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Tabet et al.

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(54) **DEVICE CATEGORY IN 3GPP COMMUNICATIONS**

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Related U.S. Application Data

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(51) **Int. Cl.**
H04W 72/12 (2009.01)
H04W 28/24 (2009.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H04W 28/24*** (2013.01); ***H04L 5/0005*** (2013.01); ***H04L 5/0044*** (2013.01); *H04W 8/22* (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC ... H04W 52/0235; H04W 8/22; H04W 28/24; H04W 36/26; H04W 36/30; H04W 72/08; H04L 5/00
See application file for complete search history.

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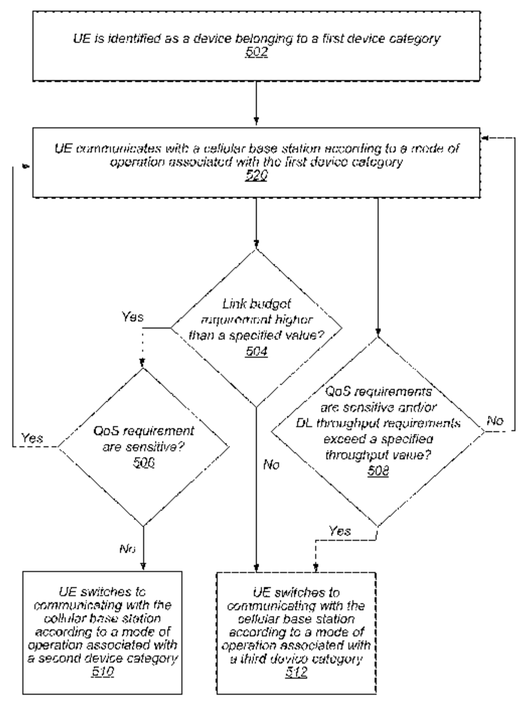
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(57) **ABSTRACT**

A user equipment (UE) device may communicate according to a new device category satisfying specified QoS (quality of service) requirements while also satisfying specified link budget requirements, and/or additional optimization requirements. The UE device may communicate with a cellular base station according to a first mode of operation associated with the new device category, and may switch to communicating with the cellular base station according to a second mode of operation associated with a second (pre-existing) device category in response to the link budget requirements exceeding a specified value and the quality of service requirements not being sensitive. The UE device may also switch to communicating with the cellular base station according to a third mode of operation associated with a third (pre-existing) device type in response to the link budget requirement not exceeding the specified value, or the
(Continued)



QoS requirements being sensitive and a downlink throughput requirement exceeding a specified throughput value.

20 Claims, 12 Drawing Sheets

(51) **Int. Cl.**

H04L 5/00	(2006.01)
H04W 52/02	(2009.01)
H04W 8/22	(2009.01)

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

CPC *H04W 52/0235* (2013.01); *Y02D 70/1224* (2018.01); *Y02D 70/1242* (2018.01); *Y02D 70/1262* (2018.01); *Y02D 70/1264* (2018.01); *Y02D 70/142* (2018.01); *Y02D 70/144* (2018.01); *Y02D 70/146* (2018.01); *Y02D 70/164* (2018.01); *Y02D 70/168* (2018.01); *Y02D 70/21* (2018.01); *Y02D 70/23* (2018.01); *Y02D 70/26* (2018.01)

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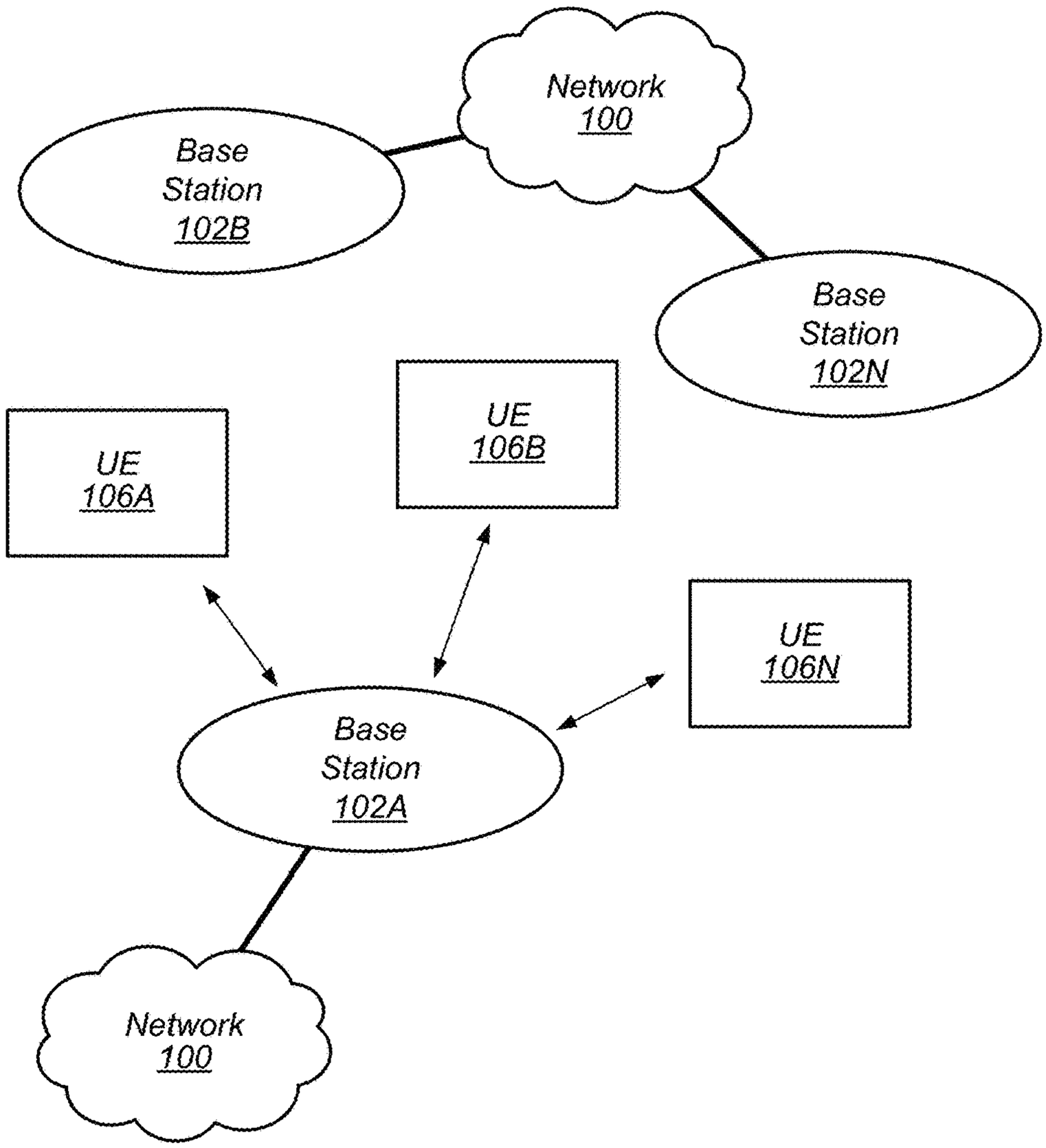

Network
100
Base
Station
102B
Base
Station
102N
UE
106A
UE
106B
UE
106N
Base
Station
102A
Network
100

FIG. 1

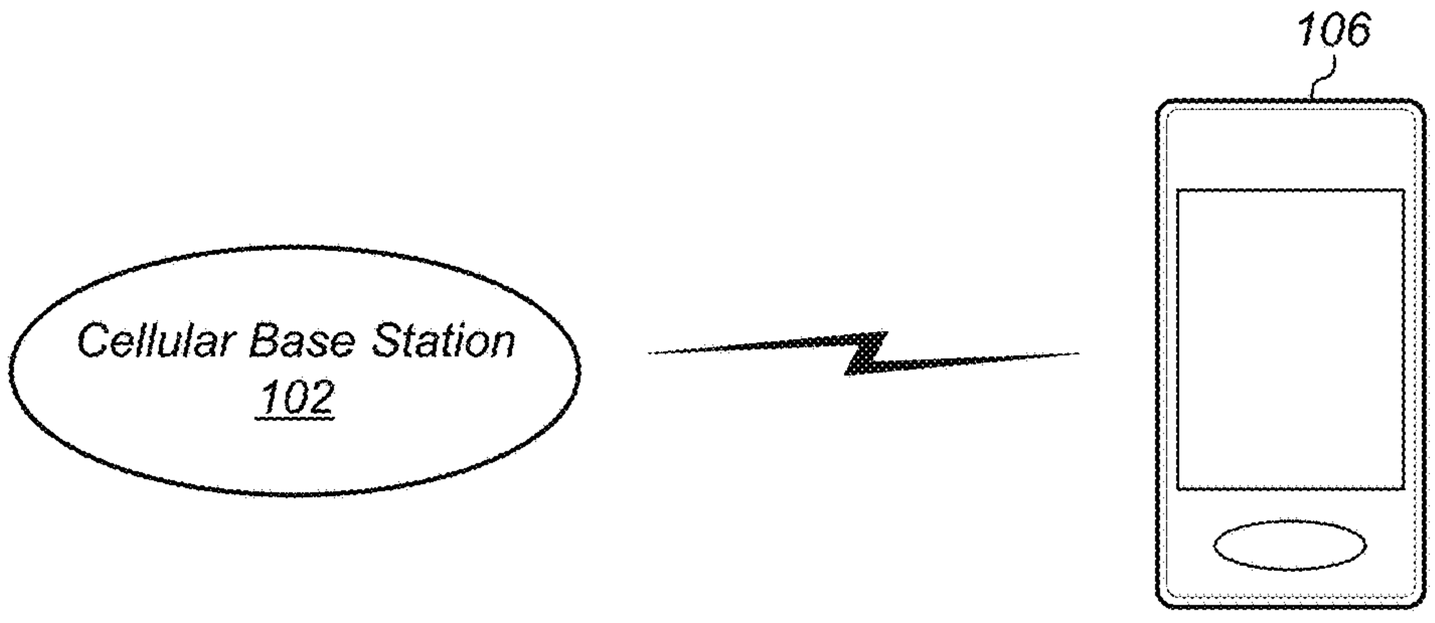

106
Cellular Base Station
102

FIG. 2

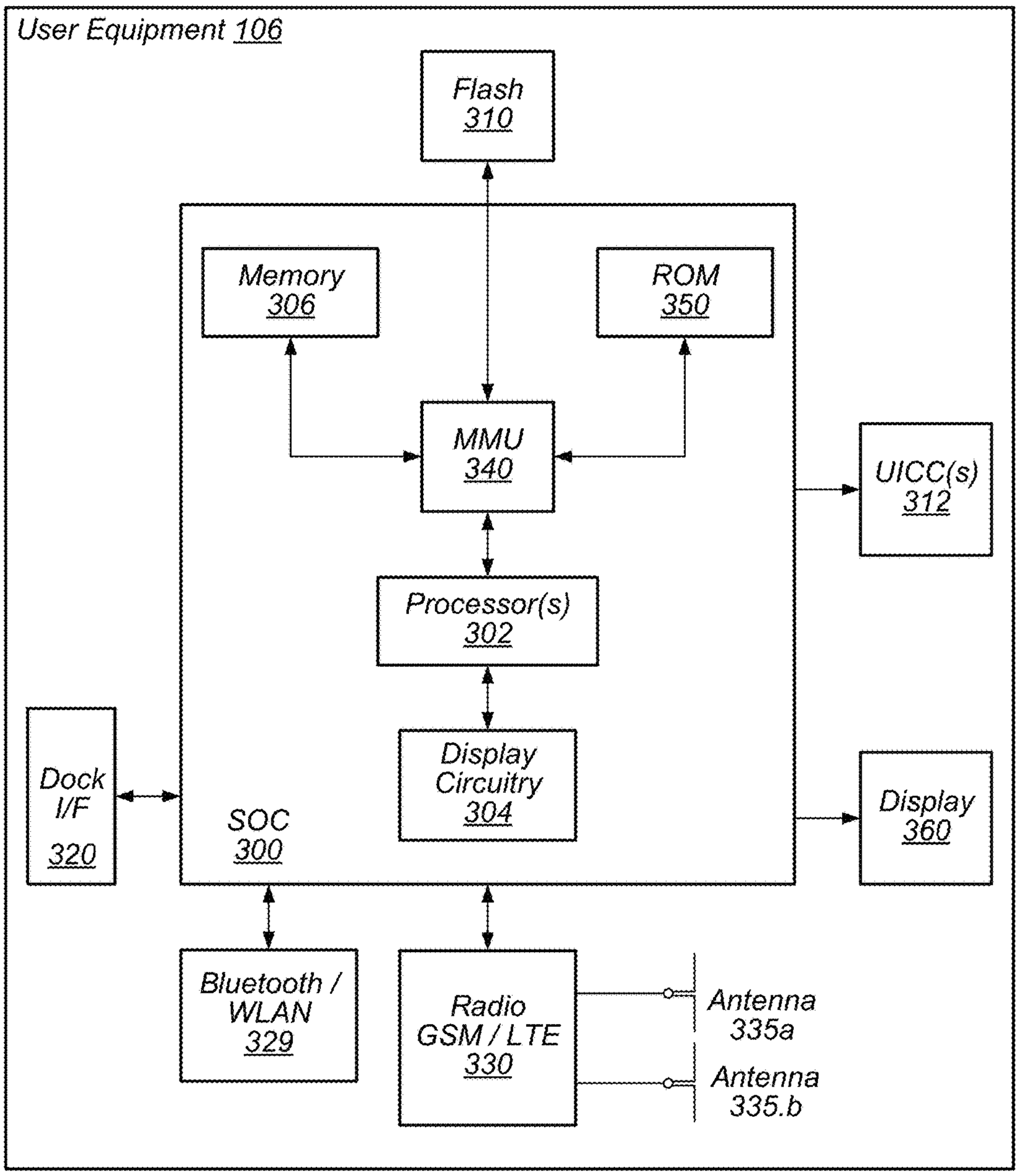

User Equipment 106
Flash 310
Memory 306
ROM 350
MMU 340
Processor(s) 302
Display Circuitry 304
SOC 300
Dock I/F 320
UICC(s) 312
Display 360
Bluetooth / WLAN 329
Radio GSM / LTE 330
Antenna 335a
Antenna 335.b

