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(54) EXTENDED REALITY (XR) ENHANCEMENT

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(21) Appl. No.: **19/195,795**

(22) Filed: **May 1, 2025**

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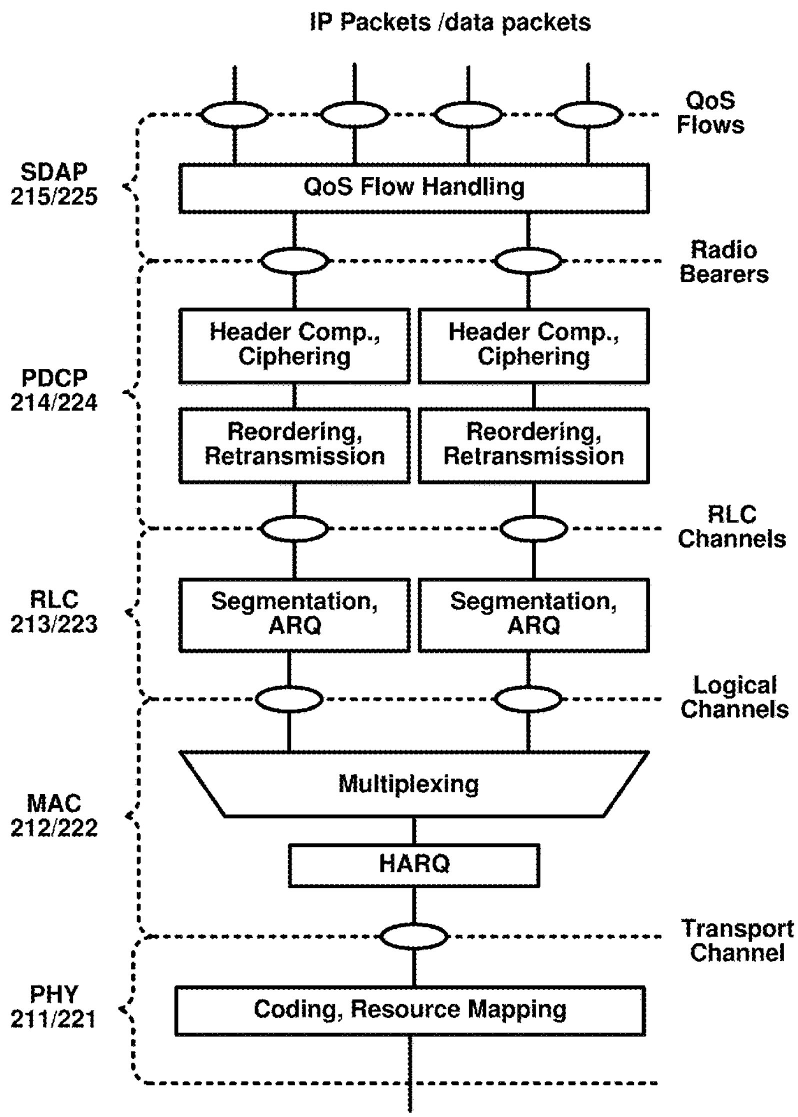
H04W 88/00 (2009.01)

(52) **U.S. Cl.**
CPC ***H04W 4/50*** (2018.02); *H04W 88/00* (2013.01)

(57) **ABSTRACT**

A first base station receives, from a second base station, a message requesting a configuration of a data radio bearer (DRB) for a wireless device, wherein the message indicates that the DRB is associated with a protocol data unit (PDU) set of an application.



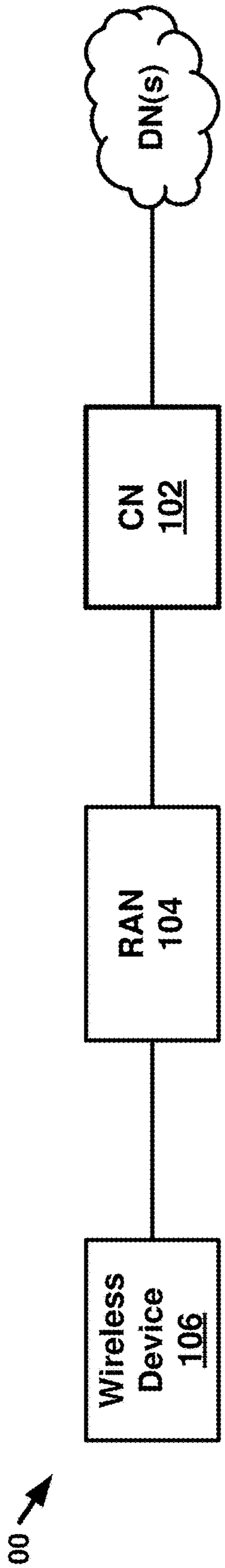

100
Wireless Device 106
RAN 104
CN 102
DN(s)

FIG. 1A

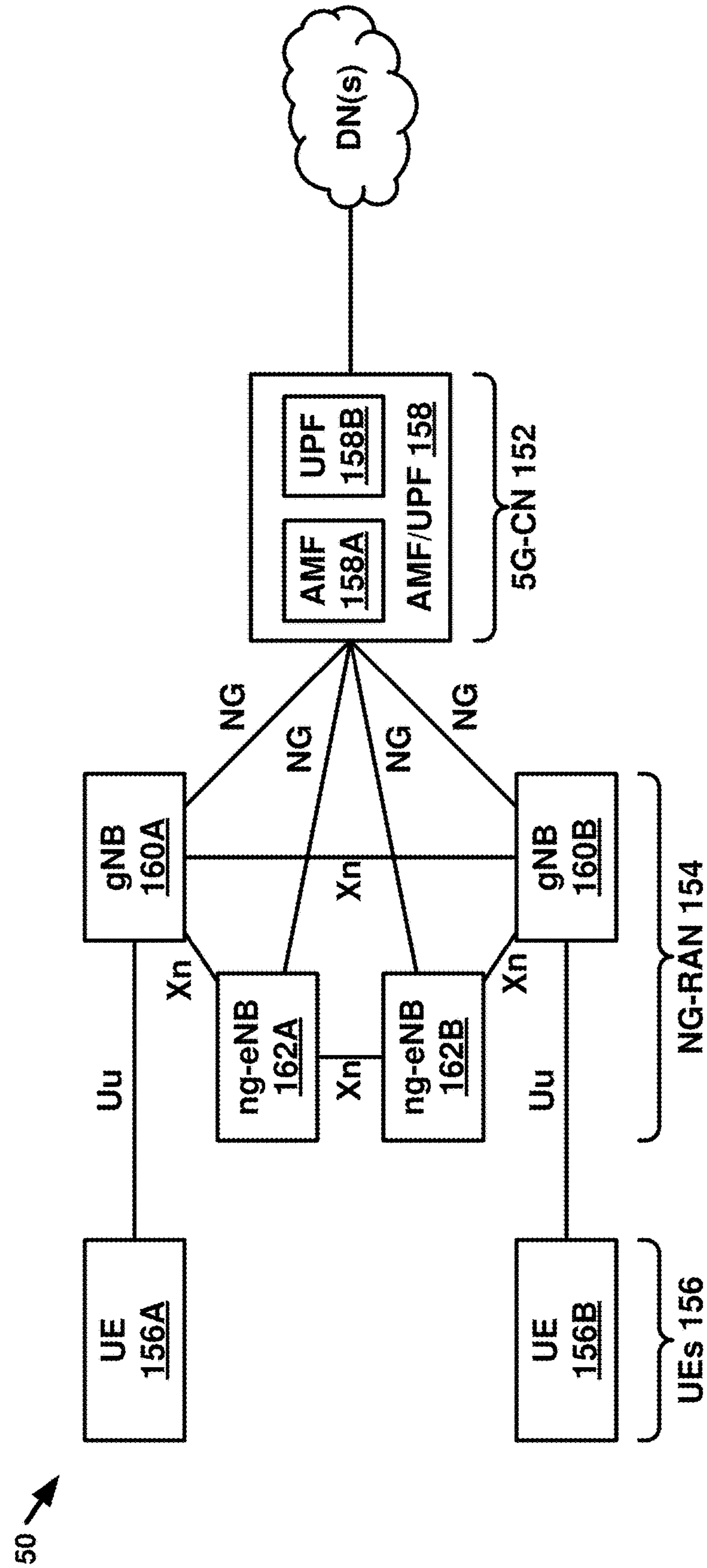

150
UE 156A
UE 156B
UEs 156
Uu
Uu
gNB 160A
gNB 160B
ng-eNB 162A
ng-eNB 162B
Xn
Xn
Xn
Xn
NG-RAN 154
NG
NG
NG
NG
AMF 158A
UPF 158B
AMF/UPF 158
5G-CN 152
DN(s)

