to track the state of charge (SoCh) of the battery **930**. The BMS may be used to monitor other parameters of the battery **930** to provide failure predictions, such as the state of health (SoH) and the state of function (SoF) of the battery **930**. The BMS may communicate the information of the battery **930** to the application circuitry **905** or other components of the platform **900**. The BMS may also include an analog-to-digital (ADC) convertor that allows the application circuitry **905** to directly monitor the voltage of the battery **930** or the current flow from the battery **930**. The battery parameters may be used to determine actions that the platform **900** may perform, such as transmission frequency, network operation, sensing frequency, and the like.

A power block, or other power supply coupled to an electrical grid may be coupled with the BMS to charge the battery **930**. In some examples, the power block XS**30** may be replaced with a wireless power receiver to obtain the power wirelessly, for example, through a loop antenna in the computer platform **900**. In these examples, a wireless battery charging circuit may be included in the BMS. The specific charging circuits chosen may depend on the size of the battery **930**, and thus, the current required. The charging may be performed using the Airfuel standard promulgated by the Airfuel Alliance, the Qi wireless charging standard promulgated by the Wireless Power Consortium, or the Rezence charging standard promulgated by the Alliance for Wireless Power, among others.

User interface circuitry **950** includes various input/output (I/O) devices present within, or connected to, the platform **900**, and includes one or more user interfaces designed to enable user interaction with the platform **900** and/or peripheral component interfaces designed to enable peripheral component interaction with the platform **900**. The user interface circuitry **950** includes input device circuitry and output device circuitry. Input device circuitry includes any physical or virtual means for accepting an input including, inter alia, one or more physical or virtual buttons (e.g., a reset button), a physical keyboard, keypad, mouse, touchpad, touchscreen, microphones, scanner, headset, and/or the like. The output device circuitry includes any physical or virtual means for showing information or otherwise conveying information, such as sensor readings, actuator position(s), or other like information. Output device circuitry may include any number and/or combinations of audio or visual display, including, inter alia, one or more simple visual outputs/indicators (e.g., binary status indicators (e.g., light emitting diodes (LEDs)) and multi-character visual outputs, or more complex outputs such as display devices or touchscreens (e.g., Liquid Chrystal Displays (LCD), LED displays, quantum dot displays, projectors, etc.), with the output of characters, graphics, multimedia objects, and the like being generated or produced from the operation of the platform **900**. The output device circuitry may also include speakers or other audio emitting devices, printer(s), and/or the like. In some embodiments, the sensor circuitry **921** may be used as the input device circuitry (e.g., an image capture device, motion capture device, or the like) and one or more EMCs may be used as the output device circuitry (e.g., an actuator to provide haptic feedback or the like). In another example, NFC circuitry comprising an NFC controller coupled with an antenna element and a processing device may be included to read electronic tags and/or connect with another NFC-enabled device. Peripheral component interfaces may include, but are not limited to, a non-volatile memory port, a USB port, an audio jack, a power supply interface, etc.

Although not shown, the components of platform **900** may communicate with one another using a suitable bus or interconnect (IX) technology, which may include any number of technologies, including ISA, EISA, PCI, PCIx, PCIe, a Time-Trigger Protocol (TTP) system, a FlexRay system, or any number of other technologies. The bus/IX may be a proprietary bus/IX, for example, used in a SoC based system. Other bus/IX systems may be included, such as an I2C interface, an SPI interface, point-to-point interfaces, and a power bus, among others.

FIG. **10** illustrates example components of baseband circuitry **100** and radio front end modules (RFEM) **1015** in accordance with various embodiments. The baseband circuitry **1010** corresponds to the baseband circuitry **810** and **910** of FIGS. **8** and **9**, respectively. The RFEM **1015** corresponds to the RFEM **815** and **915** of FIGS. **8** and **9**, respectively. As shown, the RFEMs **1015** may include Radio Frequency (RF) circuitry **1006**, front-end module (FEM) circuitry **1008**, antenna array **1011** coupled together at least as shown.

The baseband circuitry **1010** includes circuitry and/or control logic configured to carry out various radio/network protocol and radio control functions that enable communication with one or more radio networks via the RF circuitry **1006**. 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 **1010** may include Fast-Fourier Transform (FFT), precoding, or constellation mapping/demapping functionality. In some embodiments, encoding/decoding circuitry of the baseband circuitry **1010** 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. The baseband circuitry **1010** is configured to process baseband signals received from a receive signal path of the RF circuitry **1006** and to generate baseband signals for a transmit signal path of the RF circuitry **1006**. The baseband circuitry **1010** is configured to interface with application circuitry **805**/**905** (see FIGS. **8** and **9**) for generation and processing of the baseband signals and for controlling operations of the RF circuitry **1006**. The baseband circuitry **1010** may handle various radio control functions.

The aforementioned circuitry and/or control logic of the baseband circuitry **1010** may include one or more single or multi-core processors. For example, the one or more processors may include a 3G baseband processor **1004**A, a 4G/LTE baseband processor **1004**B, a 5G/NR baseband processor **1004**C, or some other baseband processor(s) **1004**D for other existing generations, generations in development or to be developed in the future (e.g., sixth generation (6G), etc.). In other embodiments, some or all of the functionality of baseband processors **1004**A-D may be included in modules stored in the memory **1004**G and executed via a Central Processing Unit (CPU) **1004**E. In other embodiments, some or all of the functionality of baseband processors **1004**A-D may be provided as hardware accelerators (e.g., FPGAs, ASICs, etc.) loaded with the appropriate bit streams or logic blocks stored in respective memory cells. In various embodiments, the memory **1004**G may store program code of a real-time OS (RTOS), which when executed by the CPU **1004**E (or other baseband processor), is to cause the CPU **1004**E (or other baseband processor) to manage resources of the baseband circuitry **1010**, schedule tasks, etc. Examples of the RTOS may include Operating System Embedded (OSE)™ provided by Enea®, Nucleus RTOS™ provided by Mentor Graphics®, Versatile Real-Time Executive (VRTX) provided by Mentor Graphics®, ThreadX™ provided by Express Logic®, FreeRTOS, REX OS provided by Qualcomm®, OKL4 provided by Open Kernel (OK) Labs®, or any other suitable RTOS, such as those discussed herein. In addition, the baseband circuitry **1010** includes one or more audio digital signal processor(s) (DSP) **1004**F. The audio DSP(s) **1004**F include elements for compression/decompression and echo cancellation and may include other suitable processing elements in other embodiments.