FIG. 3

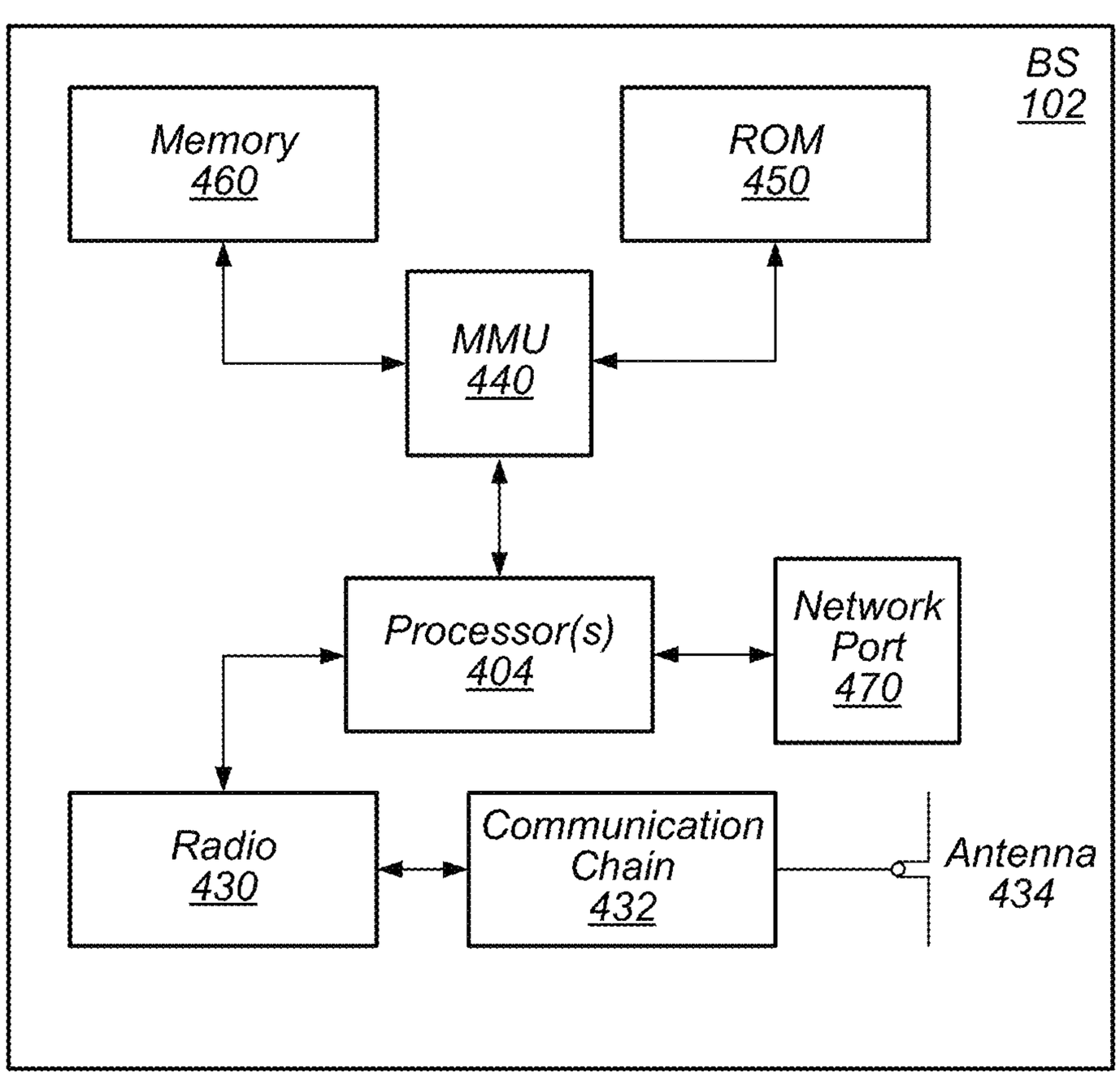

BS
102
Memory
460
ROM
450
MMU
440
Processor(s)
404
Network
Port
470
Radio
430
Communication
Chain
432
Antenna
434

FIG. 4

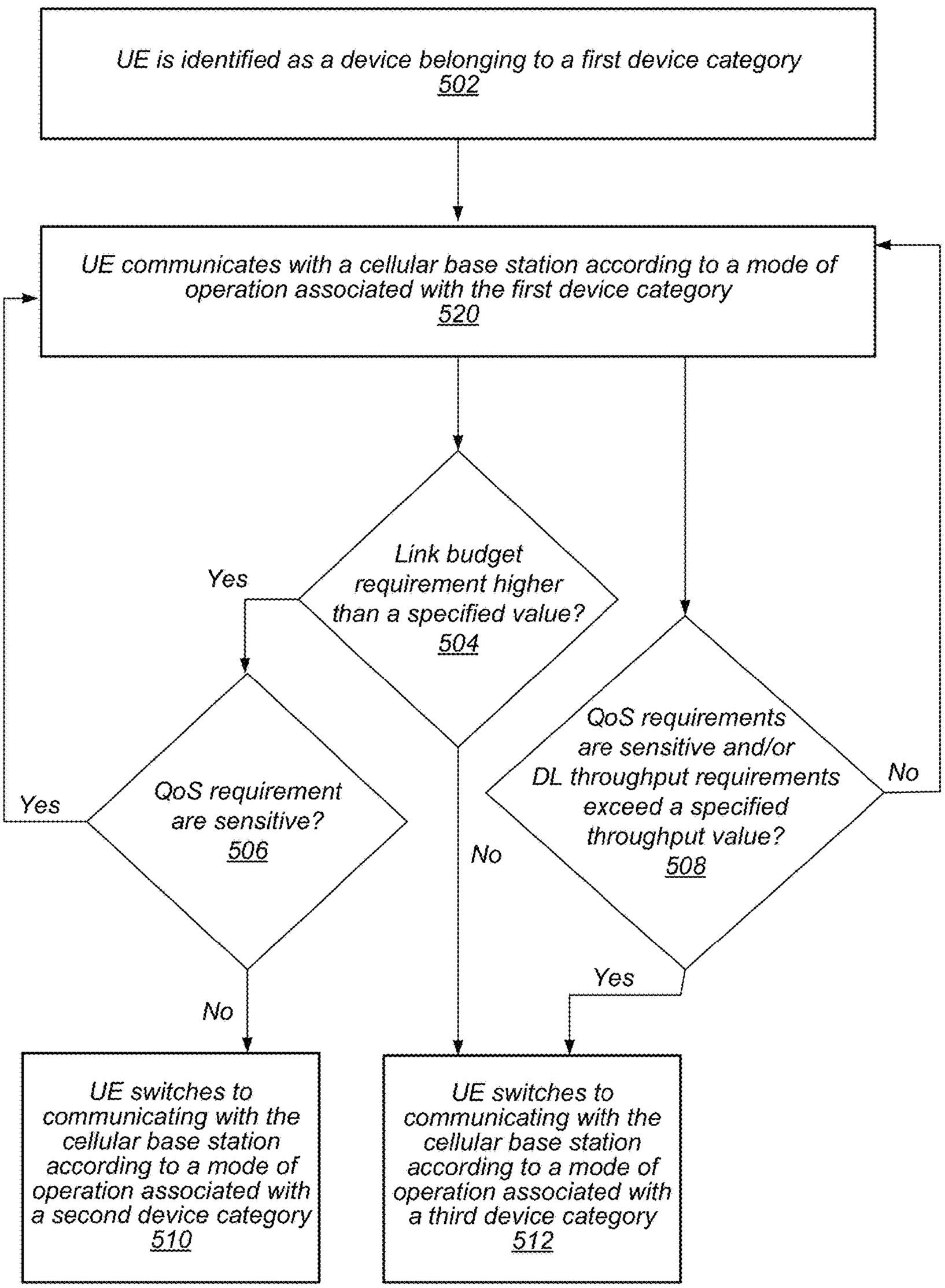

UE is identified as a device belonging to a first device category
502
UE communicates with a cellular base station according to a mode of operation associated with the first device category
520
Link budget requirement higher than a specified value?
504
Yes
QoS requirement are sensitive?
506
Yes
No
QoS requirements are sensitive and/or DL throughput requirements exceed a specified throughput value?
508
No
Yes
UE switches to communicating with the cellular base station according to a mode of operation associated with a second device category
510
UE switches to communicating with the cellular base station according to a mode of operation associated with a third device category
512

FIG. 5

Feature Parameters	CAT "1"	CAT "0"	CAT "M" (under discussion in 3GPP)		Cat-A
3GPP Release number	Release 8 and onwards	Release 12 Low Cost	Release 3 Range Improvement		
Maximum Throughput	TBS 10000 TBS 5000	Data: TBS 1000 Control: TBS 2200	Data: TBS 1000 Control: TBS 2200		TBS 10000 DL TBS 5000 UL
Number of receive antennas	2 Receive Antennas	1 Receive Antenna	1 Receive Antenna		1 Receive Antenna
Bandwidth	Entire System Bandwidth	1.4 MHz (not finalized)	1.4 MHz		1.4 MHz, 3 MHz in UL Up to 10 MHz, 20 MHz in DL
Duplexer	Full Duplex + Half Duplex (4/8)	Half Duplex (3/8)	Half Duplex (3/8)		Half Duplex desirable (4/8): TTI-B
Power Amplifier	Power Class 3: 23dBm	Power Class 3: 23dBm	New Power Class Reduced Power output (20 dBm)		Power Class 3: 23dBm
Modulation	DL: QPSK, 16QAM, 64QAM UL: QPSK, 16QAM	DL: QPSK, 16QAM, 64QAM UL: QPSK, 16QAM	QPSK/16QAM		DL: QPSK, 16QAM UL: QPSK, 16QAM/64QAM
Scenarios	Supports all use cases	Access Barring No Real Time Applications	Access Barring No Real Time Applications		Access to NW all times + VoLTE

FIG. 6 Desirable Not suitable Suitable

I_{TBS}	N_{PRB}									
	1	2	3	4	5	6	7	8	9	10
0	16	32	56	88	120	152	176	208	224	256
1	24	56	88	144	176	208	224	256	328	344
2	32	72	144	176	208	256	296	328	376	424
3	40	104	176	208	256	328	392	440	504	568
4	56	120	208	256	328	408	488	552	632	696
5	72	144	224	328	424	504	600	680	776	872
6	328	176	256	392	504	600	712	808	936	1032
7	104	224	328	472	584	712	840	968	1096	1224
8	120	256	392	536	680	808	968	1096	1256	1384
9	136	296	456	616	776	936	1096	1256	1416	1544
10	144	328	504	680	872	1032	1224	1384	1544	1736
11	176	376	584	776	1000	1192	1384	1608	1800	2024
12	208	440	680	904	1128	1352	1608	1800	2024	2280
13	224	488	744	1000	1256	1544	1800	2024	2280	2536
14	256	552	840	1128	1416	1736	1992	2280	2600	2856
15	280	600	904	1224	1544	1800	2152	2472	2728	3112
16	328	632	968	1288	1608	1928	2280	2600	2984	3240
17	336	696	1064	1416	1800	2152	2536	2856	3240	3624
18	376	776	1160	1544	1992	2344	2792	3112	3624	4008
19	408	840	1288	1736	2152	2600	2984	3496	3880	4264
20	440	904	1384	1864	2344	2702	3240	3752	4136	4584
21	488	1000	1480	1992	2472	2984	3496	4008	4584	4968
22	520	1064	1608	2152	2664	3240	3752	4264	4776	5352
23	552	1128	1736	2280	2856	3496	4008	4584	5160	5736
24	584	1192	1800	2408	2984	3624	4264	4968	5544	5992
25	616	1256	1864	2536	3112	3752	4392	5160	5736	6200
26	712	1480	2216	2984	3752	4392	5160	5992	6712	7480

2MHz

1.4MHz

I_{TBS}	N_{PRB}									
	11	12	13	14	15	16	17	18	19	20
0	288	328	344	376	392	424	456	488	504	536
1	376	424	456	488	520	568	600	632	680	712
2	472	520	568	616	648	696	744	776	840	872
3	616	680	744	808	872	904	968	1032	1096	1160
4	776	840	904	1000	1064	1128	1192	1288	1352	1416
5	968	1032	1128	1224	1320	1384	1480	1544	1672	1736
6	1128	1224	1352	1480	1544	1672	1736	1864	1992	2088
7	1320	1480	1608	1672	1800	1928	2088	2216	2344	2472
8	1544	1672	1800	1928	2088	2216	2344	2536	2664	2792
9	1736	1864	2024	2216	2344	2536	2664	2856	2984	3112
10	1928	2088	2280	2472	2664	2792	2984	3112	3368	3496
11	2216	2408	2600	2792	2984	3240	3496	3624	3880	4008
12	2472	2728	2984	3240	3368	3624	3880	4136	4392	4584
13	2856	3112	3368	3624	3880	4136	4392	4584	4968	5160
14	3112	3496	3752	4008	4264	4584	4968	5160	5544	5736
15	3368	3624	4008	4264	4584	4968	5160	5544	5736	6200
16	3624	3880	4264	4584	4968	5160	5544	5992	6200	6456
17	4008	4392	4776	5160	5352	5736	6200	6456	6712	7224
18	4392	4776	5160	5544	5992	6200	6712	7224	7480	7992
19	4776	5160	5544	5992	6456	6968	7224	7736	8248	8504
20	5160	5544	5992	6456	6968	7480	7992	8248	8760	9144
21	5544	5992	6456	6968	7480	7992	8504	9144	9528	9912
22	5992	6456	6968	7480	7992	8504	9144	9528	10296	10680
23	6200	6968	7480	7992	8504	9144	9912	10296	11064	11448
24	6712	7224	7992	8504	9144	9912	10296	11064	11448	12216
25	6968	7480	8248	8760	9528	10296	10680	11448	12216	12576
26	8248	8760	9528	10296	11064	11832	12576	13536	14112	14688