FIG. 1B

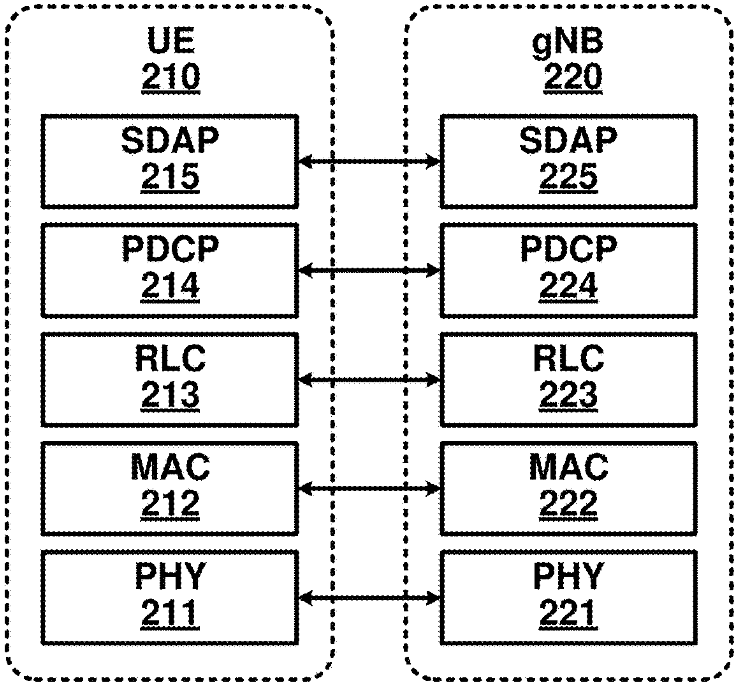

UE
210
SDAP
215
PDCP
214
RLC
213
MAC
212
PHY
211
gNB
220
SDAP
225
PDCP
224
RLC
223
MAC
222
PHY
221

FIG. 2A

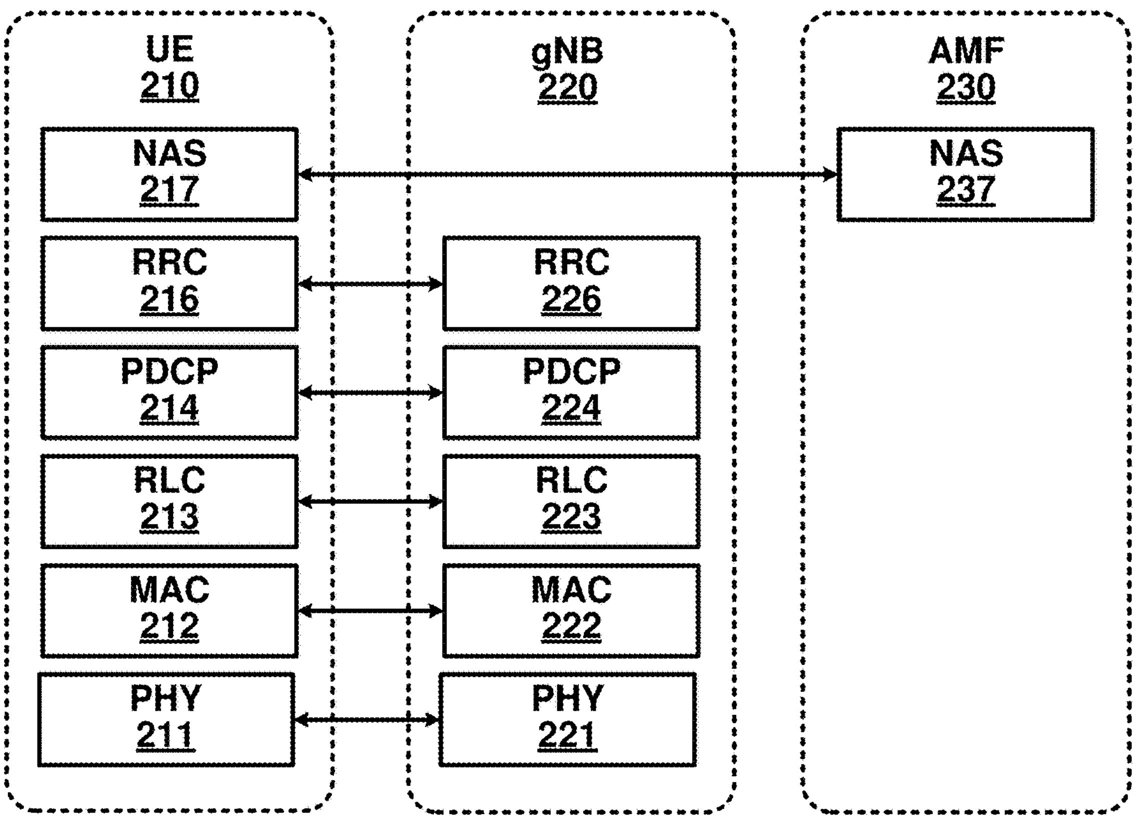

UE
210
NAS
217
RRC
216
PDCP
214
RLC
213
MAC
212
PHY
211
gNB
220
RRC
226
PDCP
224
RLC
223
MAC
222
PHY
221
AMF
230
NAS
237

FIG. 2B

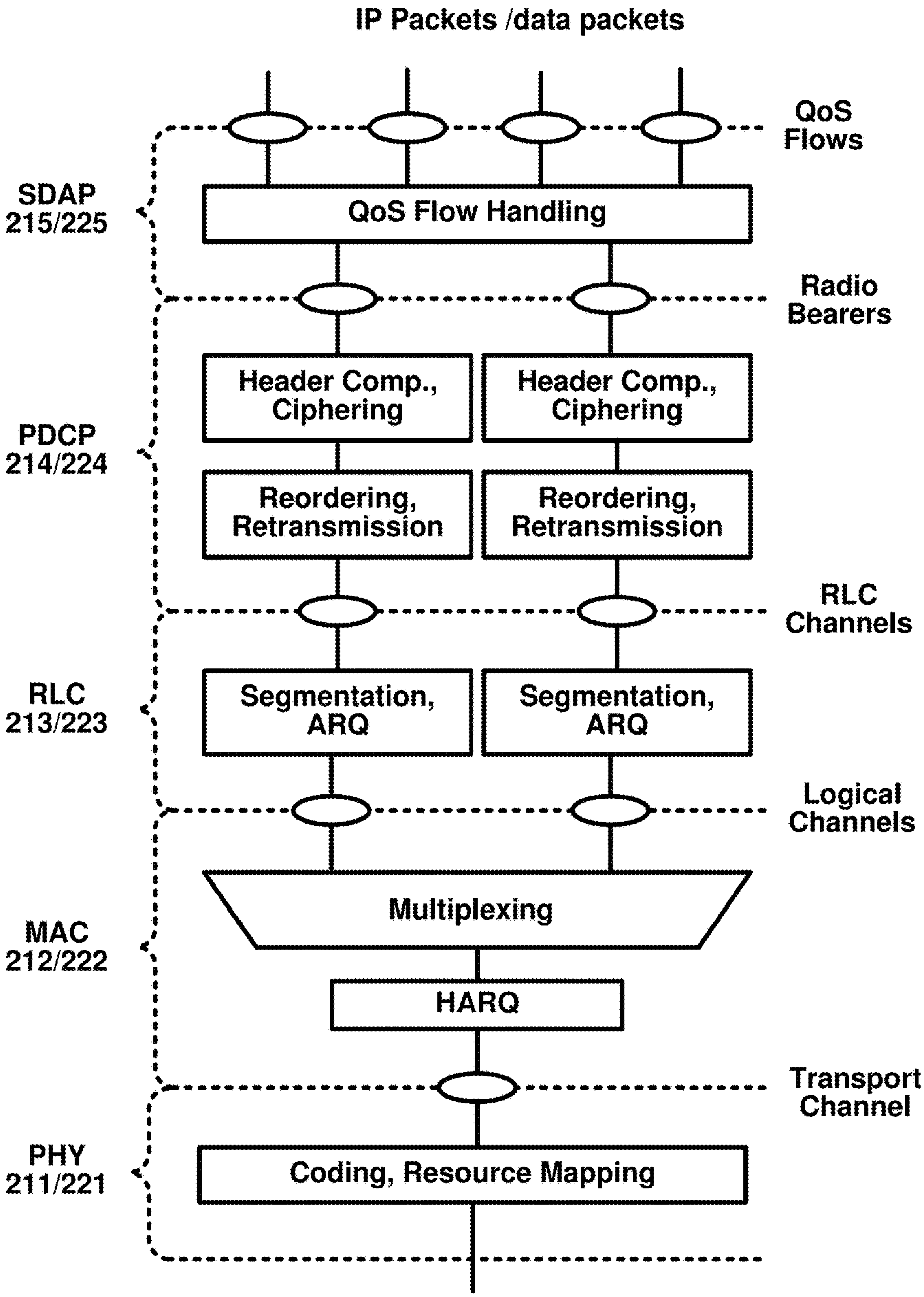

IP Packets /data packets
QoS Flows
SDAP 215/225
QoS Flow Handling
Radio Bearers
Header Comp., Ciphering
Header Comp., Ciphering
PDCP 214/224
Reordering, Retransmission
Reordering, Retransmission
RLC Channels
RLC 213/223
Segmentation, ARQ
Segmentation, ARQ
Logical Channels
Multiplexing
MAC 212/222
HARQ
Transport Channel
PHY 211/221
Coding, Resource Mapping