In some embodiments, each of the processors **1004**A-**1004**E include respective memory interfaces to send/receive data to/from the memory **1004**G. The baseband circuitry **1010** may further include one or more interfaces to communicatively couple to other circuitries/devices, such as an interface to send/receive data to/from memory external to the baseband circuitry **1010**; an application circuitry interface to send/receive data to/from the application circuitry **805**/**905** of FIGS. **8**-**10**); an RF circuitry interface to send/receive data to/from RF circuitry **1006** of FIG. **10**; a wireless hardware connectivity interface to send/receive data to/from one or more wireless hardware elements (e.g., Near Field Communication (NFC) components, Bluetooth®/Bluetooth® Low Energy components, Wi-Fi® components, and/or the like); and a power management interface to send/receive power or control signals to/from the PMIC **925**.

In alternate embodiments (which may be combined with the above described embodiments), baseband circuitry **1010** comprises one or more digital baseband systems, which are coupled with one another via an interconnect subsystem and to a CPU subsystem, an audio subsystem, and an interface subsystem. The digital baseband subsystems may also be coupled to a digital baseband interface and a mixed-signal baseband subsystem via another interconnect subsystem. Each of the interconnect subsystems may include a bus system, point-to-point connections, network-on-chip (NOC) structures, and/or some other suitable bus or interconnect technology, such as those discussed herein. The audio subsystem may include DSP circuitry, buffer memory, program memory, speech processing accelerator circuitry, data converter circuitry such as analog-to-digital and digital-to-analog converter circuitry, analog circuitry including one or more of amplifiers and filters, and/or other like components. In an aspect of the present disclosure, baseband circuitry **1010** may include protocol processing circuitry with one or more instances of control circuitry (not shown) to provide control functions for the digital baseband circuitry and/or radio frequency circuitry (e.g., the radio front end modules **1015**).

Although not shown by FIG. **10**, in some embodiments, the baseband circuitry **1010** includes individual processing device(s) to operate one or more wireless communication protocols (e.g., a "multi-protocol baseband processor" or "protocol processing circuitry") and individual processing device(s) to implement PHY layer functions. In these embodiments, the PHY layer functions include the aforementioned radio control functions. In these embodiments, the protocol processing circuitry operates or implements various protocol layers/entities of one or more wireless communication protocols. In a first example, the protocol processing circuitry may operate LTE protocol entities and/or 5G/NR protocol entities when the baseband circuitry **1010** and/or RF circuitry **1006** are part of mmWave communication circuitry or some other suitable cellular communication circuitry. In the first example, the protocol processing circuitry would operate MAC, RLC, PDCP, SDAP, RRC, and NAS functions. In a second example, the protocol processing circuitry may operate one or more IEEE-based protocols when the baseband circuitry **1010** and/or RF circuitry **1006** are part of a Wi-Fi communication system. In the second example, the protocol processing circuitry would operate Wi-Fi MAC and logical link control (LLC) functions. The protocol processing circuitry may include one or more memory structures (e.g., **1004**G) to store program code and data for operating the protocol functions, as well as one or more processing cores to execute the program code and perform various operations using the data. The baseband circuitry **1010** may also support radio communications for more than one wireless protocol.

The various hardware elements of the baseband circuitry **1010** discussed herein may be implemented, for example, as a solder-down substrate including one or more integrated circuits (ICs), a single packaged IC soldered to a main circuit board or a multi-chip module containing two or more ICs. In one example, the components of the baseband circuitry **1010** may be suitably combined in a single chip or chipset, or disposed on a same circuit board. In another example, some or all of the constituent components of the baseband circuitry **1010** and RF circuitry **1006** may be implemented together such as, for example, a system on a chip (SoC) or System-in-Package (SiP). In another example, some or all of the constituent components of the baseband circuitry **1010** may be implemented as a separate SoC that is communicatively coupled with and RF circuitry **1006** (or multiple instances of RF circuitry **1006**). In yet another example, some or all of the constituent components of the baseband circuitry **1010** and the application circuitry **805**/**905** may be implemented together as individual SoCs mounted to a same circuit board (e.g., a "multi-chip package").

In some embodiments, the baseband circuitry **1010** may provide for communication compatible with one or more radio technologies. For example, in some embodiments, the baseband circuitry **1010** may support communication with an E-UTRAN or other WMAN, a WLAN, a WPAN. Embodiments in which the baseband circuitry **1010** is configured to support radio communications of more than one wireless protocol may be referred to as multi-mode baseband circuitry.

RF circuitry **1006** may enable communication with wireless networks using modulated electromagnetic radiation through a non-solid medium. In various embodiments, the RF circuitry **1006** may include switches, filters, amplifiers, etc. to facilitate the communication with the wireless network. RF circuitry **1006** may include a receive signal path, which may include circuitry to down-convert RF signals received from the FEM circuitry **1008** and provide baseband signals to the baseband circuitry **1010**. RF circuitry **1006** may also include a transmit signal path, which may include circuitry to up-convert baseband signals provided by the baseband circuitry **1010** and provide RF output signals to the FEM circuitry **1008** for transmission.

In some embodiments, the receive signal path of the RF circuitry **1006** may include mixer circuitry **1006***a*, amplifier circuitry **1006***b* and filter circuitry **1006***c*. In some embodiments, the transmit signal path of the RF circuitry **1006** may include filter circuitry **1006***c* and mixer circuitry **1006***a*. RF circuitry **1006** may also include synthesizer circuitry **1006***d* for synthesizing a frequency for use by the mixer circuitry **1006***a* of the receive signal path and the transmit signal path. In some embodiments, the mixer circuitry **1006***a* of the receive signal path may be configured to down-convert RF signals received from the FEM circuitry **1008** based on the synthesized frequency provided by synthesizer circuitry **1006***d*. The amplifier circuitry **1006***b* may be configured to amplify the down-converted signals and the filter circuitry **1006***c* 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 **1010** for further processing. In some embodiments, the output baseband signals may be zero-frequency baseband signals, although this is not a requirement. In some embodiments, mixer circuitry **1006***a* of the receive signal path may comprise passive mixers, although the scope of the embodiments is not limited in this respect.

In some embodiments, the mixer circuitry **1006***a* of the transmit signal path may be configured to up-convert input baseband signals based on the synthesized frequency provided by the synthesizer circuitry **1006***d* to generate RF output signals for the FEM circuitry **1008**. The baseband signals may be provided by the baseband circuitry **1010** and may be filtered by filter circuitry **1006***c*.