3MHz

FIG. 7

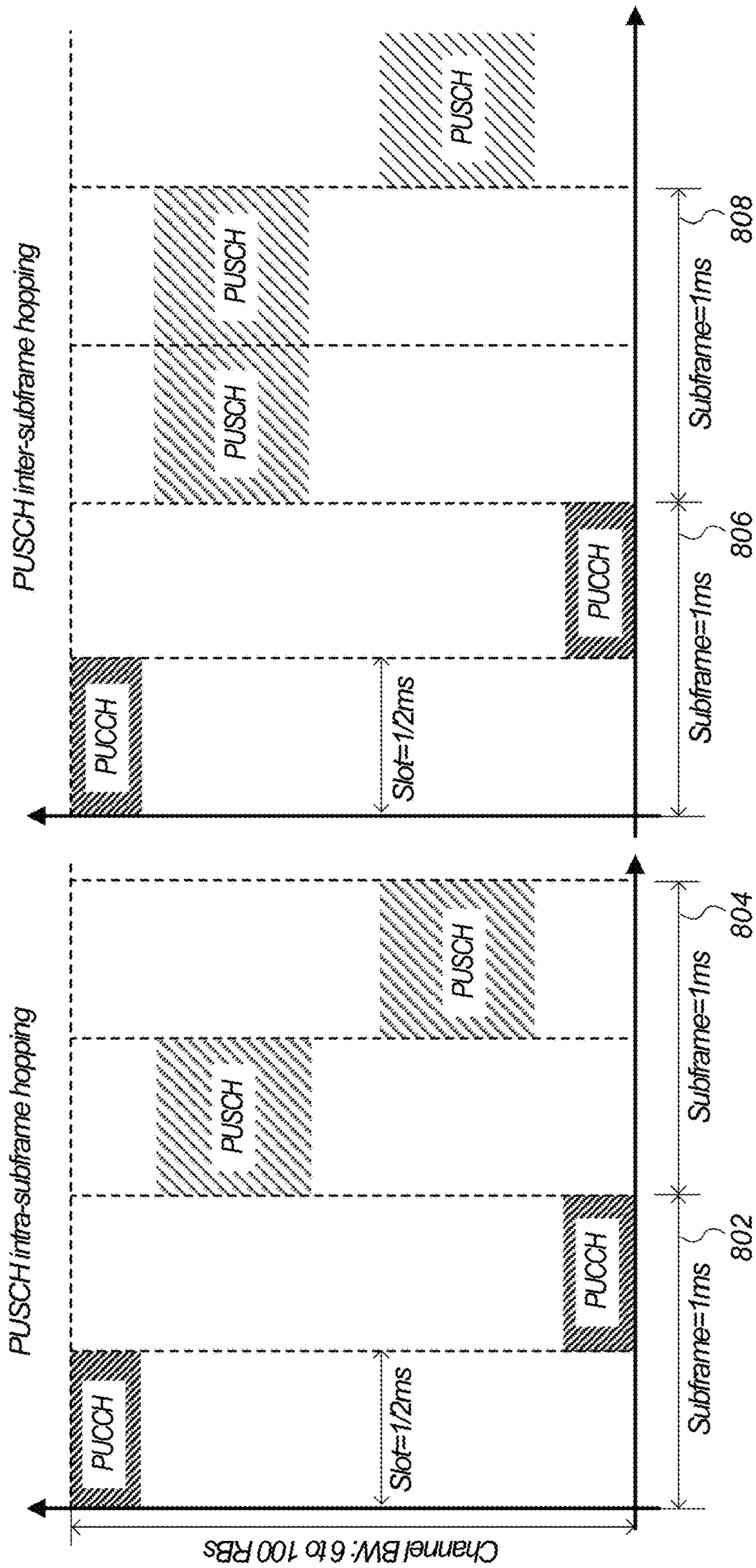

PUSCH inter-subframe hopping
PUSCH
PUSCH
PUSCH
PUCCH
PUCCH
Slot=1/2ms
Subframe=1ms
808
806
804
802
PUSCH intra-subframe hopping
PUSCH
PUSCH
PUSCH
PUCCH
PUCCH
Slot=1/2ms
Subframe=1ms
Channel BW: 6 to 100 RBs

FIG. 8

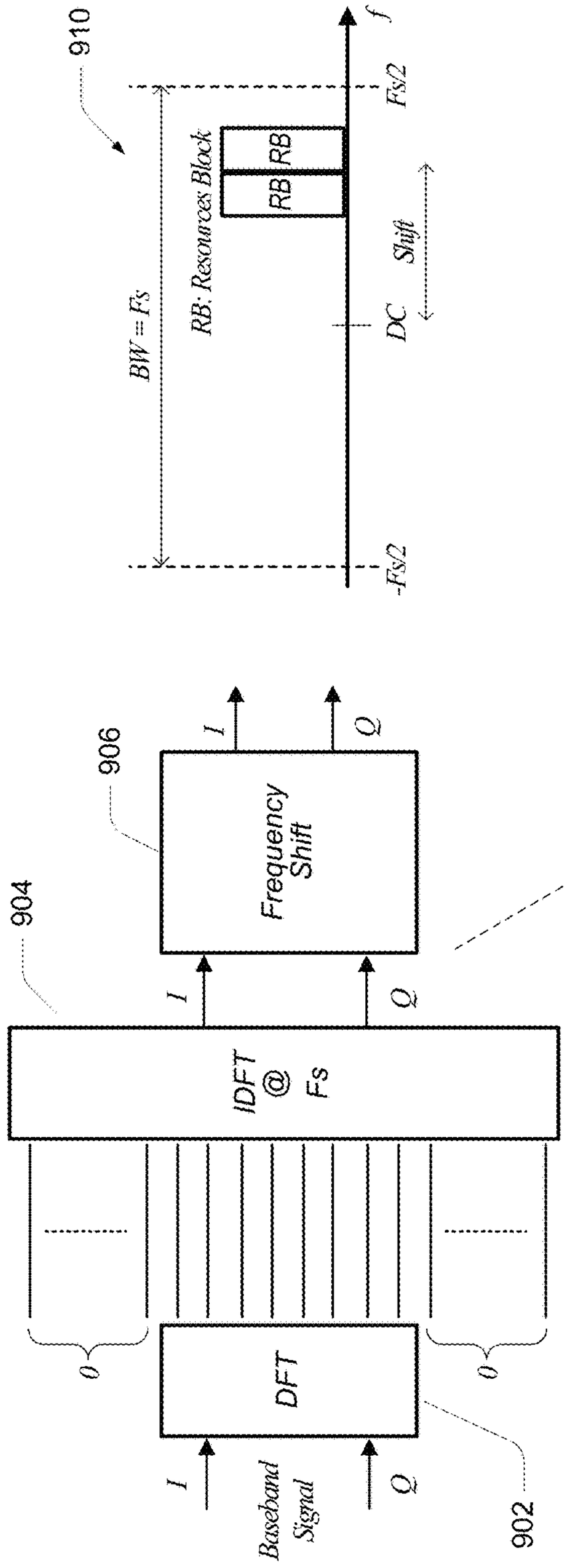

910
f
Fs/2
RB: Resources Block
RB
RB
DC
Shift
BW = Fs
-Fs/2
912
BW = N x RBs
RB
RB
DC
Fs/2
-Fs/2
906
Frequency Shift
I
Q
904
IDFT @ Fs
I
Q
0
0
DFT
Baseband Signal
I
Q
902