FIG. 3

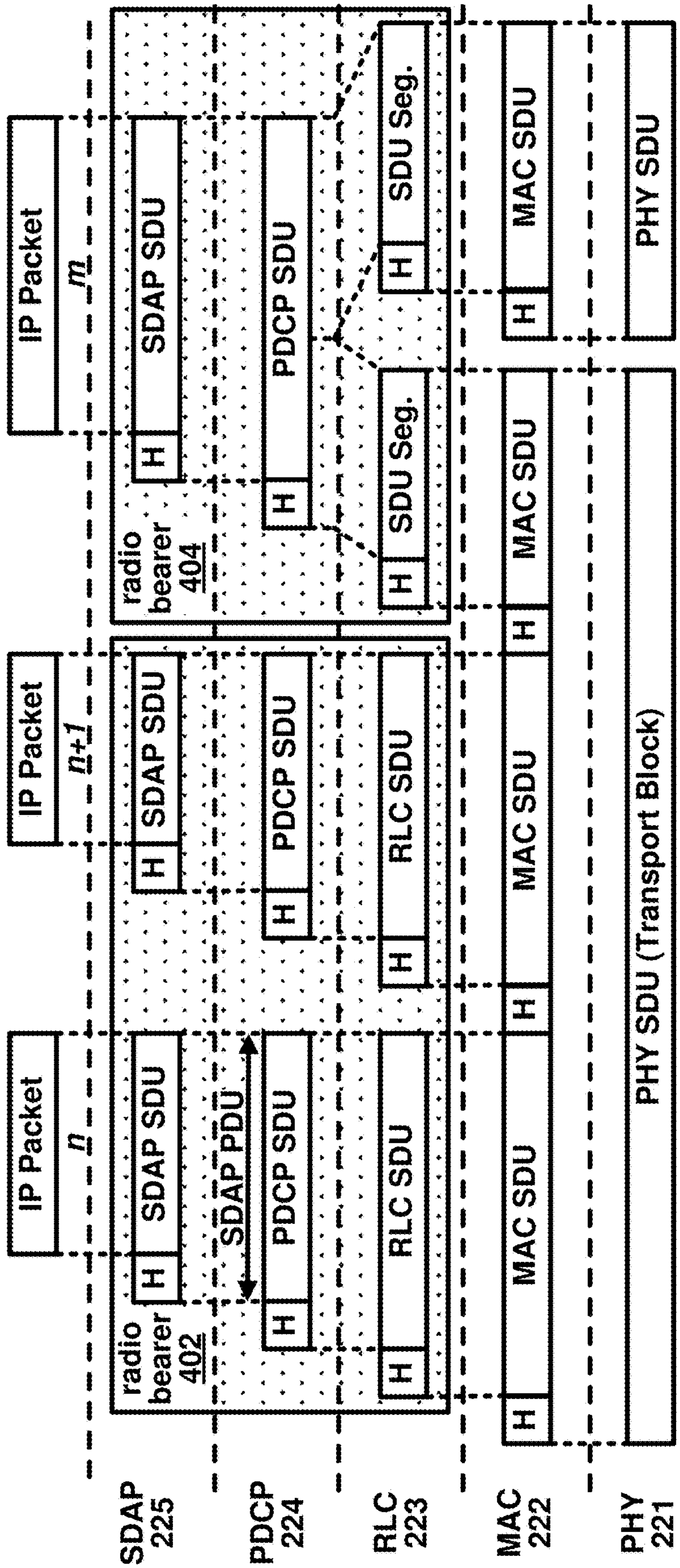

IP Packet n
IP Packet n+1
IP Packet m
SDAP 225
PDCP 224
RLC 223
MAC 222
PHY 221
radio bearer 402
radio bearer 404
H
SDAP SDU
SDAP PDU
PDCP SDU
RLC SDU
SDU Seg.
MAC SDU
PHY SDU (Transport Block)
PHY SDU

FIG. 4A

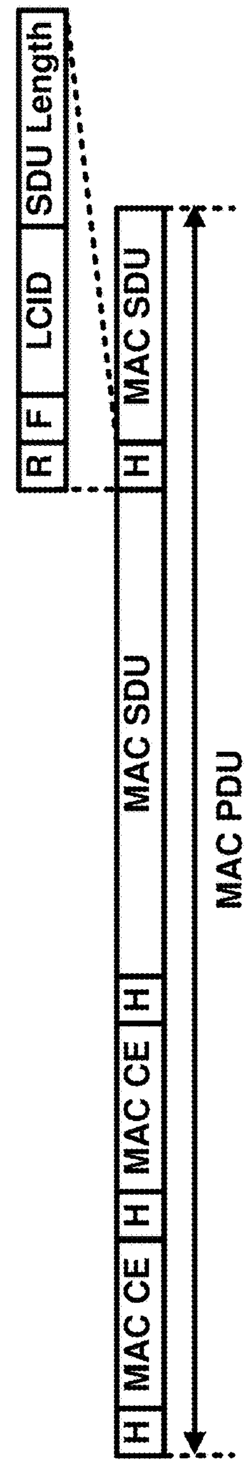

R
F
LCID
SDU Length
H
MAC CE
MAC SDU
MAC PDU

FIG. 4B

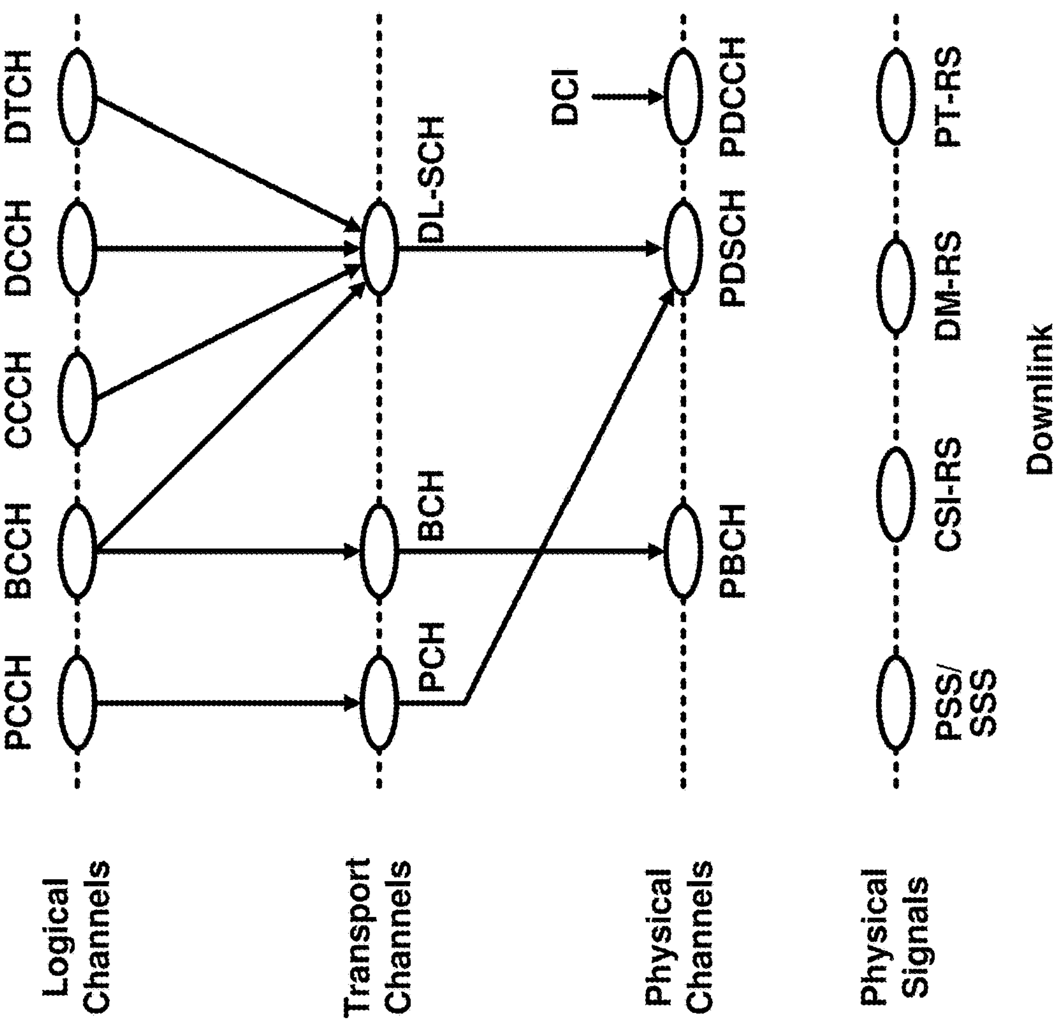

Logical Channels
Transport Channels
Physical Channels
Physical Signals
PCCH
BCCH
CCCH
DCCH
DTCH
PCH
BCH
DL-SCH
DCI
PBCH
PDSCH
PDCCH
PSS/SSS
CSI-RS
DM-RS
PT-RS
Downlink