In some embodiments, the mixer circuitry **1006***a* of the receive signal path and the mixer circuitry **1006***a* 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 **1006***a* of the receive signal path and the mixer circuitry **1006***a* 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 **1006***a* of the receive signal path and the mixer circuitry **1006***a* of the transmit signal path may be arranged for direct downconversion and direct upconversion, respectively. In some embodiments, the mixer circuitry **1006***a* of the receive signal path and the mixer circuitry **1006***a* of the transmit signal path may be configured for super-heterodyne operation.

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 **1006** may include analog-to-digital converter (ADC) and digital-to-analog converter (DAC) circuitry and the baseband circuitry **1010** may include a digital baseband interface to communicate with the RF circuitry **1006**.

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.

In some embodiments, the synthesizer circuitry **1006***d* 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 **1006***d* may be a delta-sigma synthesizer, a frequency multiplier, or a synthesizer comprising a phase-locked loop with a frequency divider.

The synthesizer circuitry **1006***d* may be configured to synthesize an output frequency for use by the mixer circuitry **1006***a* of the RF circuitry **1006** based on a frequency input and a divider control input. In some embodiments, the synthesizer circuitry **1006***d* may be a fractional N/N+1 synthesizer.

In some embodiments, frequency input may be provided by a voltage controlled oscillator (VCO), although that is not a requirement. Divider control input may be provided by either the baseband circuitry **1010** or the application circuitry **805/905** 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 application circuitry **805/905**.

Synthesizer circuitry **1006***d* of the RF circuitry **1006** 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.

In some embodiments, synthesizer circuitry **1006***d* 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 **1006** may include an IQ/polar converter.

FEM circuitry **1008** may include a receive signal path, which may include circuitry configured to operate on RF signals received from antenna array **1011**, amplify the received signals and provide the amplified versions of the received signals to the RF circuitry **1006** for further processing. FEM circuitry **1008** may also include a transmit signal path, which may include circuitry configured to amplify signals for transmission provided by the RF circuitry **1006** for transmission by one or more of antenna elements of antenna array **1011**. In various embodiments, the amplification through the transmit or receive signal paths may be done solely in the RF circuitry **1006**, solely in the FEM circuitry **1008**, or in both the RF circuitry **1006** and the FEM circuitry **1008**.

In some embodiments, the FEM circuitry **1008** may include a TX/RX switch to switch between transmit mode and receive mode operation. The FEM circuitry **1008** may include a receive signal path and a transmit signal path. The receive signal path of the FEM circuitry **1008** 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 **1006**). The transmit signal path of the FEM circuitry **1008** may include a power amplifier (PA) to amplify input RF signals (e.g., provided by RF circuitry **1006**), and one or more filters to generate RF signals for subsequent transmission by one or more antenna elements of the antenna array **1011**.

The antenna array **1011** comprises one or more antenna elements, each of which is configured convert electrical signals into radio waves to travel through the air and to convert received radio waves into electrical signals. For example, digital baseband signals provided by the baseband circuitry **1010** is converted into analog RF signals (e.g., modulated waveform) that will be amplified and transmitted via the antenna elements of the antenna array **1011** including one or more antenna elements (not shown). The antenna elements may be omnidirectional, direction, or a combination thereof. The antenna elements may be formed in a multitude of arranges as are known and/or discussed herein. The antenna array **1011** may comprise microstrip antennas or printed antennas that are fabricated on the surface of one or more printed circuit boards. The antenna array **1011** may be formed in as a patch of metal foil (e.g., a patch antenna) in a variety of shapes, and may be coupled with the RF circuitry **1006** and/or FEM circuitry **1008** using metal transmission lines or the like.

Processors of the application circuitry **805**/**905** and processors of the baseband circuitry **1010** may be used to execute elements of one or more instances of a protocol stack. For example, processors of the baseband circuitry **1010**, alone or in combination, may be used execute Layer 3, Layer 2, or Layer 1 functionality, while processors of the application circuitry **805**/**905** may utilize data (e.g., packet data) received from these layers and further execute Layer 4 functionality (e.g., TCP and UDP layers). As referred to herein, Layer 3 may comprise a RRC layer, described in further detail below. As referred to herein, Layer 2 may comprise a MAC layer, an RLC layer, and a PDCP layer, described in further detail below. As referred to herein, Layer 1 may comprise a PHY layer of a UE/RAN node, described in further detail below.

FIG. **11** illustrates various protocol functions that may be implemented in a wireless communication device according to various embodiments. In particular, FIG. **11** includes an arrangement **1100** showing interconnections between various protocol layers/entities. The following description of FIG. **11** is provided for various protocol layers/entities that operate in conjunction with the 5G/NR system standards and LTE system standards, but some or all of the aspects of FIG. **11** may be applicable to other wireless communication network systems as well.

The protocol layers of arrangement **1100** may include one or more of PHY **1110**, MAC **1120**, RLC **1130**, PDCP **1140**, SDAP **1147**, RRC **1155**, and NAS layer **1157**, in addition to other higher layer functions not illustrated. The protocol layers may include one or more service access points (e.g., items **1159**, **1156**, **1150**, **1149**, **1145**, **1135**, **1125**, and **1115** in FIG. **11**) that may provide communication between two or more protocol layers.

The PHY **1110** may transmit and receive physical layer signals **1105** that may be received from or transmitted to one or more other communication devices. The physical layer signals **1105** may comprise one or more physical channels, such as those discussed herein. The PHY **1110** may further perform link adaptation or adaptive modulation and coding (AMC), power control, cell search (e.g., for initial synchronization and handover purposes), and other measurements used by higher layers, such as the RRC **1155**. The PHY **1110** may still further perform error detection on the transport channels, forward error correction (FEC) coding/decoding of the transport channels, modulation/demodulation of physical channels, interleaving, rate matching, mapping onto physical channels, and MIMO antenna processing. In embodiments, an instance of PHY **1110** may process requests from and provide indications to an instance of MAC **1120** via one or more PHY-SAP **1115**. According to some embodiments, requests and indications communicated via PHY-SAP **1115** may comprise one or more transport channels.