FIG. 9

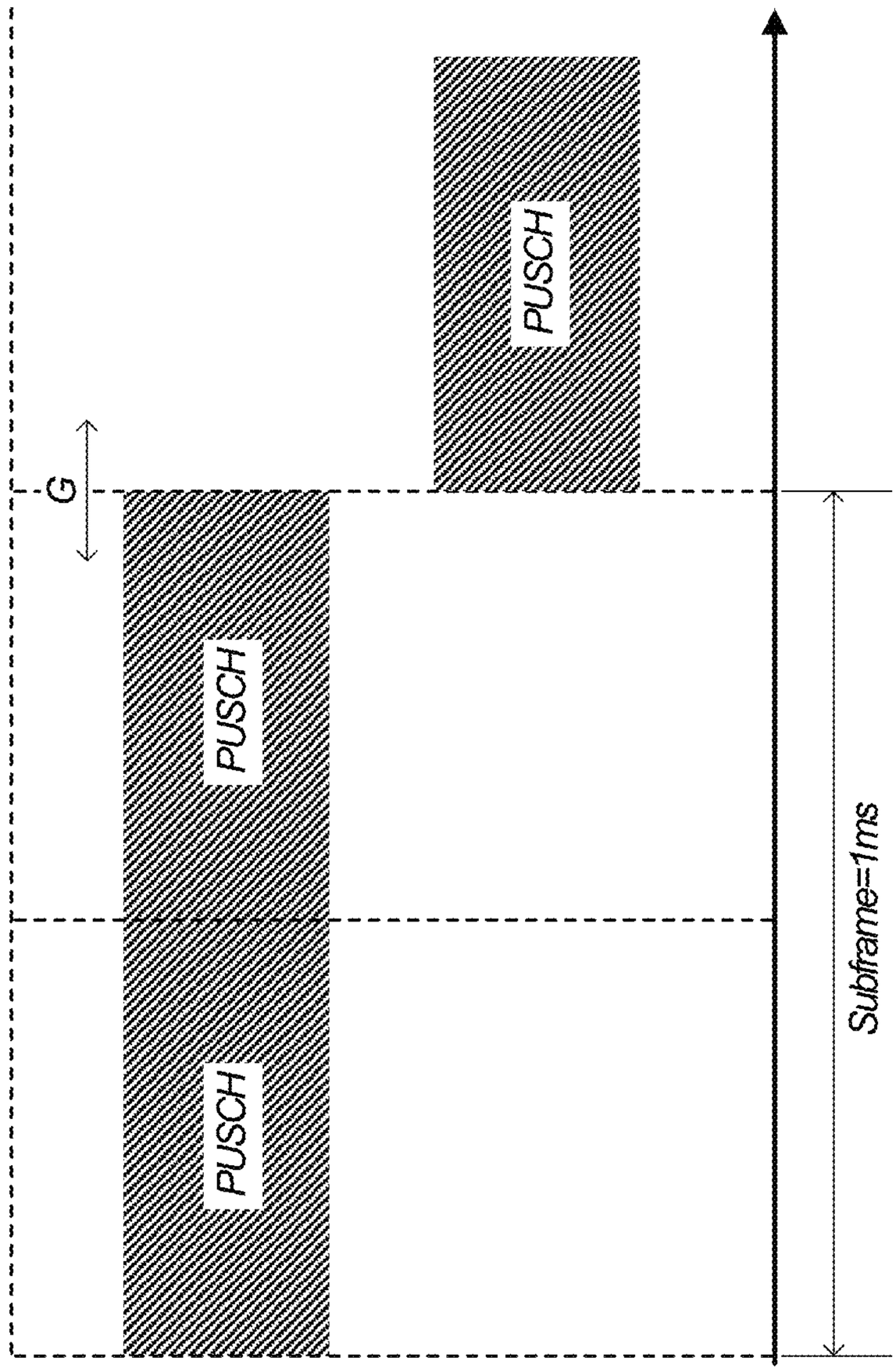


FIG.10

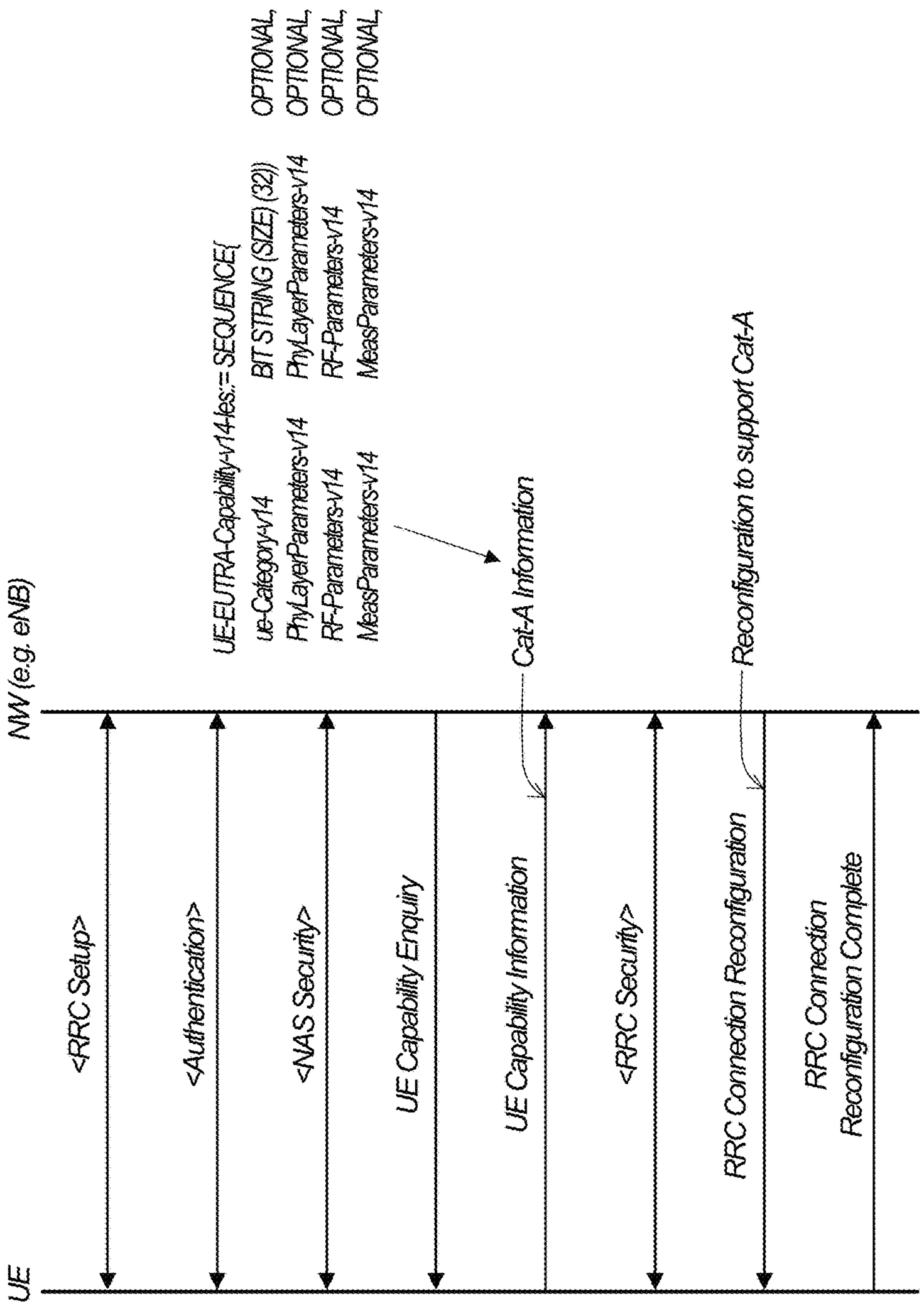

UE
NW (e.g. eNB)
<RRC Setup>
<Authentication>
<NAS Security>
UE Capability Enquiry
UE Capability Information
<RRC Security>
RRC Connection Reconfiguration
RRC Connection Reconfiguration Complete
UE-EUTRA-Capability-v14-les:= SEQUENCE{
ue-Category-v14
PhyLayerParameters-v14
RF-Parameters-v14
MeasParameters-v14
BIT STRING (SIZE) (32))
PhyLayerParameters-v14
RF-Parameters-v14
MeasParameters-v14
OPTIONAL,
OPTIONAL,
OPTIONAL,
OPTIONAL,
Cat-A Information
Reconfiguration to support Cat-A

FIG. 11

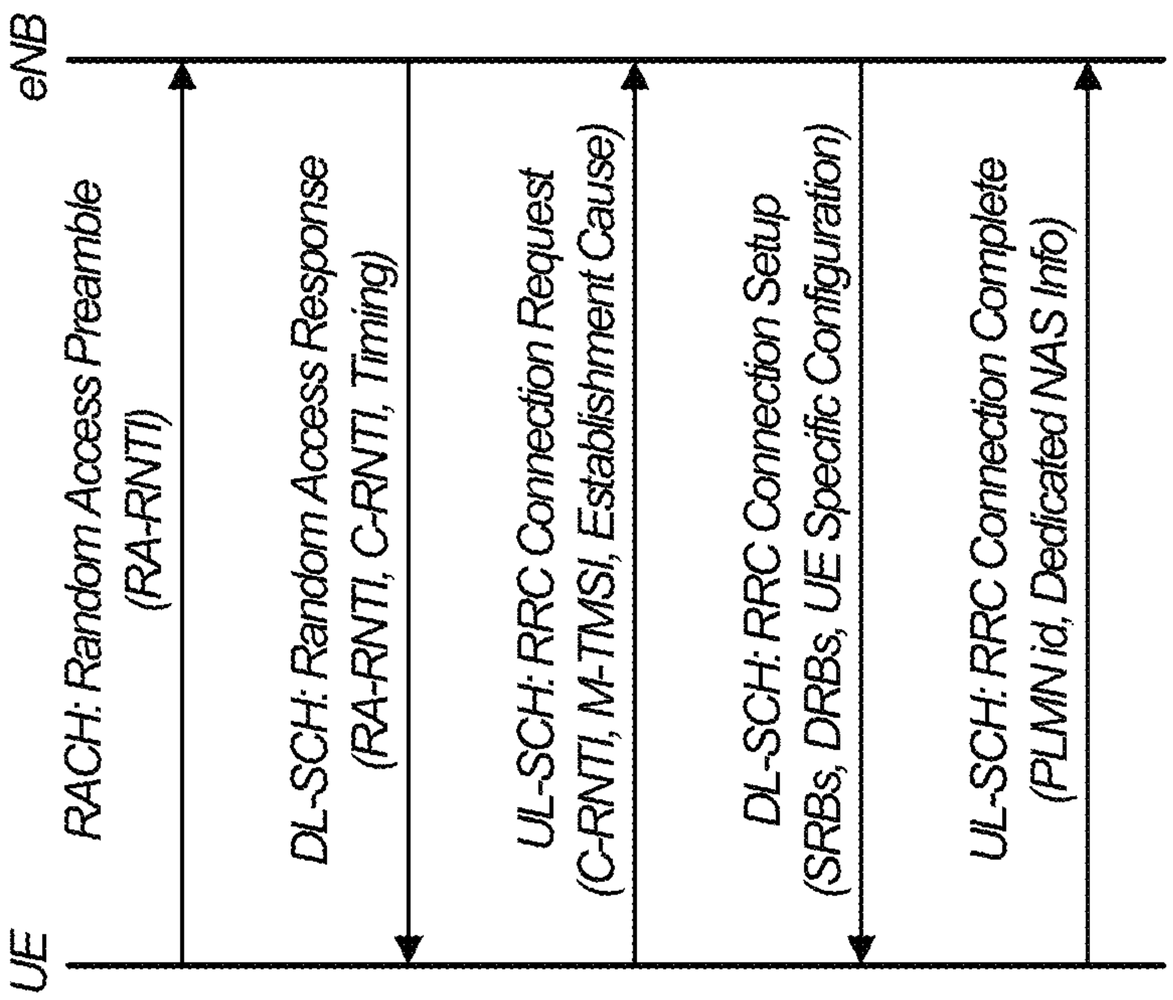

UE
eNB
RACH: Random Access Preamble
(RA-RNTI)
DL-SCH: Random Access Response
(RA-RNTI, C-RNTI, Timing)
UL-SCH: RRC Connection Request
(C-RNTI, M-TMSI, Establishment Cause)
DL-SCH: RRC Connection Setup
(SRBs, DRBs, UE Specific Configuration)
UL-SCH: RRC Connection Complete
(PLMN id, Dedicated NAS Info)

FIG. 12

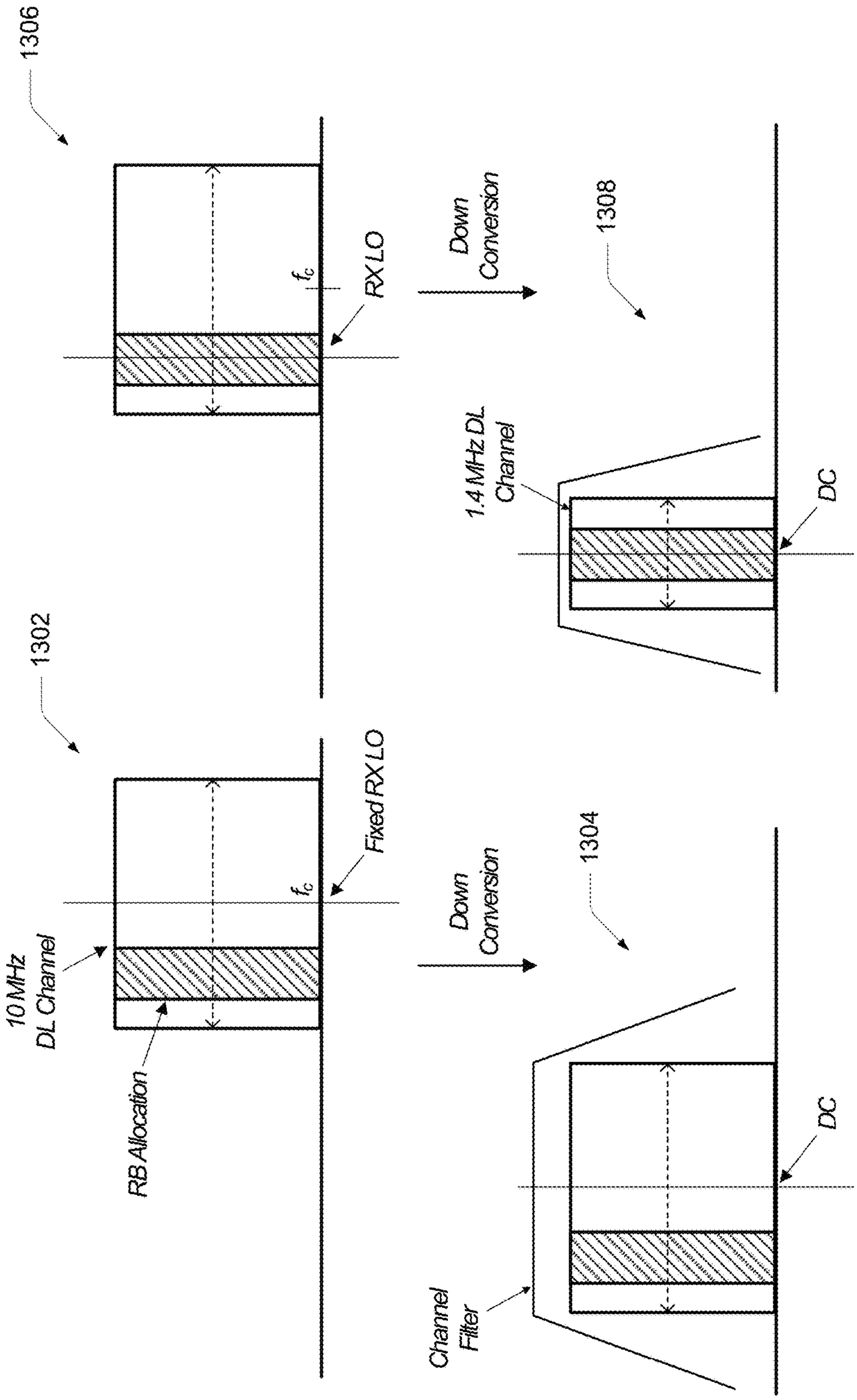

1306
f_c
RX LO
Down Conversion
1308
1.4 MHz DL Channel
DC
1302
10 MHz DL Channel
Fixed RX LO
f_c
RB Allocation
Down Conversion
1304
Channel Filter
DC

FIG. 13

DEVICE CATEGORY IN 3GPP COMMUNICATIONS

PRIORITY CLAIM

This application claims benefit of priority of U.S. Provisional Patent Application Ser. No. 62/274,353 titled "New Device Category in 3GPP Communications", filed on Jan. 3, 2016, which is hereby incorporated by reference as though fully and completely set forth herein.

FIELD OF THE INVENTION

The present application relates to wireless communications, and more particularly to a new category of devices in 3GPP wireless communications.

DESCRIPTION OF THE RELATED ART

Wireless communication systems are rapidly growing in usage. In recent years, wireless devices such as smart phones and tablet computers have become increasingly sophisticated. In addition to supporting telephone calls, many mobile devices (i.e., user equipment devices or UEs) now provide access to the internet, email, text messaging, and navigation using the global positioning system (GPS), and are capable of operating sophisticated applications that utilize these functionalities. Additionally, there exist numerous different wireless communication technologies and standards. Some examples of wireless communication standards include GSM, UMTS (WCDMA, TDS-CDMA), LTE, LTE Advanced (LTE-A), HSPA, 3GPP2 CDMA2000 (e.g., 1×RTT, 1×EV-DO, HRPD, eHRPD), IEEE 802.11 (WLAN or Wi-Fi), IEEE 802.16 (WiMAX), BLUETOOTH, etc.

Various ones of the wireless communications standards, such as LTE, utilize packet switched networks. The LTE specification defines a number of User Equipment (UE) categories, where each LTE category defines the overall performance and the capabilities of a UE. These LTE categories define the standards to which a particular handset, dongle or other equipment will operate in the communication system. The LTE categories or UE classes are used to ensure that the base station (eNodeB or eNB) can communicate correctly with the user equipment. The UE relays the LTE UE category information to the base station, and thus the base station is able to determine the performance characteristics of the UE, and communicate with the UE accordingly. This enables the eNB to communicate using capabilities that it knows the UE possesses. The LTE UE category information is therefore of great importance. While users may not be particularly aware of the category of their UE, the performance of the UE matches the UE's category and allows the eNB to communicate effectively with all the UEs that are connected to it. However, the eNB will be less likely to communicate beyond the performance of the UE corresponding to the category of the UE.

Accordingly, improvements in the field are desirable.

SUMMARY OF THE INVENTION

Embodiments are presented herein of, inter alia, methods for wireless communication devices communicating, e.g. with cellular base stations, according to a new device category, and of devices that implement the methods. Embodiments are further presented herein for wireless communication systems containing user equipment (UE) devices and base stations communicating with each other within the wireless communication systems.

In various embodiments, a UE device may communicate according to a new device category satisfying specified QoS requirements while also satisfying specified link budget requirements, and, in some embodiments, additional optimization requirements. The UE device may communicate with a cellular base station according to the new device category, and may switch to communicating with the cellular base station in a way that the UE uses physical channels and/or procedures that are specific to one or more other, different device categories. For example, the UE device may switch to using physical channels and/or procedures associated with a second (pre-existing) device category if the link budget requirements exceed a specified value and the QoS requirements are not sensitive, while communicating with the cellular base station. The UE device may also switch to using physical channels and/or procedures associated with a third (pre-existing) device type if either the link budget requirement does not exceed the specified value, or the QoS requirements are sensitive and a downlink throughput requirement exceeds a specified throughput value, while communicating with the cellular base station.

Note that the techniques described herein may be implemented in and/or used with a number of different types of devices, including but not limited to, base stations, access points, cellular phones, portable media players, tablet computers, wearable devices, and various other computing devices.