FIG. 5A

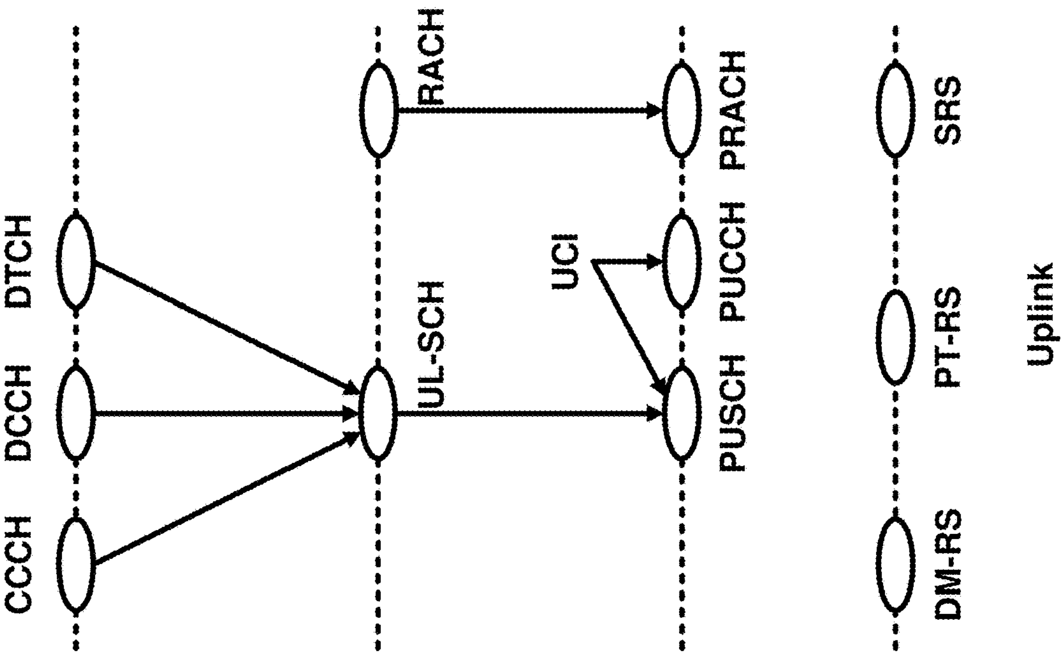

CCCH
DCCH
DTCH
UL-SCH
RACH
UCI
PUSCH
PUCCH
PRACH
DM-RS
PT-RS
SRS
Uplink

FIG. 5B

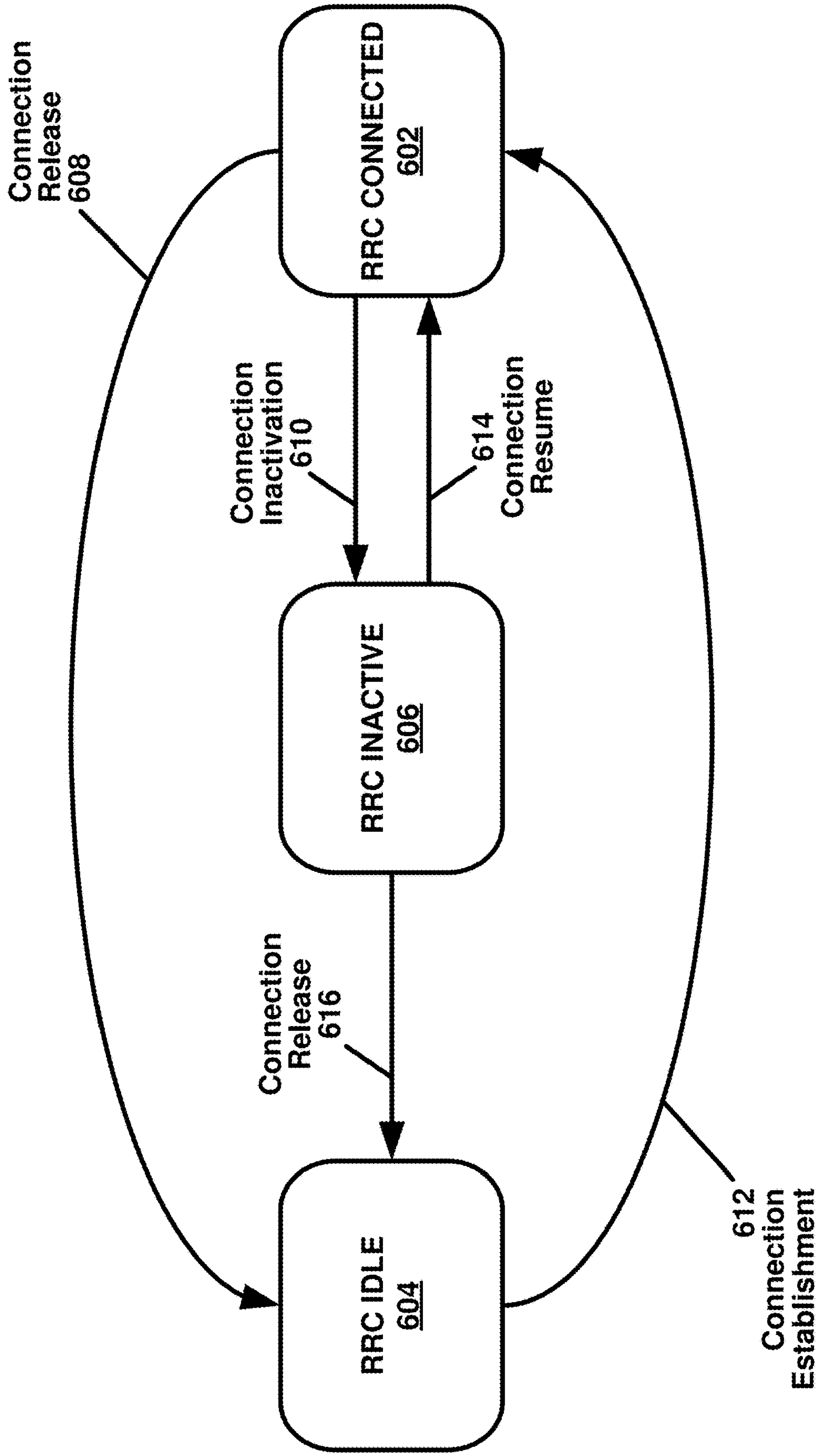

RRC CONNECTED
602
RRC INACTIVE
606
RRC IDLE
604
Connection
Release
608
Connection
Inactivation
610
614
Connection
Resume
Connection
Release
616
612
Connection
Establishment