Instance(s) of MAC **1120** may process requests from, and provide indications to, an instance of RLC **1130** via one or more MAC-SAPs **1125**. These requests and indications communicated via the MAC-SAP **1125** may comprise one or more logical channels. The MAC **1120** may perform mapping between the logical channels and transport channels, multiplexing of MAC SDUs from one or more logical channels onto TBs to be delivered to PHY **1110** via the transport channels, de-multiplexing MAC SDUs to one or more logical channels from TBs delivered from the PHY **1110** via transport channels, multiplexing MAC SDUs onto TBs, scheduling information reporting, error correction through HARQ, and logical channel prioritization.

Instance(s) of RLC **1130** may process requests from and provide indications to an instance of PDCP **1140** via one or more radio link control service access points (RLC-SAP) **1135**. These requests and indications communicated via RLC-SAP **1135** may comprise one or more RLC channels. The RLC **1130** may operate in a plurality of modes of operation, including: Transparent Mode (TM), Unacknowledged Mode (UM), and Acknowledged Mode (AM). The RLC **1130** may execute transfer of upper layer protocol data units (PDUs), error correction through automatic repeat request (ARQ) for AM data transfers, and concatenation, segmentation and reassembly of RLC SDUs for UM and AM data transfers. The RLC **1130** may also execute re-segmentation of RLC data PDUs for AM data transfers, reorder RLC data PDUs for UM and AM data transfers, detect duplicate data for UM and AM data transfers, discard RLC SDUs for UM and AM data transfers, detect protocol errors for AM data transfers, and perform RLC re-establishment.

Instance(s) of PDCP **1140** may process requests from and provide indications to instance(s) of RRC **1155** and/or instance(s) of SDAP **1147** via one or more packet data convergence protocol service access points (PDCP-SAP) **1145**. These requests and indications communicated via PDCP-SAP **1145** may comprise one or more radio bearers. The PDCP **1140** may execute header compression and decompression of IP data, maintain PDCP Sequence Numbers (SNs), perform in-sequence delivery of upper layer PDUs at re-establishment of lower layers, eliminate duplicates of lower layer SDUs at re-establishment of lower layers for radio bearers mapped on RLC AM, cipher and decipher control plane data, perform integrity protection and integrity verification of control plane data, control timer-based discard of data, and perform security operations (e.g., ciphering, deciphering, integrity protection, integrity verification, etc.).

Instance(s) of SDAP **1147** may process requests from and provide indications to one or more higher layer protocol entities via one or more SDAP-SAP **1149**. These requests and indications communicated via SDAP-SAP **1149** may comprise one or more QoS flows. The SDAP **1147** may map QoS flows to DRBs, and vice versa, and may also mark QFIs in DL and UL packets. A single SDAP entity **1147** may be configured for an individual PDU session. In the UL direction, the NG-RAN **510** may control the mapping of QoS Flows to DRB(s) in two different ways, reflective mapping or explicit mapping. For reflective mapping, the SDAP **1147** of a UE **501** may monitor the QFIs of the DL packets for each DRB, and may apply the same mapping for packets flowing in the UL direction. For a DRB, the SDAP **1147** of the UE **501** may map the UL packets belonging to the QoS flows(s) corresponding to the QoS flow ID(s) and PDU session observed in the DL packets for that DRB. To enable reflective mapping, the NG-RAN **710** may mark DL packets over the Uu interface with a QoS flow ID. The explicit mapping may involve the RRC **1155** configuring the SDAP **1147** with an explicit QoS flow to DRB mapping rule, which may be stored and followed by the SDAP **1147**. In embodiments, the SDAP **1147** may only be used in NR implementations and may not be used in LTE implementations.

The RRC **1155** may configure, via one or more management service access points (M-SAP), aspects of one or more protocol layers, which may include one or more instances of PHY **1110**, MAC **1120**, RLC **1130**, PDCP **1140** and SDAP **1147**. In embodiments, an instance of RRC **1155** may process requests from and provide indications to one or more NAS entities **1157** via one or more RRC-SAPs **1156**. The main services and functions of the RRC **1155** may include broadcast of system information (e.g., included in MIBs or SIBs related to the NAS), broadcast of system information related to the access stratum (AS), paging, establishment, maintenance and release of an RRC connection between the UE **501** and RAN **510** (e.g., RRC connection paging, RRC connection establishment, RRC connection modification, and RRC connection release), establishment, configuration, maintenance and release of point to point Radio Bearers, security functions including key management, inter-RAT mobility, and measurement configuration for UE measurement reporting. The MIBs and SIBs may comprise one or more IEs, which may each comprise individual data fields or data structures.

The NAS **1157** may form the highest stratum of the control plane between the UE **501** and the AMF **721**. The NAS **1157** may support the mobility of the UEs **501** and the session management procedures to establish and maintain IP connectivity between the UE **501** and a P-GW in LTE systems.

According to various embodiments, one or more protocol entities of arrangement **1100** may be implemented in UEs **501**, RAN nodes **511**, AMF **721** in NR implementations or MME **621** in LTE implementations, UPF **702** in NR implementations or S-GW **622** and P-GW **623** in LTE implementations, or the like to be used for control plane or user plane communications protocol stack between the aforementioned devices. In such embodiments, one or more protocol entities that may be implemented in one or more of UE **501**, gNB **511**, AMF **721**, etc. may communicate with a respective peer protocol entity that may be implemented in or on another device using the services of respective lower layer protocol entities to perform such communication. In some embodiments, a gNB-CU of the gNB **511** may host the RRC **1155**, SDAP **1147**, and PDCP **1140** of the gNB that controls the operation of one or more gNB-DUs, and the gNB-DUs of the gNB **511** may each host the RLC **1130**, MAC **1120**, and PHY **1110** of the gNB **511**.

In a first example, a control plane protocol stack may comprise, in order from highest layer to lowest layer, NAS **1157**, RRC **1155**, PDCP **1140**, RLC **1130**, MAC **1120**, and PHY **1110**. In this example, upper layers **1160** may be built on top of the NAS **1157**, which includes an IP layer **1161**, an SCTP **1162**, and an application layer signaling protocol (AP) **1163**.

In NR implementations, the AP **1163** may be an NG application protocol layer (NGAP or NG-AP) **1163** for the NG interface **513** defined between the NG-RAN node **511** and the AMF **721**, or the AP **1163** may be an Xn application protocol layer (XnAP or Xn-AP) **1163** for the Xn interface **512** that is defined between two or more RAN nodes **511**.