This Summary is intended to provide a brief overview of some of the subject matter described in this document. Accordingly, it will be appreciated that the above-described features are merely examples and should not be construed to narrow the scope or spirit of the subject matter described herein in any way. Other features, aspects, and advantages of the subject matter described herein will become apparent from the following Detailed Description, Figures, and Claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates an exemplary (and simplified) wireless communication system, according to some embodiments;

FIG. **2** illustrates an exemplary base station in communication with an exemplary wireless user equipment (UE) device, according to some embodiments;

FIG. **3** illustrates an exemplary block diagram of a UE, according to some embodiments;

FIG. **4** illustrates an exemplary block diagram of a base station, according to some embodiments;

FIG. **5** shows an exemplary flow diagram illustrating communication between a UE device and a base station, according to some embodiments;

FIG. **6** shows a table of select device category definitions that include a newly proposed category A (Cat-A), according to some embodiments;

FIG. **7** shows an exemplary table illustrating uplink requirements for some wireless communications according to some embodiments;

FIG. **8** illustrates the uplink narrow bandwidth operation of a wireless communication device, according to some embodiments;

FIG. **9** illustrates the signal generation on the PUSCH during uplink narrow bandwidth operation of a wireless communication device, according to some embodiments;

FIG. **10** illustrates an example of a tuning gap according to some embodiments;

FIG. **11** shows a partial timing diagram illustrating signaling for a new category (Cat-A) device, according to some embodiments;

FIG. **12** shows a flow diagram illustrating signaling for a new category (Cat-A) device, according to some embodiments; and

FIG. **13** shows an exemplary frequency spectrum diagram illustrating the downlink mode of operation of a new category (Cat-A) device, according to some embodiments.

While features described herein are susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the drawings and detailed description thereto are not intended to be limiting to the particular form disclosed, but on the contrary, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the subject matter as defined by the appended claims.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Acronyms

Various acronyms are used throughout the present application. Definitions of the most prominently used acronyms that may appear throughout the present application are provided below:

UE: User Equipment
RF: Radio Frequency
BS: Base Station
DL: Downlink (from BS to UE)
UL: Uplink (from UE to BS)
FDD: Frequency Division Duplexing
TDD: Time Division Duplexing
GSM: Global System for Mobile Communication
LTE: Long Term Evolution
TX: Transmission/Transmit
RX: Reception/Receive
UMTS: Universal Mobile Telecommunication System
LAN: Local Area Network
WLAN: Wireless LAN
AP: Access Point
APR: Applications Processor
APN: Access Point Name
GPRS: General Packet Radio Service
GTP: GPRS Tunneling Protocol
PDN: Packet Data Network
PGW: PDN Gateway
SGW: Serving Gateway
RAT: Radio Access Technology
Wi-Fi: Wireless Local Area Network (WLAN) RAT based on the Institute of Electrical and Electronics Engineers' (IEEE) 802.11 standards
PDCP: Packet Data Convergence Protocol
BSR: Buffer Size Report
CMR: Change Mode Request
TBS: Transport Block Size
ROHC: Robust Header Compression
SID: System Identification Number
PDU: Protocol Data Unit
PT: Payload Type
FT: Frame Type
AMR-WB: Adaptive Multi-Rate Wideband
RTP: Real-time Transport Protocol
IR: Initialization and Refresh state

FO: First-Order state
DYN: Dynamic

Terms

The following is a glossary of terms that may appear in the present application:

Memory Medium—Any of various types of memory devices or storage devices. The term "memory medium" is intended to include an installation medium, e.g., a CD-ROM, floppy disks **104**, or tape device; a computer system memory or random access memory such as DRAM, DDR RAM, SRAM, EDO RAM, Rambus RAM, etc.; a non-volatile memory such as a Flash, magnetic media, e.g., a hard drive, or optical storage; registers, or other similar types of memory elements, etc. The memory medium may comprise other types of memory as well or combinations thereof. In addition, the memory medium may be located in a first computer system in which the programs are executed, or may be located in a second different computer system which connects to the first computer system over a network, such as the Internet. In the latter instance, the second computer system may provide program instructions to the first computer system for execution. The term "memory medium" may include two or more memory mediums which may reside in different locations, e.g., in different computer systems that are connected over a network.

Carrier Medium—a memory medium as described above, as well as a physical transmission medium, such as a bus, network, and/or other physical transmission medium that conveys signals such as electrical, electromagnetic, or digital signals.

Computer System (or Computer)—any of various types of computing or processing systems, including a personal computer system (PC), mainframe computer system, workstation, network appliance, Internet appliance, personal digital assistant (PDA), television system, grid computing system, or other device or combinations of devices. In general, the term "computer system" may be broadly defined to encompass any device (or combination of devices) having at least one processor that executes instructions from a memory medium.

User Equipment (UE) (or "UE Device")—any of various types of computer systems devices which are mobile or portable and which performs wireless communications. Also referred to as wireless communication devices. Examples of UE devices include mobile telephones or smart phones (e.g., iPhone™, Android™-based phones) and tablet computers such as iPad™ Samsung Galaxy™, etc., portable gaming devices (e.g., Nintendo DS™, PlayStation Portable™, Gameboy Advance™, iPod™), laptops, wearable devices (e.g. Apple Watch™, Google Glass™) PDAs, portable Internet devices, music players, data storage devices, or other handheld devices, etc. Various other types of devices would fall into this category if they include Wi-Fi or both cellular and Wi-Fi communication capabilities and/or other wireless communication capabilities, for example over short-range radio access technologies (SRATs) such as BLUETOOTH™, etc. In general, the term "UE" or "UE device" may be broadly defined to encompass any electronic, computing, and/or telecommunications device (or combination of devices) which is easily transported by a user and capable of wireless communication.

Base Station (BS)—The term "Base Station" has the full breadth of its ordinary meaning, and at least includes a

wireless communication station installed at a fixed location and used to communicate as part of a wireless telephone system or radio system.

Processing Element—refers to various elements or combinations of elements that are capable of performing a function in a device, e.g. in a user equipment device or in a cellular network device. Processing elements may include, for example: processors and associated memory, portions or circuits of individual processor cores, entire processor cores, processor arrays, circuits such as an ASIC (Application Specific Integrated Circuit), programmable hardware elements such as a field programmable gate array (FPGA), as well any of various combinations of the above.

Wireless Device (or wireless communication device)—any of various types of computer systems devices which performs wireless communications using WLAN communications, SRAT communications, Wi-Fi communications and the like. As used herein, the term "wireless device" may refer to a UE device, as defined above, or to a stationary device, such as a stationary wireless client or a wireless base station. For example a wireless device may be any type of wireless station of an 802.11 system, such as an access point (AP) or a client station (UE), or any type of wireless station of a cellular communication system communicating according to a cellular radio access technology (e.g. LTE, CDMA, GSM), such as a base station or a cellular telephone, for example.

Wi-Fi—The term "Wi-Fi" has the full breadth of its ordinary meaning, and at least includes a wireless communication network or RAT that is serviced by wireless LAN (WLAN) access points and which provides connectivity through these access points to the Internet. Most modern Wi-Fi networks (or WLAN networks) are based on IEEE 802.11 standards and are marketed under the name "Wi-Fi". A Wi-Fi (WLAN) network is different from a cellular network.

BLUETOOTH™—The term "BLUETOOTH™" has the full breadth of its ordinary meaning, and at least includes any of the various implementations of the Bluetooth standard, including Bluetooth Low Energy (BTLE) and Bluetooth Low Energy for Audio (BTLEA), including future implementations of the Bluetooth standard, among others.

Personal Area Network—The term "Personal Area Network" has the full breadth of its ordinary meaning, and at least includes any of various types of computer networks used for data transmission among devices such as computers, phones, tablets and input/output devices. Bluetooth is one example of a personal area network. A PAN is an example of a short range wireless communication technology.

Automatically—refers to an action or operation performed by a computer system (e.g., software executed by the computer system) or device (e.g., circuitry, programmable hardware elements, ASICs, etc.), without user input directly specifying or performing the action or operation. Thus the term "automatically" is in contrast to an operation being manually performed or specified by the user, where the user provides input to directly perform the operation. An automatic procedure may be initiated by input provided by the user, but the subsequent actions that are performed "automatically" are not specified by the user, i.e., are not performed "manually", where the user specifies each action to perform. For example, a user filling out an electronic form by selecting each field and providing input specifying information (e.g., by typing information, selecting check boxes, radio selections, etc.) is filling out the form manually, even though the computer system must update the form in response to the user actions. The form may be automatically filled out by the computer system where the computer system (e.g., software executing on the computer system) analyzes the fields of the form and fills in the form without any user input specifying the answers to the fields. As indicated above, the user may invoke the automatic filling of the form, but is not involved in the actual filling of the form (e.g., the user is not manually specifying answers to fields but rather they are being automatically completed). The present specification provides various examples of operations being automatically performed in response to actions the user has taken.

Station (STA)—The term "station" herein refers to any device that has the capability of communicating wirelessly, e.g. by using the 802.11 protocol. A station may be a laptop, a desktop PC, PDA, access point or Wi-Fi phone or any type of device similar to a UE. An STA may be fixed, mobile, portable or wearable. Generally in wireless networking terminology, a station (STA) broadly encompasses any device with wireless communication capabilities, and the terms station (STA), wireless client (UE) and node (BS) are therefore often used interchangeably.

Configured to—Various components may be described as "configured to" perform a task or tasks. In such contexts, "configured to" is a broad recitation generally meaning "having structure that" performs the task or tasks during operation. As such, the component can be configured to perform the task even when the component is not currently performing that task (e.g., a set of electrical conductors may be configured to electrically connect a module to another module, even when the two modules are not connected). In some contexts, "configured to" may be a broad recitation of structure generally meaning "having circuitry that" performs the task or tasks during operation. As such, the component can be configured to perform the task even when the component is not currently on. In general, the circuitry that forms the structure corresponding to "configured to" may include hardware circuits.

Various components may be described as performing a task or tasks, for convenience in the description. Such descriptions should be interpreted as including the phrase "configured to." Reciting a component that is configured to perform one or more tasks is expressly intended not to invoke 35 U.S.C. § 112, paragraph six, interpretation for that component.

FIGS. **1** and **2**—Exemplary Communication System

FIG. **1** illustrates an exemplary (and simplified) wireless communication system, according to some embodiments. It is noted that the system of FIG. **1** is merely one example of a possible system, and embodiments may be implemented in any of various systems, as desired.

As shown, the exemplary wireless communication system includes a base station **102** which communicates over a transmission medium with one or more user devices **106-1** through **106**-N. Each of the user devices may be referred to herein as a "user equipment" (UE) or UE device. Thus, the user devices **106** are referred to as UEs or UE devices. Various ones of the UE devices may operate according to a new category [definition] as detailed herein.

The base station **102** may be a base transceiver station (BTS) or cell site, and may include hardware that enables wireless communication with the UEs **106**A through **106**N. The base station **102** may also be equipped to communicate with a network **100** (e.g., a core network of a cellular service provider, a telecommunication network such as a public switched telephone network (PSTN), and/or the Internet, among various possibilities). Thus, the base station **102** may

facilitate communication between the user devices and/or between the user devices and the network **100**. The communication area (or coverage area) of the base station may be referred to as a "cell." As also used herein, from the perspective of UEs, a base station may sometimes be considered as representing the network insofar as uplink and downlink communications of the UE are concerned. Thus, a UE communicating with one or more base stations in the network may also be interpreted as the UE communicating with the network.

The base station **102** and the user devices may be configured to communicate over the transmission medium using any of various radio access technologies (RATs), also referred to as wireless communication technologies, or telecommunication standards, such as GSM, UMTS (WCDMA), LTE, LTE-Advanced (LTE-A), 3GPP2 CDMA2000 (e.g., 1×RTT, 1×EV-DO, HRPD, eHRPD), Wi-Fi, WiMAX etc. In some embodiments, the base station **102** communicates with at least one UE using improved UL (Uplink) and DL (Downlink) decoupling, preferably through LTE or a similar RAT standard.

UE **106** may be capable of communicating using multiple wireless communication standards. For example, a UE **106** might be configured to communicate using either or both of a 3GPP cellular communication standard (such as LTE) or a 3GPP2 cellular communication standard (such as a cellular communication standard in the CDMA2000 family of cellular communication standards). In some embodiments, the UE **106** may be configured to communicate with base station **102** at least according to a new and improved category designation/definition of UE **106** as described herein. Base station **102** and other similar base stations operating according to the same or a different cellular communication standard may thus be provided as one or more networks of cells, which may provide continuous or nearly continuous overlapping service to UE **106** and similar devices over a wide geographic area via one or more cellular communication standards.

The UE **106** might also or alternatively be configured to communicate using WLAN, BLUETOOTH™, one or more global navigational satellite systems (GNSS, e.g., GPS or GLONASS), one and/or more mobile television broadcasting standards (e.g., ATSC-M/H or DVB-H), etc. Other combinations of wireless communication standards (including more than two wireless communication standards) are also possible.

FIG. **2** illustrates an exemplary user equipment **106** (e.g., one of the devices **106-1** through **106**-N) in communication with the base station **102**, according to some embodiments. The UE **106** may be a device with wireless network connectivity such as a mobile phone, a hand-held device, a computer or a tablet, or virtually any type of wireless device. The UE **106** may include a processor that is configured to execute program instructions stored in memory. The UE **106** may perform any of the method embodiments described herein by executing such stored instructions. Alternatively, or in addition, the UE **106** may include a programmable hardware element such as an FPGA (field-programmable gate array) that is configured to perform any of the method embodiments described herein, or any portion of any of the method embodiments described herein. The UE **106** may be configured to communicate using any of multiple wireless communication protocols. For example, the UE **106** may be configured to communicate using two or more of CDMA2000, LTE, LTE-A, WLAN, or GNSS. Other combinations of wireless communication standards are also possible.