FIG. 6

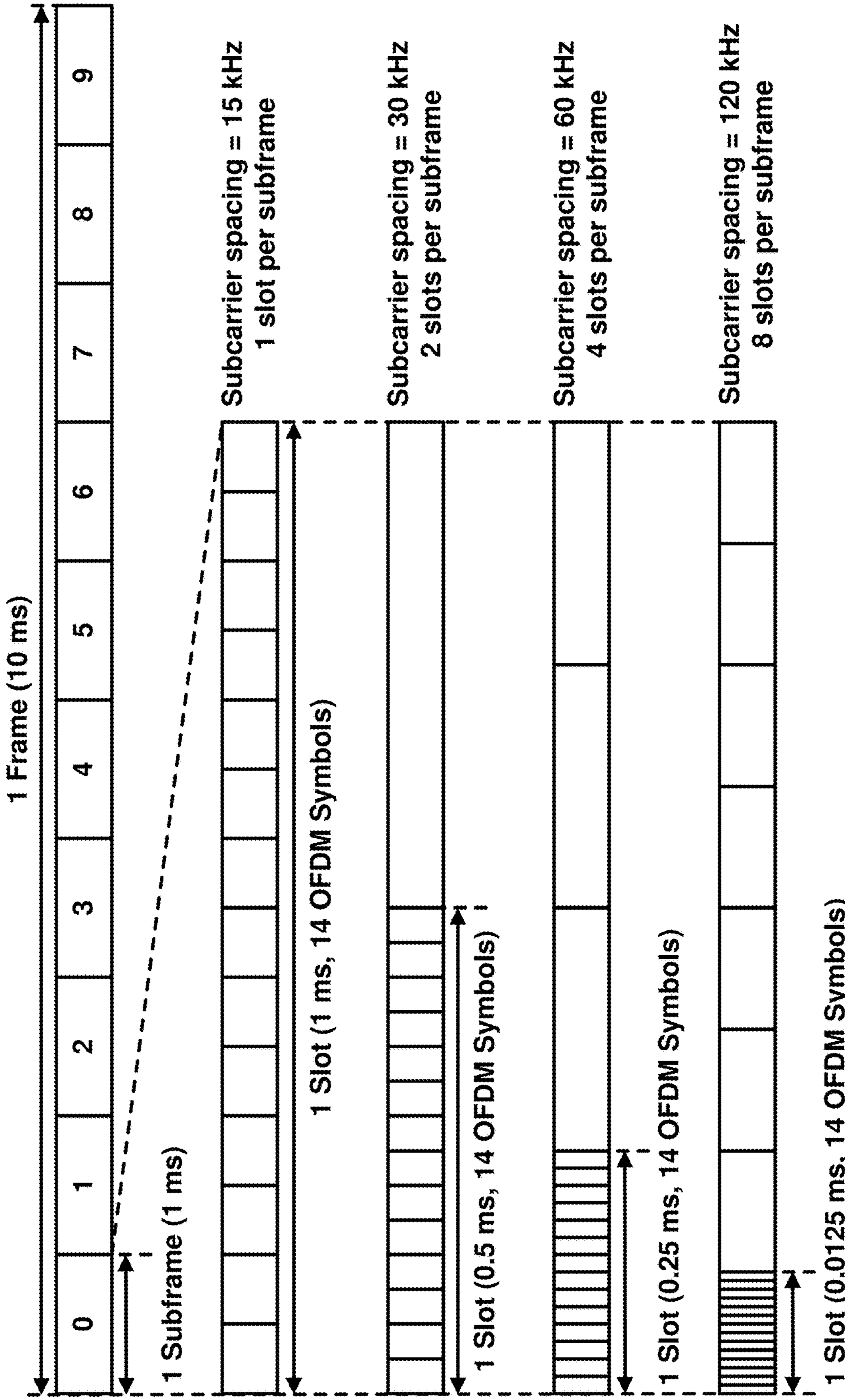

1 Frame (10 ms)
0
1
2
3
4
5
6
7
8
9
1 Subframe (1 ms)
Subcarrier spacing = 15 kHz
1 slot per subframe
1 Slot (1 ms, 14 OFDM Symbols)
Subcarrier spacing = 30 kHz
2 slots per subframe
1 Slot (0.5 ms, 14 OFDM Symbols)
Subcarrier spacing = 60 kHz
4 slots per subframe
1 Slot (0.25 ms, 14 OFDM Symbols)
Subcarrier spacing = 120 kHz
8 slots per subframe
1 Slot (0.0125 ms, 14 OFDM Symbols)

FIG. 7

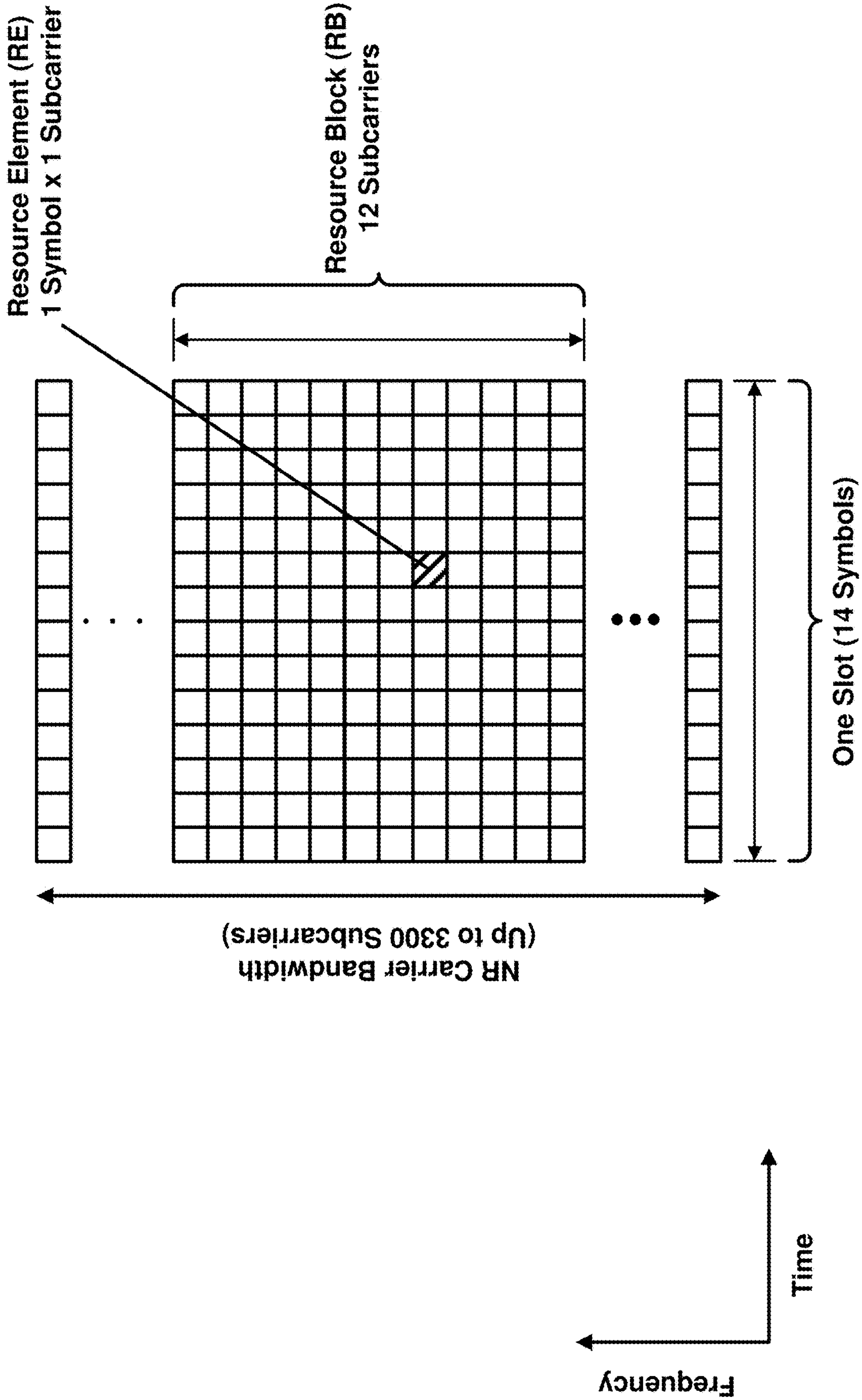

Resource Element (RE)
1 Symbol x 1 Subcarrier
Resource Block (RB)
12 Subcarriers
NR Carrier Bandwidth
(Up to 3300 Subcarriers)
One Slot (14 Symbols)
Time
Frequency