The NG-AP **1163** may support the functions of the NG interface **513** and may comprise Elementary Procedures (EPs). An NG-AP EP may be a unit of interaction between the NG-RAN node **511** and the AMF **721**. The NG-AP **1163** services may comprise two groups: UE-associated services (e.g., services related to a UE **501**) and non-UE-associated services (e.g., services related to the whole NG interface instance between the NG-RAN node **511** and AMF **721**). These services may include functions including, but not limited to: a paging function for the sending of paging requests to NG-RAN nodes **511** involved in a particular paging area; a UE context management function for allowing the AMF **721** to establish, modify, and/or release a UE context in the AMF **721** and the NG-RAN node **511**; a mobility function for UEs **501** in ECM-CONNECTED mode for intra-system HOs to support mobility within NG-RAN and inter-system HOs to support mobility from/to EPS systems; a NAS Signaling Transport function for transporting or rerouting NAS messages between UE **501** and AMF **721**; a NAS node selection function for determining an association between the AMF **721** and the UE **501**; NG interface management function(s) for setting up the NG interface and monitoring for errors over the NG interface; a warning message transmission function for providing means to transfer warning messages via NG interface or cancel ongoing broadcast of warning messages; a Configuration Transfer function for requesting and transferring of RAN configuration information (e.g., SON information, performance measurement (PM) data, etc.) between two RAN nodes **511** via CN **520**; and/or other like functions.

The XnAP **1163** may support the functions of the Xn interface **512** and may comprise XnAP basic mobility procedures and XnAP global procedures. The XnAP basic mobility procedures may comprise procedures used to handle UE mobility within the NG RAN **511** (or E-UTRAN **610**), such as handover preparation and cancellation procedures, SN Status Transfer procedures, UE context retrieval and UE context release procedures, RAN paging procedures, dual connectivity related procedures, and the like. The XnAP global procedures may comprise procedures that are not related to a specific UE **501**, such as Xn interface setup and reset procedures, NG-RAN update procedures, cell activation procedures, and the like.

In LTE implementations, the AP **1163** may be an S1 Application Protocol layer (S1-AP) **1163** for the S1 interface **513** defined between an E-UTRAN node **511** and an MME, or the AP **1163** may be an X2 application protocol layer (X2AP or X2-AP) **1163** for the X2 interface **512** that is defined between two or more E-UTRAN nodes **511**.

The S1 Application Protocol layer (S1-AP) **1163** may support the functions of the S1 interface, and similar to the NG-AP discussed previously, the S1-AP may comprise S1-AP EPs. An S1-AP EP may be a unit of interaction between the E-UTRAN node **511** and an MME **621** within an LTE CN **520**. The S1-AP **1163** services may comprise two groups: UE-associated services and non-UE-associated services. These services perform functions including, but not limited to: E-UTRAN Radio Access Bearer (E-RAB) management, UE capability indication, mobility, NAS signaling transport, RAN Information Management (RIM), and configuration transfer.

The X2AP **1163** may support the functions of the X2 interface **512** and may comprise X2AP basic mobility procedures and X2AP global procedures. The X2AP basic mobility procedures may comprise procedures used to handle UE mobility within the E-UTRAN **520**, such as handover preparation and cancellation procedures, SN Status Transfer procedures, UE context retrieval and UE context release procedures, RAN paging procedures, dual connectivity related procedures, and the like. The X2AP global procedures may comprise procedures that are not related to a specific UE **501**, such as X2 interface setup and reset procedures, load indication procedures, error indication procedures, cell activation procedures, and the like.

The SCTP layer (alternatively referred to as the SCTP/IP layer) **1162** may provide guaranteed delivery of application layer messages (e.g., NGAP or XnAP messages in NR implementations, or S1-AP or X2AP messages in LTE implementations). The SCTP **1162** may ensure reliable delivery of signaling messages between the RAN node **511** and the AMF **721**/MME **621** based, in part, on the IP protocol, supported by the IP **1161**. The Internet Protocol layer (IP) **1161** may be used to perform packet addressing and routing functionality. In some implementations the IP layer **1161** may use point-to-point transmission to deliver and convey PDUs. In this regard, the RAN node **511** may comprise L2 and L1 layer communication links (e.g., wired or wireless) with the MMEAMF to exchange information.

In a second example, a user plane protocol stack may comprise, in order from highest layer to lowest layer, SDAP **1147**, PDCP **1140**, RLC **1130**, MAC **1120**, and PHY **1110**. The user plane protocol stack may be used for communication between the UE **501**, the RAN node **511**, and UPF **702** in NR implementations or an S-GW **622** and P-GW **623** in LTE implementations. In this example, upper layers **1151** may be built on top of the SDAP **1147**, and may include a user datagram protocol (UDP) and IP security layer (UDP/IP) **1152**, a General Packet Radio Service (GPRS) Tunneling Protocol for the user plane layer (GTP-U) **1153**, and a User Plane PDU layer (UP PDU) **1163**.

The transport network layer **1154** (also referred to as a "transport layer") may be built on IP transport, and the GTP-U **1153** may be used on top of the UDP/IP layer **1152** (comprising a UDP layer and IP layer) to carry user plane PDUs (UP-PDUs). The IP layer (also referred to as the "Internet layer") may be used to perform packet addressing and routing functionality. The IP layer may assign IP addresses to user data packets in any of IPv4, IPv6, or PPP formats, for example.

The GTP-U **1153** may be used for carrying user data within the GPRS core network and between the radio access network and the core network. The user data transported can be packets in any of IPv4, IPv6, or PPP formats, for example. The UDP/IP **1152** may provide checksums for data integrity, port numbers for addressing different functions at the source and destination, and encryption and authentication on the selected data flows. The RAN node **511** and the S-GW **622** may utilize an S1-U interface to exchange user plane data via a protocol stack comprising an L1 layer (e.g., PHY **1110**), an L2layer (e.g., MAC **1120**, RLC **1130**, PDCP **1140**, and/or SDAP **1147**), the UDP/IP layer **1152**, and the GTP-U **1153**. The S-GW **622** and the P-GW **623** may utilize an S5/S8a interface to exchange user plane data via a protocol stack comprising an L1 layer, an L2layer, the UDP/IP layer **1152**, and the GTP-U **1153**. As discussed previously, NAS protocols may support the mobility of the UE **501** and the session management procedures to establish and maintain IP connectivity between the UE **501** and the P-GW **623**.