The UE **106** may include one or more antennas for communicating using one or more wireless communication protocols according to one or more RAT standards. In some embodiments, the UE **106** may share one or more parts of a receive chain and/or transmit chain between multiple wireless communication standards. The shared radio may include a single antenna, or may include multiple antennas (e.g., for MIMO) for performing wireless communications. Alternatively, the UE **106** may include separate transmit and/or receive chains (e.g., including separate antennas and other radio components) for each wireless communication protocol with which it is configured to communicate. As another alternative, the UE **106** may include one or more radios which are shared between multiple wireless communication protocols, and one or more radios which are used exclusively by a single wireless communication protocol. For example, the UE **106** may include a shared radio for communicating using either of LTE or CDMA2000 1×RTT, and separate radios for communicating using each of Wi-Fi and BLUETOOTH™. Other configurations are also possible.

FIG. **3**—Block Diagram of an Exemplary UE

FIG. **3** illustrates a block diagram of an exemplary UE **106**, according to some embodiments. As shown, the UE **106** may include a system on chip (SOC) **300**, which may include portions for various purposes. For example, as shown, the SOC **300** may include processor(s) **302** which may execute program instructions for the UE **106** and display circuitry **304** which may perform graphics processing and provide display signals to the display **360**. The processor(s) **302** may also be coupled to memory management unit (MMU) **340**, which may be configured to receive addresses from the processor(s) **302** and translate those addresses to locations in memory (e.g., memory **306**, read only memory (ROM) **350**, NAND flash memory **310**) and/or to other circuits or devices, such as the display circuitry **304**, radio **330**, connector I/F **320**, and/or display **360**. The MMU **340** may be configured to perform memory protection and page table translation or set up. In some embodiments, the MMU **340** may be included as a portion of the processor(s) **302**.

As shown, the SOC **300** may be coupled to various other circuits of the UE **106**. For example, the UE **106** may include various types of memory (e.g., including NAND flash **310**), a connector interface **320** (e.g., for coupling to the computer system), the display **360**, and wireless communication circuitry (e.g., for LTE, LTE-A, CDMA2000, BLUETOOTH™, Wi Fi, GPS, etc.). The UE device **106** may include at least one antenna (e.g. **335***a*), and possibly multiple antennas (e.g. illustrated by antennas **335***a* and **335***b*), for performing wireless communication with base stations and/or other devices. Antennas **335***a* and **335***b* are shown by way of example, and UE device **106** may include more antennas. Overall, the one or more antennas are collectively referred to as antenna **335**. For example, the UE device **106** may use antenna **335** to perform the wireless communication with the aid of radio circuitry **330**. As noted above, the UE may be configured to communicate wirelessly using multiple wireless communication standards in some embodiments.

As described further subsequently herein, the UE **106** (and/or base station **102**) may include hardware and software components for implementing methods for UE **106** [and base station **102**] communicating [with each other] at least according to a new and improved category designation of UE **106**. The processor(s) **302** of the UE device **106** may be configured to implement part or all of the methods

described herein, e.g., by executing program instructions stored on a memory medium (e.g., a non-transitory computer-readable memory medium). In other embodiments, processor(s) **302** may be configured as a programmable hardware element, such as an FPGA (Field Programmable Gate Array), or as an ASIC (Application Specific Integrated Circuit). Furthermore, processor(s) **302** may be coupled to and/or may interoperate with other components as shown in FIG. **3**, to implement communications by UE **106** that incorporates communications corresponding to a new, improved category designation of UE **106** according to various embodiments disclosed herein. Specifically, processor(s) **302** may be coupled to and/or may interoperate with other components as shown in FIG. **3** to facilitate UE **106** communicating in an adaptive manner that seeks to optimize power consumption and performance during wireless communications of UE **106**. Processor(s) **302** may also implement various other applications and/or end-user applications running on UE **106**.

In some embodiments, radio **330** may include separate controllers dedicated to controlling communications for various respective RAT standards. For example, as shown in FIG. **3**, radio **330** may include a Wi Fi controller **350**, a cellular controller (e.g. LTE controller) **352**, and BLUETOOTH™ controller **354**, and in at least some embodiments, one or more or all of these controllers may be implemented as respective integrated circuits (ICs or chips, for short) in communication with each other and with SOC **300** (and more specifically with processor(s) **302**) as will be further described below. For example, Wi Fi controller **350** may communicate with cellular controller **352** over a cell-ISM link or WCI interface, and/or BLUETOOTH™ controller **354** may communicate with cellular controller **352** over a cell-ISM link, etc. While three separate controllers are illustrated within radio **330**, other embodiments have fewer or more similar controllers for various different RATs that may be implemented in UE device **106**.

FIG. **4**—Block Diagram of an Exemplary Base Station

FIG. **4** illustrates a block diagram of an exemplary base station **102**, according to some embodiments. It is noted that the base station of FIG. **4** is merely one example of a possible base station. As shown, the base station **102** may include processor(s) **404** which may execute program instructions for the base station **102**. The processor(s) **404** may also be coupled to memory management unit (MMU) **440**, which may be configured to receive addresses from the processor(s) **404** and translate those addresses to locations in memory (e.g., memory **460** and read only memory (ROM) **450**) or to other circuits or devices.

The base station **102** may include at least one network port **470**. The network port **470** may be configured to couple to a telephone network and provide a plurality of devices, such as UE devices **106**, access to the telephone network as described above in FIGS. **1** and **2**. The network port **470** (or an additional network port) may also or alternatively be configured to couple to a cellular network, e.g., a core network of a cellular service provider. The core network may provide mobility related services and/or other services to a plurality of devices, such as UE devices **106**. In some cases, the network port **470** may couple to a telephone network via the core network, and/or the core network may provide a telephone network (e.g., among other UE devices serviced by the cellular service provider).

The base station **102** may include at least one antenna **434**, and possibly multiple antennas. The at least one antenna **434** may be configured to operate as a wireless transceiver and may be further configured to communicate with UE devices **106** via radio **430**. The antenna **434** communicates with the radio **430** via communication chain **432**. Communication chain **432** may be a receive chain, a transmit chain or both. The radio **430** may be designed to communicate via various wireless telecommunication standards, including, but not limited to, LTE, LTE-A WCDMA, CDMA2000, etc. The processor **404** of the base station **102** may be configured to implement part or all of the methods described herein for base station **102** to communicate with a UE device belonging to a new category of devices capable of adaptively improving power consumption, link budget management, and performance during wireless communications, e.g., by executing program instructions stored on a memory medium (e.g., a non-transitory computer-readable memory medium). Alternatively, the processor **404** may be configured as a programmable hardware element, such as an FPGA (Field Programmable Gate Array), or as an ASIC (Application Specific Integrated Circuit), or a combination thereof. In the case of certain RATs, for example Wi-Fi, base station **102** may be designed as an access point (AP), in which case network port **470** may be implemented to provide access to a wide area network and/or local area network (s), e.g. it may include at least one Ethernet port, and radio **430** may be designed to communicate according to the Wi-Fi standard. Base station **102** may operate according to the various methods as disclosed herein for communicating with mobile devices of a wider range of device categories.

Device Categories

There are many different device category definitions for LTE devices. For example, categories 1-8 are designated for smartphones, and most phones operate according to one of categories 3 to 8. In other words, smartphones typically operate as a device belonging to one of categories 3-8. Category M (Cat-M) is typically used for MTC (Machine Type Communications) devices such as soda machines, smart meters, etc. In some embodiments, a new category A (Cat-A) may be devised and tailored to a specific group of devices, for example to wearable devices such as smart watches or smart glasses. In terms of functionality, wearable devices represent a compromise between link budget and quality of service (QoS). Thus, when considering current existing categories, it may be advantageous to retain the link budget improvement associated with Cat-M because of the form factor, while also retaining the QoS of smart phone categories. Typically, if a Cat-M device has to report its electricity usage to the network, there is no need for the device to transmit such a report during peak wireless network traffic hours such as between 9 AM and noon. Instead, the device may transmit the report during off-peak hours, e.g. 3 AM when there is little or no network traffic. It may be considered difficult for the network to access the device in the middle of the day. Moreover, Cat-M does not necessarily support real time applications. It would therefore be desirable to devise a new category satisfying QoS requirements along with an improved link budget (i.e. also satisfying certain link budget requirements), and potentially implementing additional desired optimizations.

FIG. **6** shows a table of select device category definitions that include a newly proposed category A (Cat-A), according to some embodiments. Each column (of columns 2-5) corresponds to a respective device category and includes parameter requirements/designations associated with each respective feature/designation represented in a corresponding row of column 1 (Features). A new category (Cat-A) in the fifth column may be defined—according to some embodiments—by the parameter requirements/designations

that appear in column 5. That is, the parameter requirements/designations in the Cat-A column represent parameter requirements/designations associated with (or corresponding to) a newly defined category. In some embodiments, the respective corresponding parameter requirements of Cat-A may incorporate (at least in part) the maximum throughput requirements of CAT "1", the number of transmit antennas required in CAT "0" and CAT "M", the duplexer requirement of CAT "1", the power amplifier requirements of CAT "1" and CAT "0", and the modulation requirements of CAT "M". The table also highlights various different characteristics as desirable, unsuitable or suitable.

Cat-A Requirements for UL

The bandwidth (BW) requirement for UL may be based on the link budget limitation of the UE, whereby the potential gain of a large BW may be limited. The PUSCH may be limited to a specified (e.g. small) number of resource blocks (RBs), which may be 6 to 15/25 RBs in some embodiments. In order to achieve a specified (e.g. peak) throughput, which may be 5 Mbps (in full duplex mode) in some embodiments, at least a specified BW (e.g. at least 3 MHz) may be required. The modulation designations/schemes may include QPSK, 16QAM (for peak throughput definition). FIG. **7** shows an exemplary table illustrating UL designations according to some embodiments. The numbers in the top row indicate the number of physical resource blocks, while the first column in each table indicates the transport block size. For example, as shown in FIG. **7**, no more than 15 RBs are to be used when operating at 3 MHz.

The UL physical channels (PHY) may be characterized as follows. The PUCCH may be narrowband (e.g. 1 RB), located around the extreme end of the system bandwidth in the frequency domain. The PUSCH may be narrowband/wideband allocated by a E/M/PDCCH grant (e.g. an EPDCCH grant or M-PDCCH grant or PDCCH grant). The SRS may be narrowband and wideband. The PRACH may be narrowband, e.g. 6 RBs, based on an RRC configuration. FIG. **8** illustrates the overall operation of the UE in UL narrow BW according to some embodiments. As illustrated in FIG. **8**, the UE may perform tuning across two subframes, e.g. subframes **802** and **804**, and/or subframes **806** and **808**, respectively. FIG. **8** illustrates tuning for PUSCH intra-subframe hopping and PUSCH inter-subframe hopping, respectively, across two subframes for each case.

FIG. **9** illustrates the signal generation on the PUSCH during UE narrow BW UL operation according to some embodiments. In the exemplary embodiment, the baseband signal is processed in a digital Fourier transform block (DFT **902**) and the resulting output signals are provided to an inverse digital Fourier transform block (IDFT **904**) operating at frequency Fs. The processed baseband signal is then frequency shifted (Frequency Shift block, or FSB **906**). Diagram **912** illustrates the frequency spectrum of the signals entering FSB **906**, and diagram **910** illustrates the frequency spectrum of the signals output from FSB **906**.

Referring to FIG. **8** and FIG. **9**, the operation of the UE in UL narrow BW may be partially characterized as follows. The System BW may be kept to the network configuration (e.g. 10/20 MHz), depending on the network deployment. The RF may be opened for the number of RBs needed (e.g. 1 RB for PUCCH, up to 15 RBs for PUSCH based on DCI0). The RF may be tunable to the location (in some embodiments to the exact location) of the frequency domain allocation. For example, the RF may be tuned to the location of the frequency domain allocation whenever frequency hopping is needed. The PLL may be designed to have at least a specified resolution such that tuning loss has negligible impact on performance and the tuning period is shared across a specified number of subframes, e.g. the tuning period may be shared across two subframes in this case. FIG. **10** illustrates an example of a tuning gap (denoted by "G" in the figure) according to some embodiments.

The UL narrowband "On" operation of the UE may include the following specifications.

The UL grant allocation for PUSCH may be restricted, i.e. the present system BW may be retained. This may be performed through signaling to the NW for a new category definition. Prior to attaching to the NW and prior to the UE Identification in RRC signaling, the UE may operate in a different category mode, e.g. CAT-M mode. For example, in some embodiments, MSG3 (PUSCH) and PUCCH may be using a specified frequency, such as 1.4 MHz associated with (or corresponding to) CAT-M.

SRS may be disabled, or only narrowband configuration may be allowed for SRS. Common SRS may be sent in SIB2, and UE-Specific SRS may be sent through RRC signaling (RRC connection reconfiguration). Accordingly, in some embodiments, the Cat-A device may disregard the configuration relayed through SIB2 and may instead use the configuration relayed through the RRC signaling that supports narrowband SRS for a Cat-A device. In some embodiments, a Cat-A device may be specified as not supporting the wideband SRS configuration in RRC, thereby differing from legacy UEs. In such embodiments, the eNB may not signal a wideband SRS configuration, rather a narrowband SRS may be implemented to support the narrowband mode of operation of the Cat-A device during UL operations.

FIG. **11** shows a partial timing diagram illustrating signaling for a Cat-A device according to some embodiments. As illustrated in FIG. **11**, once initial setup through RRC signaling has been established (RRC Setup, Authentication, NAS Security), the NW (e.g. base station or eNB) may query the UE for capability information (UE Capability Enquiry). The UE may respond (e.g. through RRC signaling for UE category or UE capability) indicating that it is a Cat-A device (UE Capability Information). In response, the RRC connection may be reconfigured to support Cat-A operation, as signaled in an RRC Connection Reconfiguration message, with acknowledgment sent to the eNB once the connection reconfiguration is complete.