FIG. 8

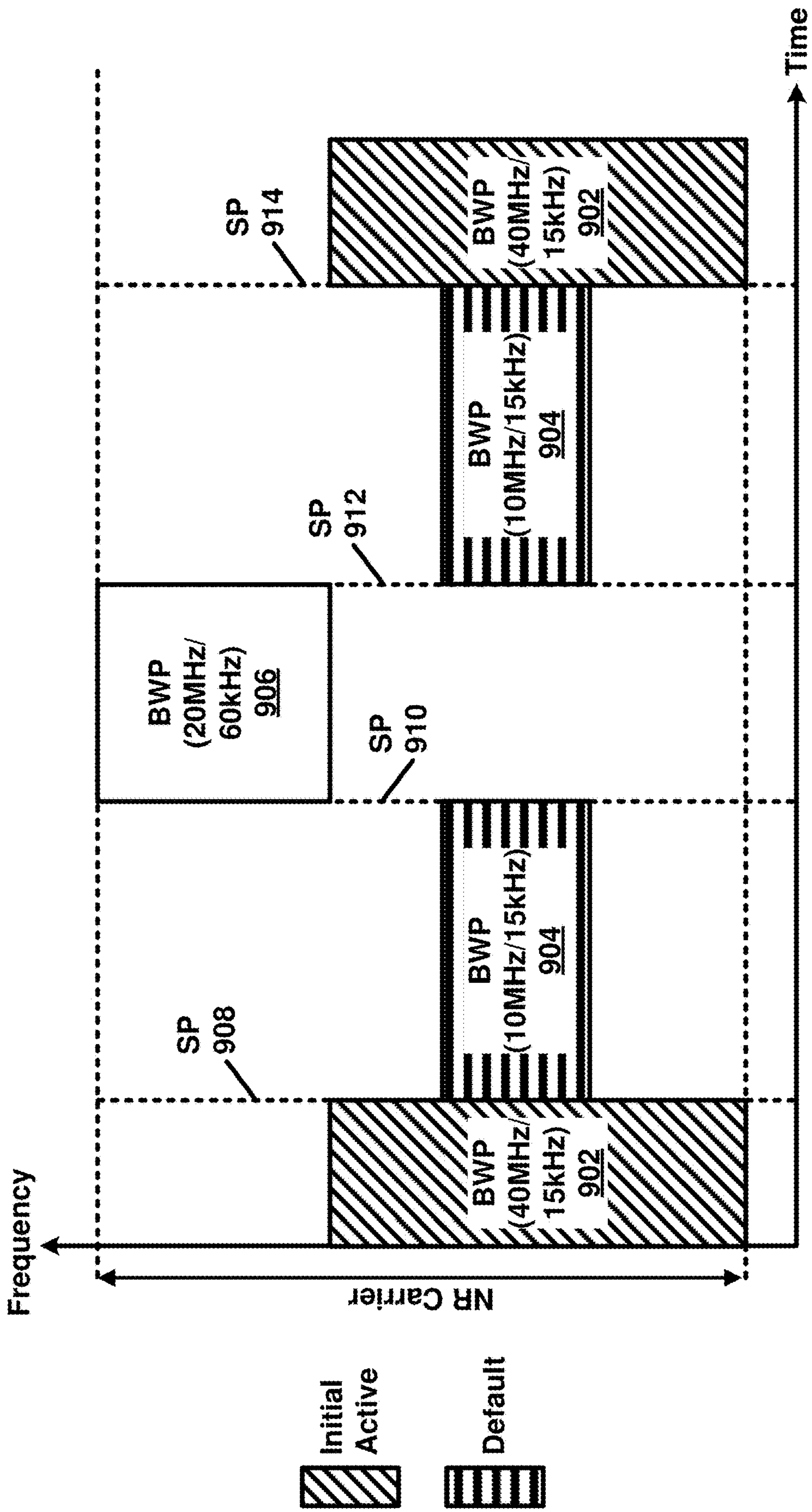

Time
SP 914
BWP (40MHz/ 15kHz) 902
SP 912
BWP (10MHz/15kHz) 904
BWP (20MHz/ 60kHz) 906
SP 910
BWP (10MHz/15kHz) 904
SP 908
BWP (40MHz/ 15kHz) 902
Frequency
NR Carrier
Initial Active
Default