Moreover, although not shown by FIG. **11**, an application layer may be present above the AP **1163** and/or the transport network layer **1154**. The application layer may be a layer in which a user of the UE **501**, RAN node **511**, or other network element interacts with software applications being executed, for example, by application circuitry **805** or application circuitry **905**, respectively. The application layer may also provide one or more interfaces for software applications to interact with communications systems of the UE **501** or RAN node **511**, such as the baseband circuitry **1010**. In some implementations the IP layer and/or the application layer may provide the same or similar functionality as layers 5-7, or portions thereof, of the Open Systems Interconnection (OSI) model (e.g., OSI Layer 7—the application layer, OSI Layer 6—the presentation layer, and OSI Layer 5—the session layer).

FIG. **12** is a block diagram illustrating components, according to some example embodiments, able to read instructions from a machine-readable or computer-readable medium (e.g., a non-transitory machine-readable storage medium) and perform any one or more of the methodologies discussed herein. Specifically, FIG. **12** shows a diagrammatic representation of hardware resources **1200** including one or more processors (or processor cores) **1210**, one or more memory/storage devices **1220**, and one or more communication resources **1230**, each of which may be communicatively coupled via a bus **1240**. For embodiments where node virtualization (e.g., NFV) is utilized, a hypervisor **1202** may be executed to provide an execution environment for one or more network slices/sub-slices to utilize the hardware resources **1200**.

The processors **1210** may include, for example, a processor **1212** and a processor **1214**. The processor(s) **1210** may be, for example, a central processing unit (CPU), a reduced instruction set computing (RISC) processor, a complex instruction set computing (CISC) processor, a graphics processing unit (GPU), a DSP such as a baseband processor, an ASIC, an FPGA, a radio-frequency integrated circuit (RFIC), another processor (including those discussed herein), or any suitable combination thereof.

The memory/storage devices **1220** may include main memory, disk storage, or any suitable combination thereof. The memory/storage devices **1220** may include, but are not limited to, any type of volatile or nonvolatile memory such as dynamic random access memory (DRAM), static random access memory (SRAM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), Flash memory, solid-state storage, etc.

The communication resources **1230** may include interconnection or network interface components or other suitable devices to communicate with one or more peripheral devices **1204** or one or more databases **1206** via a network **1208**. For example, the communication resources **1230** may include wired communication components (e.g., for coupling via USB), cellular communication components, NFC components, Bluetooth® (or Bluetooth® Low Energy) components, Wi-Fi® components, and other communication components.

Instructions **1250** may comprise software, a program, an application, an applet, an app, or other executable code for causing at least any of the processors **1210** to perform any one or more of the methodologies discussed herein. The instructions **1250** may reside, completely or partially, within at least one of the processors **1210** (e.g., within the processor's cache memory), the memory/storage devices **1220**, or any suitable combination thereof. Furthermore, any portion of the instructions **1250** may be transferred to the hardware resources **1200** from any combination of the peripheral devices **1204** or the databases **1206**. Accordingly, the memory of processors **1210**, the memory/storage devices **1220**, the peripheral devices **1204**, and the databases **1206** are examples of computer-readable and machine-readable media.

For one or more embodiments, at least one of the components set forth in one or more of the preceding figures may be configured to perform one or more operations, techniques, processes, and/or methods as set forth in the example section below. For example, the baseband circuitry as described above in connection with one or more of the preceding figures may be configured to operate in accordance with one or more of the examples set forth below. For another example, circuitry associated with a UE, base station, network element, etc. as described above in connection with one or more of the preceding figures may be configured to operate in accordance with one or more of the examples set forth below in the example section.

Terminology

For the purposes of the present document, the following terms and definitions are applicable to the examples and embodiments discussed herein.

The term "circuitry" refers to a circuit or system of multiple circuits configured to perform a particular function in an electronic device. The circuit or system of circuits may be part of, or include one or more hardware components, such as a logic circuit, a processor (shared, dedicated, or group) and/or memory (shared, dedicated, or group), an Application Specific Integrated Circuit (ASIC), a field-programmable gate array (FPGA), programmable logic device (PLD), complex PLD (CPLD), high-capacity PLD (HCPLD), System-on-Chip (SoC), System-in-Package (SiP), Multi-Chip Package (MCP), digital signal processor (DSP), etc., that are configured to provide the described functionality. In addition, the term "circuitry" may also refer to a combination of one or more hardware elements with the program code used to carry out the functionality of that program code. Some types of circuitries may execute one or more software or firmware programs to provide at least some of the described functionality. Such a combination of hardware elements and program code may be referred to as a particular type of circuitry.

The term "processor circuitry" as used herein refers to, is part of, or includes circuitry capable of sequentially and automatically carrying out a sequence of arithmetic or logical operations, or recording, storing, and/or transferring digital data. The term "processor circuitry" may refer to one or more application processors, one or more baseband processors, a physical central processing unit (CPU), a single-core processor, a dual-core processor, a triple-core processor, a quad-core processor, and/or any other device capable of executing or otherwise operating computer-executable instructions, such as program code, software modules, and/or functional processes. The terms "application circuitry" and/or "baseband circuitry" may be considered synonymous to, and may be referred to as, "processor circuitry."

The term "memory" and/or "memory circuitry" as used herein refers to one or more hardware devices for storing data, including random access memory (RAM), magnetoresistive RAM (MRAM), phase change random access memory (PRAM), dynamic random-access memory (DRAM) and/or synchronous dynamic random access memory (SDRAM), core memory, read only memory (ROM), magnetic disk storage mediums, optical storage mediums, flash memory devices or other machine readable mediums for storing data. The term "computer-readable medium" may include, but is not limited to, memory, portable or fixed storage devices, optical storage devices, and various other mediums capable of storing, containing or carrying instructions or data.

The term "interface circuitry" as used herein refers to, is part of, or includes circuitry that enables the exchange of information between two or more components or devices. The term "interface circuitry" may refer to one or more hardware interfaces, for example, buses, I/O interfaces, peripheral component interfaces, network interface cards, and/or the like.

The term "user equipment" or "UE" as used herein refers to a device with radio communication capabilities and may describe a remote user of network resources in a communications network. The term "user equipment" or "UE" may be considered synonymous to, and may be referred to as, client, mobile, mobile device, mobile terminal, user terminal, mobile unit, mobile station, mobile user, subscriber, user, remote station, access agent, user agent, receiver, radio equipment, reconfigurable radio equipment, reconfigurable mobile device, etc. Furthermore, the term "user equipment" or "UE" may include any type of wireless/wired device or any computing device including a wireless communications interface.