FIG. **12** shows a flow diagram illustrating signaling for a Cat-A device according to some embodiments. During the first phase of device Attach, the Cat-A UE may be identified during the RACH procedure as a Cat-M device, which may operate at a frequency appropriate for a Cat-M device, e.g. at 1.4 MHz. Alternatively, a new, reserved preamble may be defined for Cat-A devices, and the category [Cat-A] may be identified at the first message (@MSG1) during the RACH procedure for the Attach procedure. This may also lead to a change in the SIB, or the definition of a new SIB for Cat-A, in which case the eNB may ensure that PUSCH is restricted to up to a specified number of RB, e.g. 15 RBs, while PUCCH may be used according to legacy usage. Once the Attach procedure is complete and the NW is informed of the Cat-A capability of the UE, all subsequent RRC Connection Requests may be based on the new Cat-A. That is, PUSCH and PUCCH operations may proceed according to the Cat-A requirements (as previously defined above). For PRACH procedures, either the Cat-M RACH or the new PRACH for Cat-A may be used.

Cat-A Requirements for DL

The DL BW requirements may be different from the UL BW requirements for a Cat-A device.

The link budget may be improved by increasing the BW (more transmit power @eNB for more RBs). In some embodiments a specified frequency may be targeted, for example a 10 MHz target may be assumed. In order to achieve a desired [e.g. peak] throughput, e.g. 10 Mbps (in full duplex), in some embodiments a BW of at least a specified frequency, e.g. 3 MHz, may be designated. The modulation may be specified as QPSK, 16QAM, and 64QAM (for peak throughput definition).

The DL physical channels (PHY) may be characterized as follows. The PSS/SSS/MIB may be narrowband channels (e.g. 1.4 MHz) in the center of the bandwidth. The PHICH/PCFICH may be narrowband channels that may be bypassed or replaced by EPDCCH/M-PDCCH. The PDSCH may be based on eNB resource assignment. The PDCCH may be a wideband channel (which needs to be accounted for during narrowband mode of operation). The E-PDCCH may be a narrowband channel (e.g. 8 PRBs spread across the whole system bandwidth), and may be UE-specific, used in RRC connected mode.

Overall, the DL requirements may be considered different from the UL requirements, allowing for asymmetry between the UL and the DL BW assignment. UL operation is narrowband, and polar architecture would be a transmit architecture candidate for the transceiver to reduce power consumption. During DL operation the main advantage of narrowband is ADC, and a possible LOW IF (intermediate frequency) receiver. There may be a reduced benefit associated with using narrowband in the DL operation compared to the UL operation. In DL operation, the more RBs are used the more transmit power is required from the eNB. The desired frequency band may be thought of in terms of energy efficiency during the DL operation (e.g. 10 MHz may be desirable). By way of example, a desired payload may be a payload with a throughput of 5 Mbps (megabits per second). Cat-M supports 1 Mbps, whereby the transceiver remains awake operating at a data rate of 1 Mbps over 1.4 MHz. However, using 6 RBs at 1.4 MHz over 10 TTIs (transmit time intervals), for example, may achieve the same throughput as using 12 RBs over five TTIs. In terms of network usage both scenarios may be considered equal. Referring again to the example above, the use of 6 RBs over 10 ms may be considered the equivalent of the use of 12 RBs over 5 ms. However, from the perspective of energy efficiency, a scenario of 12 RBs over 5 ms may be more desirable because after 5 ms the transceiver may be switched off, resulting in power savings. For this reason, there may be no need to meet the bandwidth requirements of Cat-M during DL operations.

PDCCH Replacement for Cat-A

One limitation during DL operations is the control channel, PDCCH. E-PDCCH is UE-specific and is used in RRC connection mode and cannot be used for common channels like paging, SIB, RACH, etc. PDCCH may be replaced for Cat-A devices according to at least two different solutions. In a first solution, the E-PDCCH may be extended to be used for idle mode and common channels, SIB/RAR/Paging. This may require significant changes and may impact legacy UEs, especially for SIBs. For RAR and Paging it may include a definition of new reserved preambles for RACH, and a new UE ID for paging for this new category (Cat-A) devices.

In a second solution, the M-PDCCH may be reused for RAR/Paging and MTC_SIB may be used (where MTC stands for machine-type communications), while E-PDCCH may be used for UE-specific data or a modified version of M-PDCCH to support a larger number of RBs (more than 6 RBs of Cat-M). It should be noted that MTC_SIB does not require a PDCCH. Consequently, RAR and Paging may be operating at a specified frequency (e.g. 1.4 MHz) like a Cat-M device. Before RRC connection reconfiguration is reached, M-PDCCH may be used. Once RRC connection reconfiguration has been reached, a complete switch to E-PDCCH may take place since E-PDCCH in the specification is UE specific and used only in RRC connected mode (or, as stated above, a modified version of M-PDCCH). Thus, to use E-PDCCH, a configuration is expected from the network, and that configuration may be received in an RRC connection reconfiguration transmission.

Furthermore, MTC_SIB may be made to cover all legacy SIBs. Since an MTC device may not support mobility, SIB4/5 may most likely not be redefined for MTC. Hence for Cat-A, new SIBs 4/5/10/11/12 may be created. SIBs 4 and 5 may be for mobility, SIBs 11 and 12 may be for emergency calls as the new category supports emergency calls. Overall, the new SIBs may be created to operate without PDCCH, i.e. they may operate without using PDCCH as MTC_SIB. The PRBs pairs used for E-PDCCH may be restricted to fit a specified bandwidth, which is 10 MHz in some embodiments. Prior to attaching to the NW, the UE may be operating using physical channels and/or procedures associated with a different category mode, e.g. Cat-M mode, while the UE may still be identified as a Cat-A device. In other words, the UE may not be identified as Cat-M device, but at the same time the UE may use M-PDCCH and common channels (SIB/RACH/Paging) as defined for (associated with) Cat-M because M-PDCCH and the above referenced common channels support a narrowband mode of operation (1.4 MHz). An example code sequence corresponding to E-PDCCH configuration is shown below:

```
EPDCCH-SetConfig-r11 ::= SEQUENCE {
setConfigId-r11 EPDCCH-SetConfigId-r11,
transmissionType-r11 ENUMERATED {localised, distributed},
resourceBlockAssignment-r11 SEQUENCE{
numberPRB-Pairs-r11 ENUMERATED {n2, n4, n8},
resourceBlockAssignment-r11 BIT STRING (SIZE(4..38)) // This may be
restricted to fit in 10 MHz
},
```

DL Mode of Operation

Considering the new category (Cat-A), if the benefit of narrowband mode of operation is not justified, then in DL mode the UE may operate according to a legacy Cat-1 mode of operation all the while remaining identified as a Cat-A device. In other words, if there is no need for a narrowband mode of operation in DL, then a Cat-A device may simply operate according to certain features, e.g. certain channels and/or mode of operation associated with a different device category, e.g. operate according to certain features and procedures associated with a legacy Cat-1 device during DL communications/operations. For link budget enhancement, CE (coverage enhancements) from a different category, e.g. Cat-M may be reused for operation if desired. Overall, Cat-M operation may be used for all the common channels while UE-specific data may be handled according to Cat-A requirements (for a Cat-A UE). Thus, a Cat-A device may also have modes of operation associated with other device categories. In some embodiments, a Cat-A device may have Cat-1 and/or Cat-M modes of operation, which means that

the Cat-A UE may use some PHY channels and/or procedures that are specific to (associated with) those different categories. For example, Cat-1 mode of operation means use of PDCCH, Cat-M mode of operation means use of M-PDCCH and narrowband (1.4 MHz) operation. It should be noted that the modes of operation described above are also referred to herein as "operating according to a different device category". For example, when a (Cat-A) UE device is said to be operating according to Cat-1, it means that the Cat-A UE device uses some channels and/or procedures that are specific to Cat-1, while the UE device remains identified as a Cat-A device.

It should be noted that UL communications may always take place in a narrowband mode of operation. For example, during UL operations the UE may operate in at most (i.e. maximum) a 3 MHz bandwidth. During DL communications, the UE may operate in a 10 MHz bandwidth independently of the system bandwidth, or the UE may operate in the system bandwidth. Furthermore, in some embodiments, a Cat-A device may always operate in asymmetric bandwidths for UL and DL operations. In other words, in some embodiments, a Cat-A device may operate in a first size bandwidth for DL operations and a second size bandwidth for UL operations, where the first size bandwidth differs from the second size bandwidth.

Consequently, if a narrowband mode of operation in DL is justified by the architecture, then a Cat-A device may operate in a specified system band for efficiency, e.g. in 10 MHz for energy efficiency (it should be noted that operating in a 1.4 MHz band has an impact on power consumption for heavy DL traffic). For link budget enhancement and common channels, a Cat-A UE may operate using features, channels and/or procedures specific to a Cat-M device (i.e. operate in a 1.4 MHz bandwidth). In a way, during some time periods the UE may be said to switch from operating as a Cat-A device to operating as a Cat-M device. However, as mentioned above, this doesn't mean that the UE changes its category or that the category of the UE is redefined/modified. In some embodiments, this change in mode of operation includes changing the mode of operation for the PHY channels and the system bandwidth. For example, if link budget enhancements are needed, the UE may operate in 1.4 MHz and use the M-PDCCH as a Cat-M device would, but the UE still remains a Cat-A device.

FIG. **13** shows an exemplary frequency spectrum diagram illustrating the DL mode of operation of a Cat-A device according to some embodiments. Diagram **1302** illustrates the frequency spectrum when a fixed receive local oscillator (Fixed RX LO) is used, and the resulting baseband signal frequency spectrum is illustrated in diagram **1304**. Diagram **1306** illustrates the frequency spectrum when an RX LO offset from the center frequency is used, and the resulting baseband signal frequency spectrum is illustrated in diagram **1308**.

Defining Cat-A in Terms of Cat-1

In some embodiments, Cat-A may be defined in terms of Cat-1 with narrowband operation in UL/DL. That is, a Cat-A device may be considered as a Cat-1 device with a single receive (RX) antenna, reuse of Cat-M agreements for common channels (RAR/Paging/SIB) and extensions if needed, and use of Cat-M mode (i.e. M-PDCCH, time domain repetitions and 1.4 MHz) in idle mode and during attach procedure (e.g. refer to FIG. **6** showing overlapping features between various device categories according to some embodiments). For UL, if new RACH preambles are introduced in Cat-A, the PUCCH may differ, while in Cat-M, PUCCH is restricted to 1.4 MHz whereas Cat-A operates according to legacy PUCCH.

As soon as RRC connection reconfiguration is complete, the UE may be operating as a fully Cat-A device, i.e. it may use E-PDCCH for UE-specific data, and operate in 10 MHz in DL mode, and in 3 MHz in UL mode. For a link budget improvement higher than 5 dB and QoS requirements that are not sensitive, the UE may switch to a Cat-M mode of operation as previously described (in other words, the UE may remain a Cat-A device while using a mode of operation specific to or associated with Cat-M), i.e. operating in a 1.4 MHz band with time domain repetitions. For a link budget improvement lower than 5 dB, the UE may switch to a Cat-1 mode of operation. For QCI1 (e.g. real time applications, VoLTE or similar QoS, QoS that are sensitive for e.g. real time applications)/Heavy DL throughput and regardless of the link budget improvement needed (i.e. be it more than 5 dB or less than 5 dB), the UE may again switch to a Cat-1 mode of operation.

The switch from operating according to a mode of operation associated with one category to operating according to a mode of operation associated with another category may be performed at the eNB through RRC signaling. The UE may be identified as a Cat-A device, but based on the link budget, the QoS and/or the throughput/power consumption requirements, the eNB may enable the most appropriate (or most advantageous) mode of operation (e.g. PHY channels like M-PDCCH, 1.4 MHz mode of operation, E-PDCCH, common channels procedures, etc.) The switch may be requested by the wireless communication device (e.g. in form of MAC CE/RRC signaling) or it may be triggered by the NW based on measurements available at the NW (e.g. RSRP/CQI/PHR/BSR/BLER, etc.) It should also be noted that while there are at least three modes of operation of a Cat-A device disclosed herein, operation of Cat-A devices is not restricted to the examples provided herein. For example, in some embodiments, when certain conditions are met a Cat-A device may operate according to procedures and/or use of channels associated with other device categories not specifically mentioned herein, in addition to Cat-1 and Cat-M modes of operation. Furthermore, a Cat-A device may operate according to the requirements specified for a Cat-A device (see FIG. **6** for exemplary category requirements for Cat-A) at all times, while under certain conditions—as also previously disclosed herein—the device may switch between performing respective operations according to corresponding procedures and/or use of channels associated with different categories.

FIG. **5** shows a flow diagram illustrating communications between a UE device and a cellular base station according to some embodiments. The UE device may be identified as belonging to a first device category, which may be a new device category (or type) such as Cat-A, for example, as disclosed above (**502**). The UE device may communicate with a cellular base station according to a mode of operation associated with (or specific to) the first device category (**520**). If the link budget requirement exceeds a specified value (**504**) and the QoS requirements are not sensitive, i.e. the QoS requirements don't meet certain criteria (**506**), the UE may switch to communicating with the cellular base station according to a mode of operation associated with a second device category, e.g. associated with a pre-existing device category such as Cat-M in some embodiments (**510**). If the link budget requirement does not exceed the specified value (**504**), the UE may switch to communicating with the cellular base station according to a mode of operation

associated with a third device category, e.g. associated with another pre-existing device category such as Cat-1 in some embodiments (**512**). Furthermore, if the QoS requirements are sensitive, i.e. they meet certain criteria, and/or downlink throughput requirements exceed a specified throughput value (**508**), the UE may switch to communicating with the cellular base station according to the mode of operation associated with the third device category (**512**).