FIG. 9

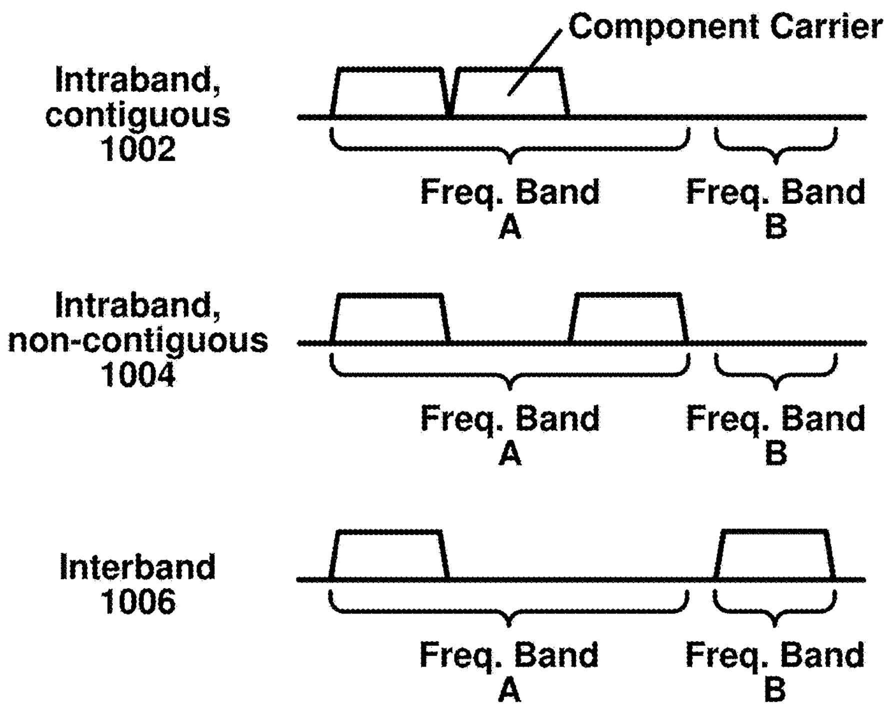


FIG. 10A

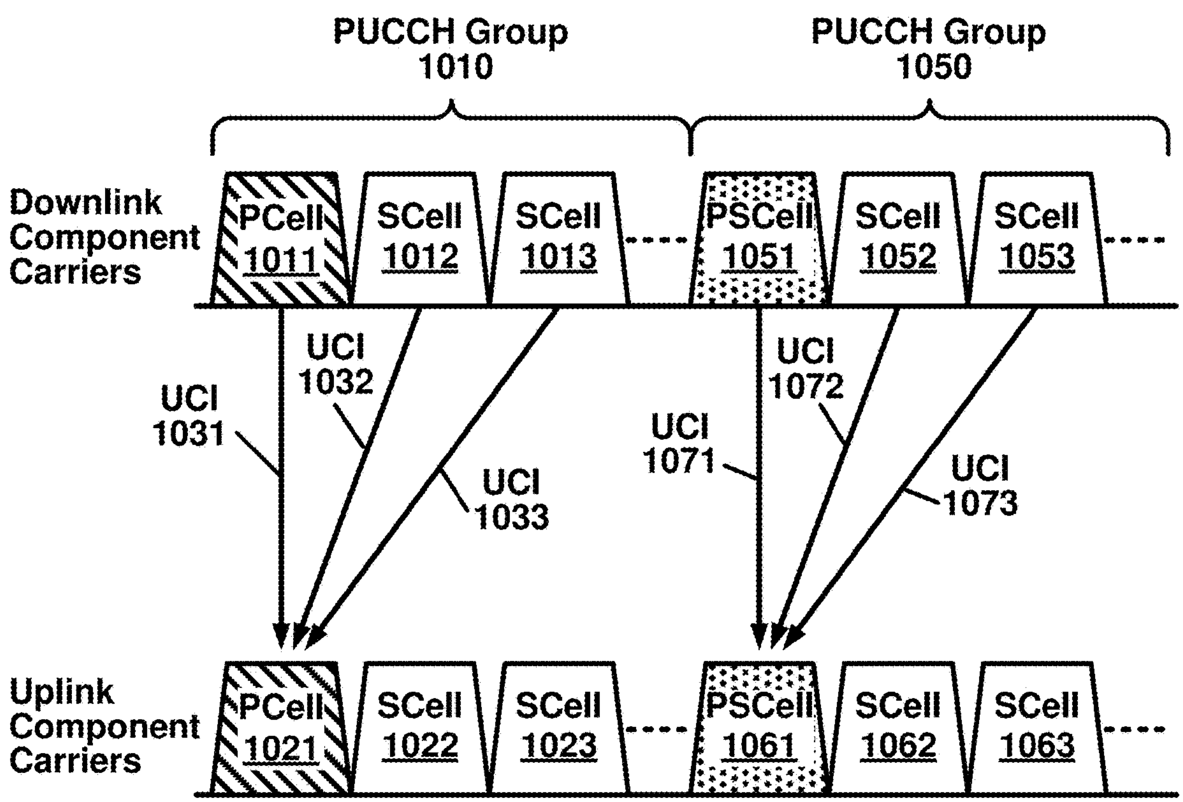


FIG. 10B

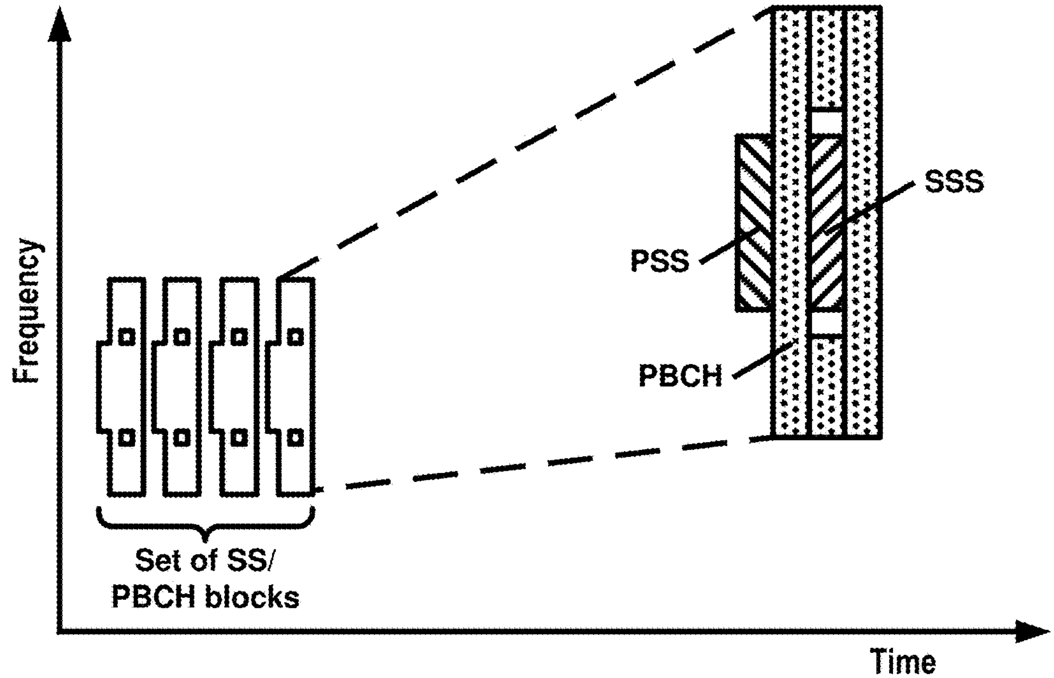


FIG. 11A

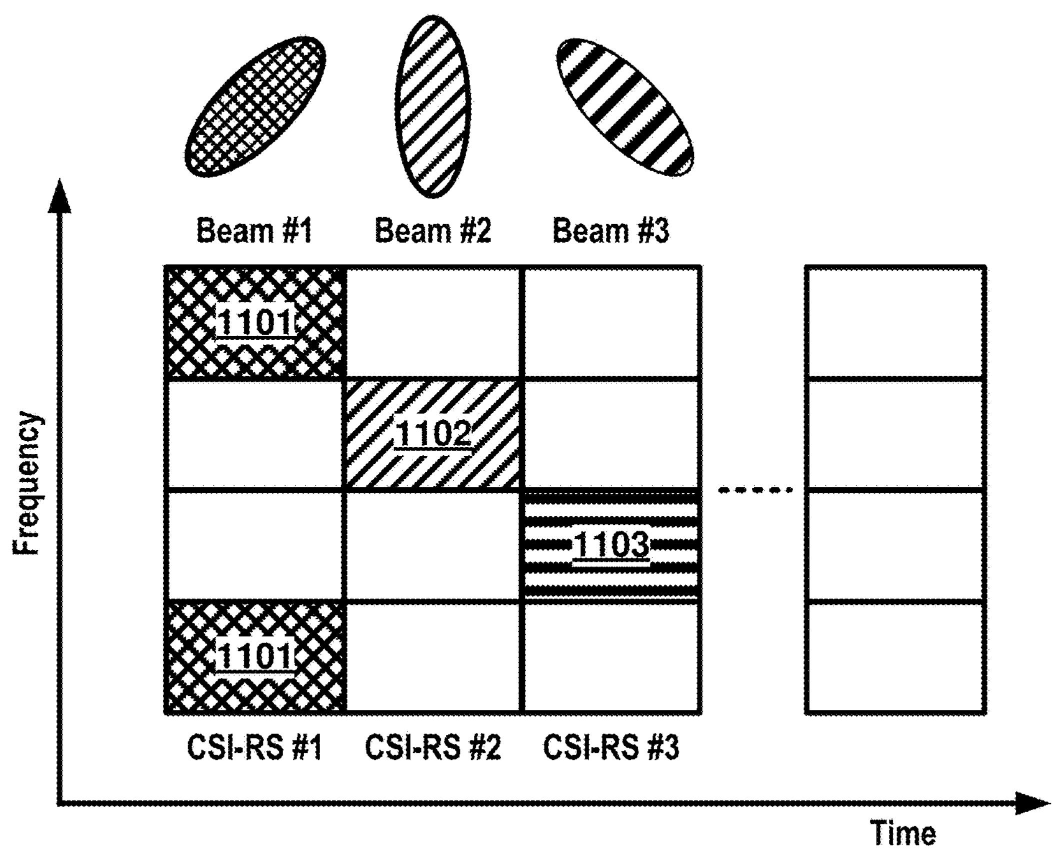


FIG. 11B

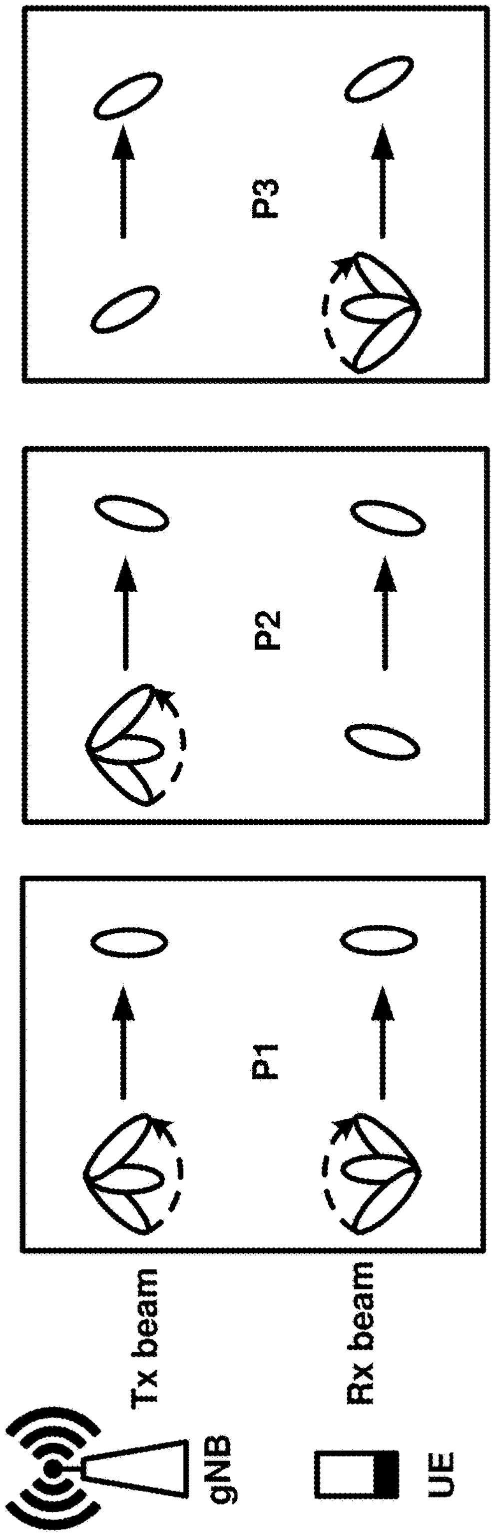


FIG. 12A