The term "network element" as used herein refers to physical or virtualized equipment and/or infrastructure used to provide wired or wireless communication network services. The term "network element" may be considered synonymous to and/or referred to as a networked computer, networking hardware, network equipment, network node, router, switch, hub, bridge, radio network controller, RAN device, RAN node, gateway, server, virtualized VNF, NFVI, and/or the like.

The term "computer system" as used herein refers to any type interconnected electronic devices, computer devices, or components thereof. Additionally, the term "computer system" and/or "system" may refer to various components of a computer that are communicatively coupled with one another. Furthermore, the term "computer system" and/or "system" may refer to multiple computer devices and/or multiple computing systems that are communicatively coupled with one another and configured to share computing and/or networking resources.

The term "appliance," "computer appliance," or the like, as used herein refers to a computer device or computer system with program code (e.g., software or firmware) that is specifically designed to provide a specific computing resource. A "virtual appliance" is a virtual machine image to be implemented by a hypervisor-equipped device that virtualizes or emulates a computer appliance or otherwise is dedicated to provide a specific computing resource.

The term "element" refers to a unit that is indivisible at a given level of abstraction and has a clearly defined boundary, wherein an element may be any type of entity including, for example, one or more devices, systems, controllers, network elements, modules, etc., or combinations thereof.

The term "device" refers to a physical entity embedded inside, or attached to, another physical entity in its vicinity, with capabilities to convey digital information from or to that physical entity.

The term "entity" refers to a distinct component of an architecture or device, or information transferred as a payload.

The term "controller" refers to an element or entity that has the capability to affect a physical entity, such as by changing its state or causing the physical entity to move.

The term "resource" as used herein refers to a physical or virtual device, a physical or virtual component within a computing environment, and/or a physical or virtual component within a particular device, such as computer devices, mechanical devices, memory space, processor/CPU time, processor/CPU usage, processor and accelerator loads, hardware time or usage, electrical power, input/output operations, ports or network sockets, channel/link allocation, throughput, memory usage, storage, network, database and applications, workload units, and/or the like. A "hardware resource" may refer to compute, storage, and/or network resources provided by physical hardware element(s). A "virtualized resource" may refer to compute, storage, and/or network resources provided by virtualization infrastructure to an application, device, system, etc. The term "network resource" or "communication resource" may refer to resources that are accessible by computer devices/systems via a communications network. The term "system resources" may refer to any kind of shared entities to provide services and may include computing and/or network resources. System resources may be considered as a set of coherent functions, network data objects or services, accessible through a server where such system resources reside on a single host or multiple hosts and are clearly identifiable.

The term "channel" as used herein refers to any transmission medium, either tangible or intangible, which is used to communicate data or a data stream. The term "channel" may be synonymous with and/or equivalent to "communications channel," "data communications channel," "transmission channel," "data transmission channel," "access channel," "data access channel," "link," "data link," "carrier," "radiofrequency carrier," and/or any other like term denoting a pathway or medium through which data is communicated. Additionally, the term "link" as used herein refers to a connection between two devices through a RAT for the purpose of transmitting and receiving information.

As used herein, the term "communication protocol" (either wired or wireless) refers to a set of standardized rules or instructions implemented by a communication device and/or system to communicate with other devices and/or systems, including instructions for packetizing/depacketizing data, modulating/demodulating signals, implementation of protocols stacks, and/or the like.

The terms "instantiate," "instantiation," and the like as used herein refers to the creation of an instance. An "instance" also refers to a concrete occurrence of an object, which may occur, for example, during execution of program code.

The terms "coupled," "communicatively coupled," along with derivatives thereof are used herein. The term "coupled" may mean two or more elements are in direct physical or electrical contact with one another, may mean that two or more elements indirectly contact each other but still cooperate or interact with each other, and/or may mean that one or more other elements are coupled or connected between the elements that are said to be coupled with each other. The term "directly coupled" may mean that two or more elements are in direct contact with one another. The term "communicatively coupled" may mean that two or more elements may be in contact with one another by a means of communication including through a wire or other interconnect connection, through a wireless communication channel or ink, and/or the like.

The term "information element" refers to a structural element containing one or more fields. The term "field" refers to individual contents of an information element, or a data element that contains content.

The term "admission control" refers to a validation process in communication systems where a check is performed before a connection is established to see if current resources are sufficient for the proposed connection.

The term "SMTC" refers to an SSB-based measurement timing configuration configured by SSB-MeasurementTimingConfiguration.

The term "SSB" refers to an SS/PBCH block.

The term "a "Primary Cell" refers to the MCG cell, operating on the primary frequency, in which the UE either performs the initial connection establishment procedure or initiates the connection re-establishment procedure.

The term "Primary SCG Cell" refers to the SCG cell in which the UE performs random access when performing the Reconfiguration with Sync procedure for DC operation.

The term "Secondary Cell" refers to a cell providing additional radio resources on top of a Special Cell for a UE configured with CA.

The term "Secondary Cell Group" refers to the subset of serving cells comprising the PSCell and zero or more secondary cells for a UE configured with DC.

The term "Serving Cell" refers to the primary cell for a UE in RRC_CONNECTED not configured with CA/DC there is only one serving cell comprising of the primary cell.

The term "serving cell" or "serving cells" refers to the set of cells comprising the Special Cell(s) and all secondary cells for a UE in RRC_CONNECTED configured with CA/.

The term "Special Cell" refers to the PCell of the MCG or the PSCell of the SCG for DC operation; otherwise, the term "Special Cell" refers to the PCell.

In the foregoing specification, the invention has been described with reference to specific embodiments thereof. It will, however, be evident that various modifications and changes can be made thereto without departing from the broader spirit and scope of the invention. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense. The specifics in the descriptions and examples provided may be used anywhere in one or more embodiments. The various features of the different embodiments or examples may be variously combined with some features included and others excluded to suit a variety of different applications. Examples may include subject matter such as a method, means for performing acts of the method, at least one machine-readable medium including instructions that, when performed by a machine cause the machine to perform acts of the method, or of an apparatus or system according to embodiments and examples described herein. Additionally, various components described herein can be a means for performing the operations or functions described in accordance with an embodiment.

Embodiments described herein provide for a user equipment (UE), comprising a processor to configure the UE to receive one or more repetitions of a transport block (TB) using a first physical downlink shared channel (PDSCH) beam, obtain a downlink control information (DCI) comprising one or more transmission configuration indicator (TCI) states, and configure the UE to switch from the first PDSCH beam to a second PDSCH beam, different from the first PDSCH beam, based at least in part on the one or more TCI states.