Various Embodiments

In some embodiments, a wireless communication device (UE) may perform communications with a cellular base station according to a mode of operation associated with a first UE category, whereby the first UE category includes communication parameter values corresponding to communication parameters that at least partially define how the UE communicates with the cellular base station. The communication parameter values may define a first maximum transport block size for downlink communications and a second maximum transport block size for uplink communications, where the first maximum transport block size is different from the second maximum transport block size. The communication parameter values may also define a first bandwidth for the uplink communications and a second bandwidth for the downlink communications, where the first bandwidth is different from the second bandwidth.

In some implementations, the first transport block size is 10000 and the second transport block size is 5000. Furthermore, the first bandwidth may be 1.4 MHz or 3 MHz, and the second bandwidth may be up to one 10 MHz or 20 MHz. During communications taking place according to the first UE category, a Physical Uplink Shared Channel (PUSCH) may be limited to a specified number of resource blocks. In addition, during communications taking place according to the first UE category, a Physical Uplink Control Channel (PUCCH) may be a narrowband channel located around an extreme end of a communications bandwidth of the UE in the frequency domain.

In some embodiments, an apparatus may include a processing element that can cause a wireless communication device (UE) to perform, during a first period of time, communications with a cellular base station according to a mode of operation associated with a first device category, where the first device category includes a first set of communication parameter values corresponding to communication parameters that at least partially define how the wireless communication device communicates with the cellular base station. The processing element may also cause the UE to perform, during a second period of time, communications with the cellular base station according to a mode of operation associated with a second device category, where the second device category includes a second set of communication parameter values corresponding to the communication parameters. During the first period of time, the UE may perform uplink communications and during the second period of time the UE may perform downlink communications.

Furthermore, the processing element may also cause the UE to communicate at least a subset of the first set of communication parameter values to the cellular base station in response to receiving a wireless communication device capability enquiry from the cellular base station. In addition, the processing element may further cause the UE to receive a reconfiguration message from the cellular base station, where the reconfiguration message instructs the UE to operate according to the first device category.

In yet other embodiments, an apparatus may include at least a processing element that may cause a UE to communicate with a cellular base station according to a first mode of operation associated with a first device category, and to switch to communicating with the cellular base station according to a second mode of operation associated with a second device category in response to a link budget requirement being higher than a specified value and quality of service (QoS) requirements not being sensitive. The UE may also switch to communicating with the cellular base station according to a third mode of operation associated with a third device category in response to the link budget requirement not being higher than the specified value or QoS requirements being sensitive and/or a downlink throughput requirement exceeding a specified throughput value regardless of the link budget requirement. The UE switching from operating according to the first mode of operation to operating according to one of the second mode of operation or the third mode of operation may be facilitated by the cellular base station in response to a control signaling request received from the wireless communication device and/or in response to measurements available at the cellular base station.

Further Embodiments

Embodiments of the present invention may be realized in any of various forms. For example, in some embodiments, the present invention may be realized as a computer-implemented method, a computer-readable memory medium, or a computer system. In other embodiments, the present invention may be realized using one or more custom-designed hardware devices such as ASICs. In other embodiments, the present invention may be realized using one or more programmable hardware elements such as FPGAs.

In some embodiments, a non-transitory computer-readable memory medium (e.g., a non-transitory memory element) may be configured so that it stores program instructions and/or data, where the program instructions, if executed by a computer system, cause the computer system to perform a method, e.g., any of a method embodiments described herein, or, any combination of the method embodiments described herein, or, any subset of any of the method embodiments described herein, or, any combination of such subsets.

In some embodiments, a device (e.g., a UE) may be configured to include a processor (or a set of processors) and a memory medium (or memory element), where the memory medium stores program instructions, where the processor is configured to read and execute the program instructions from the memory medium, where the program instructions are executable to implement any of the various method embodiments described herein (or, any combination of the method embodiments described herein, or, any subset of any of the method embodiments described herein, or, any combination of such subsets). The device may be realized in any of various forms.

Although the embodiments above have been described in considerable detail, numerous variations and modifications will become apparent to those skilled in the art once the above disclosure is fully appreciated. It is intended that the following claims be interpreted to embrace all such variations and modifications.

The invention claimed is:

1. An apparatus comprising:

a non-transitory memory element configured to store information; and

a processing element coupled to the non-transitory memory element and configured to use at least a portion of the information to cause a wireless communication device to:

identify itself to a cellular base station as a device of a first device category;

communicate with the cellular base station during a first period of time according to a first uplink bandwidth no greater than a first maximum uplink bandwidth value and-according to a first downlink bandwidth no greater than a first maximum downlink bandwidth value, wherein the first maximum uplink bandwidth value and the first maximum downlink bandwidth value are different and are associated with the first device category;

communicate with the cellular base station during a second period of time different from the first period of time according to a second uplink bandwidth no greater than a second maximum uplink bandwidth value and according to a second downlink bandwidth no greater than a second maximum downlink bandwidth value while remaining identified as a device of the first device category, wherein the second maximum uplink bandwidth value and the second maximum downlink bandwidth value are the same and are associated with a second device category distinct from the first device category; and

communicate with the cellular base station, while remaining identified as a device of the first device category, according to the first uplink bandwidth and the first downlink bandwidth, or according to the second uplink bandwidth and the second downlink bandwidth, based at least in part on a current application being executed by the wireless communication device.

2. The apparatus of claim 1, wherein the processing element is configured to further cause the wireless communication device to:

communicate with the cellular base station, while remaining identified as a device of the first device category, according to the first uplink bandwidth and the first downlink bandwidth, or according to the second uplink bandwidth and the second downlink bandwidth, based at least in part on a type of a current application being executed by the wireless communication device.

3. The apparatus of claim 1, wherein the processing element is configured to further cause the wireless communication device to:

communicate with the cellular base station, while remaining identified as a device of the first device category, according to the first uplink bandwidth and the first downlink bandwidth, or according to the second uplink bandwidth and the second downlink bandwidth, based at least in part on a quality of service required by a current application being executed by the wireless communication device.

4. The apparatus of claim 1, wherein the processing element is configured to further cause the wireless communication device to:

communicate with the cellular base station, while remaining identified as a device of the first device category, according to the first uplink bandwidth and the first downlink bandwidth, or according to the second uplink bandwidth and the second downlink bandwidth, based at least in part on a present status of a battery of the wireless communication device.

5. The apparatus of claim 1, wherein the processing element is configured to further cause the wireless communication device to:

receive an instruction from the cellular base station specifying whether to use the first uplink bandwidth and the first downlink bandwidth or use the second uplink bandwidth and the second downlink bandwidth during communication of the wireless communication device with the cellular base station.

6. The apparatus of claim 1, wherein the processing element is configured to further cause the wireless communication device to:

communicate with the cellular base station during the first period of time according to a transport block size no greater than a first maximum transport block size for uplink communications and according to a second transport block size no greater than a second maximum transport block size for downlink communications, wherein the first maximum transport block size and the second maximum transport block size are different and are associated with the first device category; and

communicate with the cellular base station during the second period of time according to a transport block size no greater than a third maximum transport block size for uplink communications and according to a transport block size no greater than a fourth maximum transport block size for downlink communications while remaining identified as a device of the first device category, wherein the third maximum transport block size and the fourth maximum transport block size are the same and are associated with the second device category.

7. The apparatus of claim 1, wherein the processing element is configured to further cause the wireless communication device to:

perform uplink communications during the first period of time; and

perform downlink communications during the second period of time.

8. A wireless communication device comprising:

radio circuitry configured to facilitate wireless communications of the wireless communication device; and

a processing element coupled to the radio circuitry and configured to interoperate with the radio circuitry to cause the wireless communication device to:

identify itself to a cellular base station as a device of a first device category;

communicate with the cellular base station during a first period of time according to a first uplink bandwidth no greater than a first maximum uplink bandwidth value and according to a first downlink bandwidth no greater than a first maximum downlink bandwidth value, wherein the first maximum uplink bandwidth value and the first maximum downlink bandwidth value are different and are associated with the first device category;

communicate with the cellular base station during a second period of time different from the first period of time according to a second uplink bandwidth no greater than a second maximum uplink bandwidth value and according to a second downlink bandwidth no greater than a second maximum downlink bandwidth value while remaining identified as a device of the first device category, wherein the second maxi-

mum uplink bandwidth value and the second maximum downlink bandwidth value are the same and are associated with a second device category distinct from the first device category; and

communicate with the cellular base station, while remaining identified as a device of the first device category, according to the first uplink bandwidth and the first downlink bandwidth, or according to the second uplink bandwidth and the second downlink bandwidth, based at least in part on a current application being executed by the wireless communication device.

9. The wireless communication device of claim **8**, wherein the processing element is configured to interoperate with the radio circuitry to further cause the wireless communication device to:

communicate with the cellular base station, while remaining identified as a device of the first device category, according to the first uplink bandwidth and the first downlink bandwidth, or according to the second uplink bandwidth and the second downlink bandwidth, based at least in part on a type of a current application being executed by the wireless communication device.

10. The wireless communication device of claim **8**, wherein the processing element is configured to interoperate with the radio circuitry to further cause the wireless communication device to:

communicate with the cellular base station, while remaining identified as a device of the first device category, according to the first uplink bandwidth and the first downlink bandwidth, or according to the second uplink bandwidth and the second downlink bandwidth, based at least in part on a quality of service required by a current application being executed by the wireless communication device.

11. The wireless communication device of claim **8**, wherein the processing element is configured to interoperate with the radio circuitry to further cause the wireless communication device to:

communicate with the cellular base station, while remaining identified as a device of the first device category, according to the first uplink bandwidth and the first downlink bandwidth, or according to the second uplink bandwidth and the second downlink bandwidth, based at least in part on a present status of a battery of the wireless communication device.

12. The wireless communication device of claim **8**, wherein the processing element is configured to interoperate with the radio circuitry to further cause the wireless communication device to:

receive an instruction from the cellular base station specifying whether to use the first uplink bandwidth and the first downlink bandwidth or use the second uplink bandwidth and the second downlink bandwidth during communication of the wireless communication device with the cellular base station.

13. The wireless communication device of claim **8**, wherein the processing element is configured to interoperate with the radio circuitry to further cause the wireless communication device to:

communicate with the cellular base station during the first period of time according to a transport block size no greater than a first maximum transport block size for uplink communications and according to a second transport block size no greater than a second maximum transport block size for downlink communications, wherein the first maximum transport block size and the second maximum transport block size are different and are associated with the first device category; and

communicate with the cellular base station during the second period of time according to a transport block size no greater than a third maximum transport block size for uplink communications and according to a transport block size no greater than a fourth maximum transport block size for downlink communications while remaining identified as a device of the first device category, wherein the third maximum transport block size and the fourth maximum transport block size are the same and are associated with the second device category.

14. A non-transitory memory element storing instructions executable by a processing element to cause a wireless communication device to:

identify itself to a cellular base station as a device of a first device category;

communicate with the cellular base station during a first period of time according to a first uplink bandwidth no greater than a first maximum uplink bandwidth value and a first downlink bandwidth no greater than a first maximum downlink bandwidth value, wherein the first maximum uplink bandwidth value and the first maximum downlink bandwidth value are different and are-associated with the first device category;

communicate with the cellular base station during a second period of time different from the first period of time according to a second uplink bandwidth no greater than a second maximum uplink bandwidth value and a second downlink bandwidth no greater than a second maximum downlink bandwidth value while remaining identified as a device of the first device category, wherein the second maximum uplink bandwidth value and the second maximum downlink bandwidth value are the same and are associated with a second device category distinct from the first device category; and

communicate with the cellular base station, while remaining identified as a device of the first device category, according to the first uplink bandwidth and the first downlink bandwidth, or according to the second uplink bandwidth and the second downlink bandwidth, based at least in part on a current application being executed by the wireless communication device.

15. The non-transitory memory element of claim **14**, wherein the instructions are further executable by the processing element to cause the wireless communication device to:

communicate with the cellular base station, while remaining identified as a device of the first device category, according to the first uplink bandwidth and the first downlink bandwidth, or according to the second uplink bandwidth and the second downlink bandwidth, based at least in part on a type of a current application being executed by the wireless communication device.

16. The non-transitory memory element of claim **14**, wherein the instructions are further executable by the processing element to cause the wireless communication device to:

communicate with the cellular base station, while remaining identified as a device of the first device category, according to the first uplink bandwidth and the first downlink bandwidth, or according to the second uplink bandwidth and the second downlink bandwidth, based at least in part on a quality of service required by a current application being executed by the wireless communication device.

17. The non-transitory memory element of claim 14, wherein the instructions are further executable by the processing element to cause the wireless communication device to:

communicate with the cellular base station, while remaining identified as a device of the first device category, according to the first uplink bandwidth and the first downlink bandwidth, or according to the second uplink bandwidth and the second downlink bandwidth, based at least in part on a present status of a battery of the wireless communication device.

18. The non-transitory memory element of claim 14, wherein the instructions are further executable by the processing element to cause the wireless communication device to:

receive an instruction from the cellular base station specifying whether to use the first uplink bandwidth and the first downlink bandwidth or use the second uplink bandwidth and the second downlink bandwidth during communication of the wireless communication device with the cellular base station.

19. The non-transitory memory element of claim 14, wherein the instructions are further executable by the processing element to cause the wireless communication device to:

communicate with the cellular base station during the first period of time according to a transport block size no greater than a first maximum transport block size for uplink communications and according to a second transport block size no greater than a second maximum transport block size for downlink communications, wherein the first maximum transport block size and the second maximum transport block size are different and are associated with the first device category; and

communicate with the cellular base station during the second period of time according to a transport block size no greater than a third maximum transport block size for uplink communications and according to a transport block size no greater than a fourth maximum transport block size for downlink communications while remaining identified as a device of the first device category, wherein the third maximum transport block size and the fourth maximum transport block size are the same and are associated with the second device category.

20. The non-transitory memory element of claim 14, wherein the instructions are further executable by the processing element to cause the wireless communication device to:

perform uplink communications during the first period of time; and

perform downlink communications during the second period of time.

* * * * *