Other embodiments described herein provide a computer-implemented method, comprising configuring a UE to receive, one or more repetitions of a transport block (TB) using a first physical downlink shared channel (PDSCH) beam, obtaining a downlink control information (DCI) comprising one or more transmission configuration indicator (TCI) states, and configuring the UE to switch from the first PDSCH beam to a second PDSCH beam, different from the first PDSCH beam, based at least in part on the one or more TCI states.

Other embodiments described herein provide a non-transitory computer readable medium comprising instructions which, when executed by a processor, configure the processor to configure a UE to receive, one or more repetitions of a transport block (TB) using a first physical downlink shared channel (PDSCH) beam, obtain a downlink control information (DCI) comprising one or more transmission configuration indicator (TCI) states, and configure the UE to switch from the first PDSCH beam to a second PDSCH beam, different from the first PDSCH beam, based at least in part on the one or more TCI states.

In some examples the UE may be configured to receive one or more repetitions of the transport block (TB) using the second physical downlink shared channel (PDSCH) beam.

In some examples the processor may determine a first PDSCH target code-rate and a first PDSCH duration for a first set of repetitions of the transport block (TB) and a second PDSCH target code-rate and a second PDSCH duration for a second set of repetitions of the transport block (TB). In some examples the process or may determine, based on a received downlink control information (DCI), a sequence of transmission configuration indicator (TCI) states representative of downlink (DL) beam repetitions, wherein one or more individual TCI states of the sequence of TCI states are representative of corresponding downlink (DL) beams and configure the UE to receive one or more DL transmissions (Tx) over one or more DL channels according to the sequence of TCI states.

In some examples the processor may configure the UE to receive a first set of downlink transmissions (DL Tx) according to a default repetition, and configure the UE to receive a second set of DL Tx according to one or more repetitions of the sequence of TCI states. In some examples the processor may configure the UE to receive the first set of downlink transmissions (DL Tx) with a first modulation order, a first target code-rate, a first transport block (TB) size, and a first DL channel duration and configure the UE to receive the second set of downlink transmissions (DL Tx) with a second modulation order, a second target code-rate, a second transport block (TB) size, and a second DL channel duration DL. Tx with the modulation order n times the target code-rate, the TB size, and 1/n times the DL channel duration. In some examples the second target code rate is a multiple of the first target code rate and the second DL channel duration is a fraction of the first DL channel duration.

Other features of the present embodiments will be apparent from the accompanying drawings and from the detailed description above. Accordingly, the true scope of the embodiments will become apparent to the skilled practitioner upon a study of the drawings, specification, and following claims.

What is claimed is:

1. A baseband processor comprising:

memory having instructions; and

a processor, coupled with the memory, the processor to execute the instructions to:

establish a communication connection with a network entity; and

generate a channel state information reference signal (CSI-RS) capability report to be transmitted to the network entity, the CSI-RS capability report to indicate a supported parameter sets for a band combination,

wherein the supported parameter set includes a first parameter to indicate a number of supported transmit antenna ports per channel state information (CSI) resource within the band combination, a second parameter to indicate a number of supported CSI resources within the band combination, and a third parameter to indicate a total number of supported transmit antenna ports within the band combination.

2. The baseband processor of claim **1**, wherein the number of supported transmit antenna ports per CSI resource is a maximum number of supported transmit antenna ports per CSI resource, the number of supported CSI resources is a maximum number of supported CSI resources, and the total number of supported transmit antenna ports is a maximum total number of supported transmit antenna ports.

3. The baseband processor of claim **1**, wherein the supported parameter set is for a first codebook type.

4. The UE-baseband processor of claim **3**, wherein the supported parameter set is a first supported parameter set and the CSI-RS capability report further includes a second supported parameter set that is for a second codebook type.

5. The baseband processor of claim **4**, wherein the first codebook type is associated with one precoding matrix indicator (PMI) subband per CSI subband and the second codebook type is associated with two PMI subbands per CSI subband.

6. One or more non-transitory, computer-readable media having instructions that, when executed, cause an apparatus to:

establish a communication connection with a network entity; and

generate a channel state information reference signal (CSI-RS) capability report to be transmitted to the network entity, the CSI-RS capability report to indicate a supported parameter set for a band combination,

wherein the supported parameter set includes a first parameter to indicate a number of supported transmit antenna ports per channel state information (CSI) resource within the band combination, a second parameter to indicate a number of supported CSI resources within the band combination, and a third parameter to indicate a total number of supported transmit antenna ports within the band combination.

7. The one or more non-transitory, computer-readable media of claim **6**, wherein the number of supported transmit antenna ports per CSI resource is a maximum number of supported transmit antenna ports per CSI resource, the number of supported CSI resources is a maximum number of supported CSI resources, and the total number of supported transmit antenna ports is a maximum total number of supported transmit antenna ports.

8. The one or more non-transitory, computer-readable media of claim **6**, wherein the supported parameter set is for a first codebook type.

9. The one or more non-transitory, computer-readable media of claim **8**, wherein: the supported parameter set is a first supported parameter set, the CSI-RS capability report further includes a second supported parameter set for a second codebook type; and the first codebook type is associated with one precoding matrix indicator (PMI) subband per CSI subband and the second codebook type is associated with two PMI subbands per CSI subband.

10. A method comprising:

establishing a communication connection with a user equipment (UE); and

receiving, from the UE, a channel state information reference signal (CSI-RS) capability report to indicate a supported parameter set for a band combination,

wherein the supported parameter set includes a first parameter to indicate a number of supported transmit antenna ports per channel state information (CSI) resource within the band combination, a second parameter to indicate a number of supported CSI resources within the band combination, and a third parameter to indicate a total number of supported transmit antenna ports within the band combination.

11. The method of claim **10**, wherein the number of supported transmit antenna ports per CSI resource is a maximum number of supported transmit antenna ports per CSI resource, the number of supported CSI resources is a maximum number of supported CSI resources, and the total number of supported transmit antenna ports is a maximum total number of supported transmit antenna ports.

12. The method of claim **10**, wherein the supported parameter set is for a first codebook type.

13. The method of claim **12**, wherein: the supported parameter set is a first supported parameter set, and the CSI-RS capability report is to further indicate a second supported parameter sets for a second codebook type; and the first codebook type is associated with one precoding matrix indicator (PMI) subband per CSI subband and the second codebook type is associated with two PMI subbands per CSI subband.

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