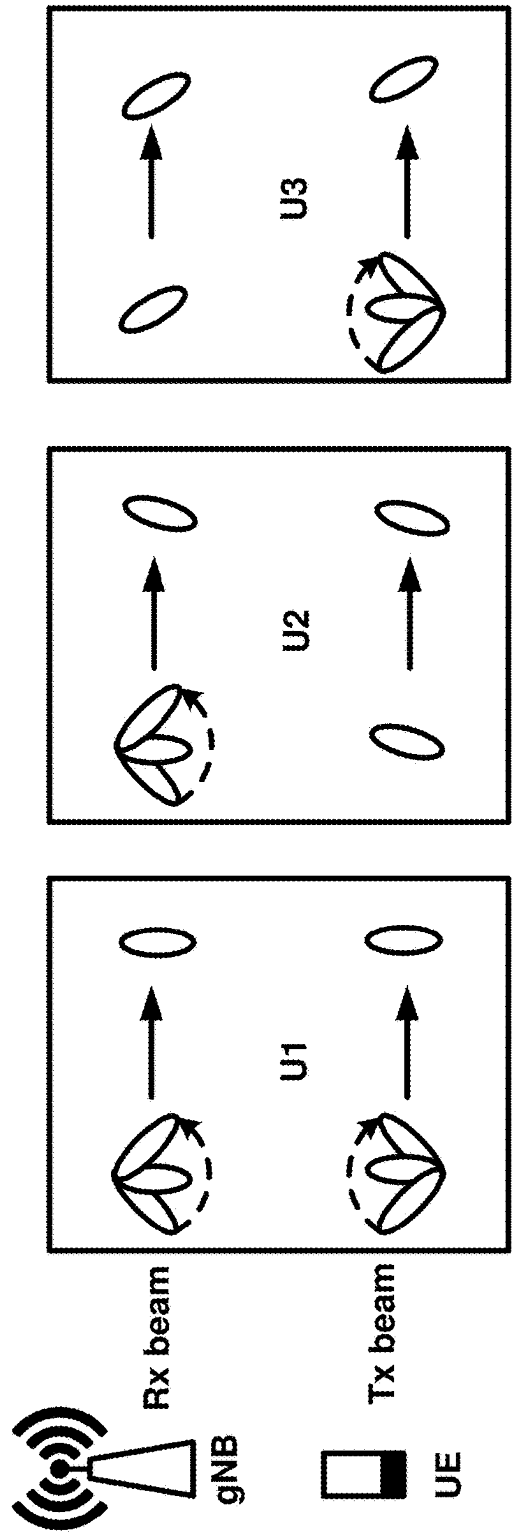


FIG. 12B

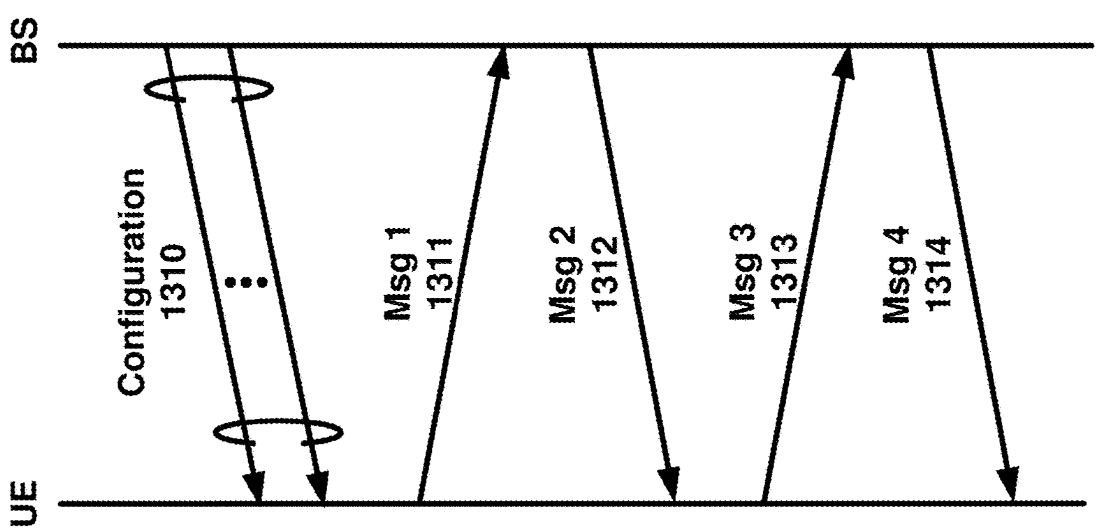


FIG. 13A

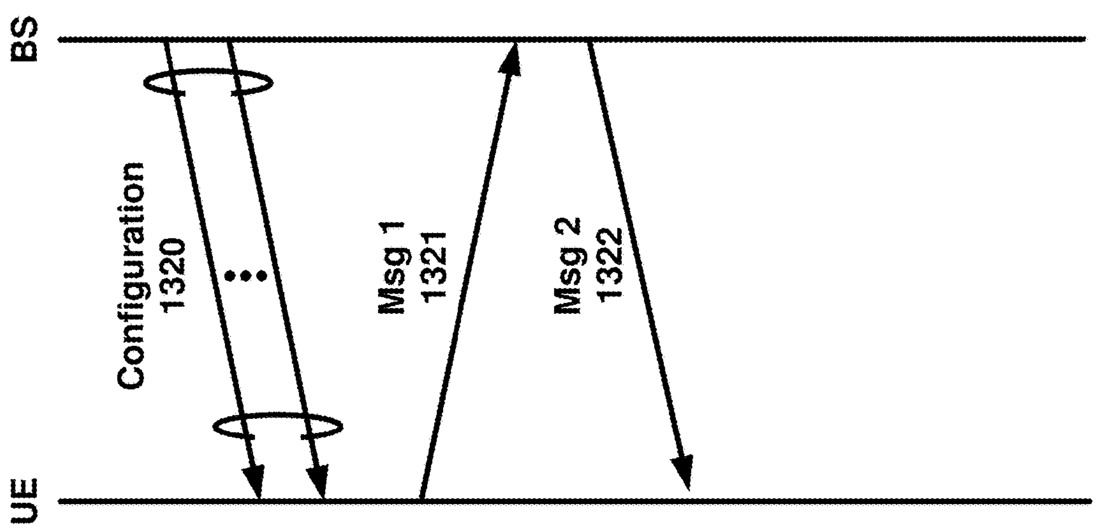


FIG. 13B

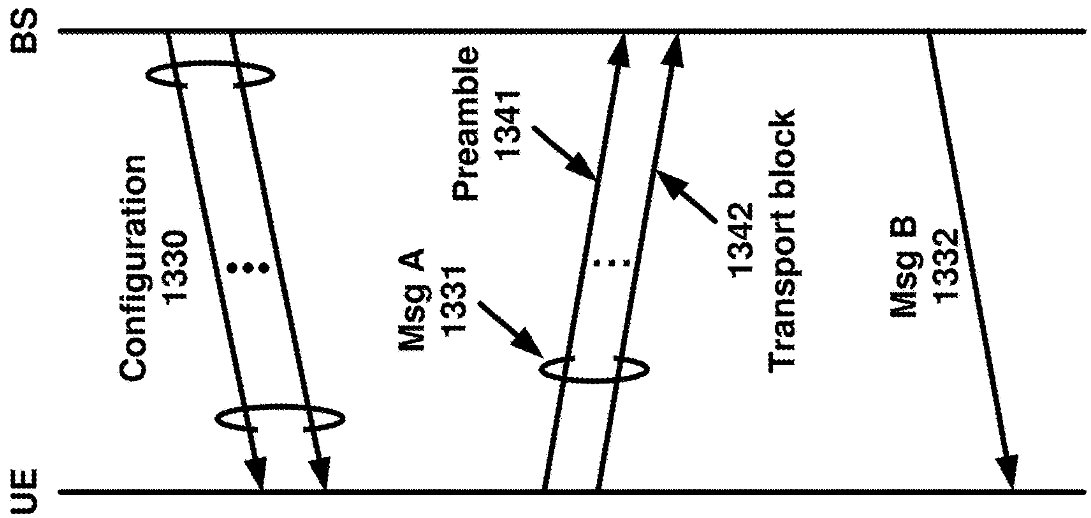


FIG. 13C

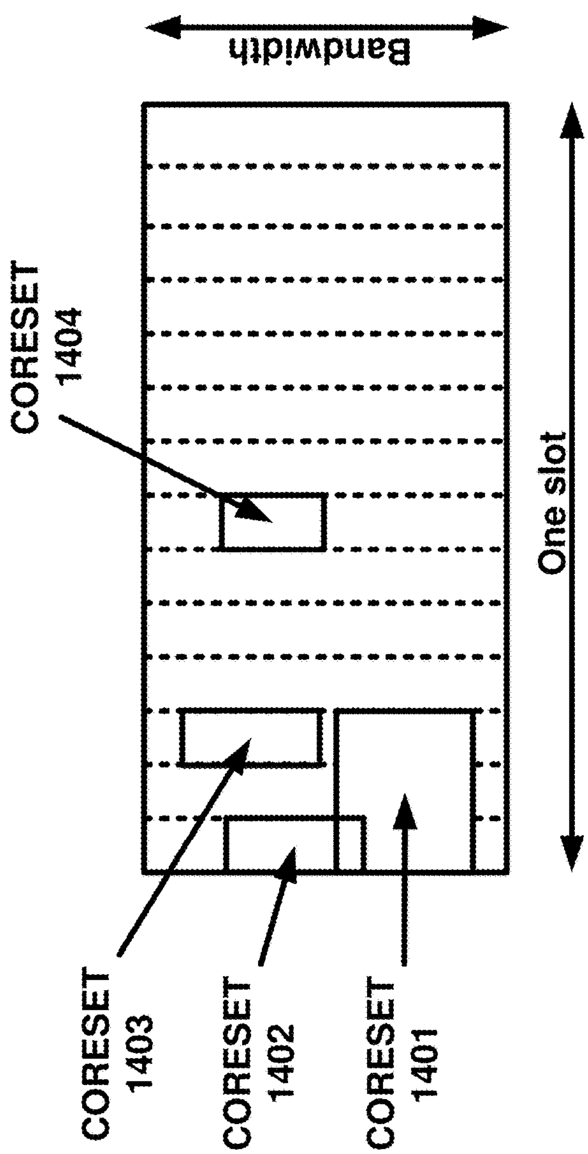


FIG. 14A

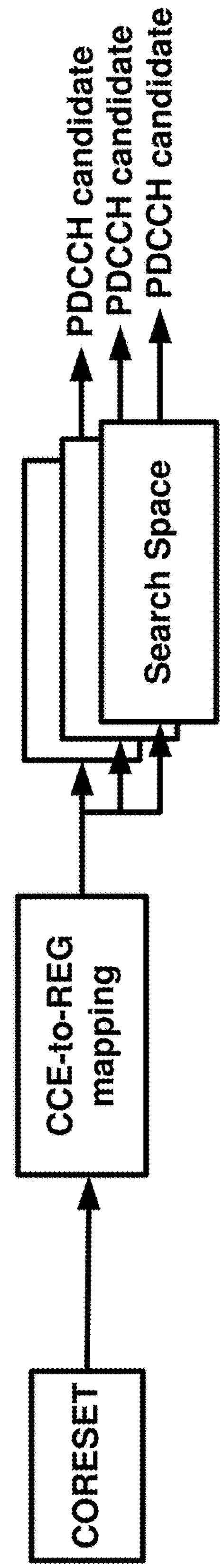
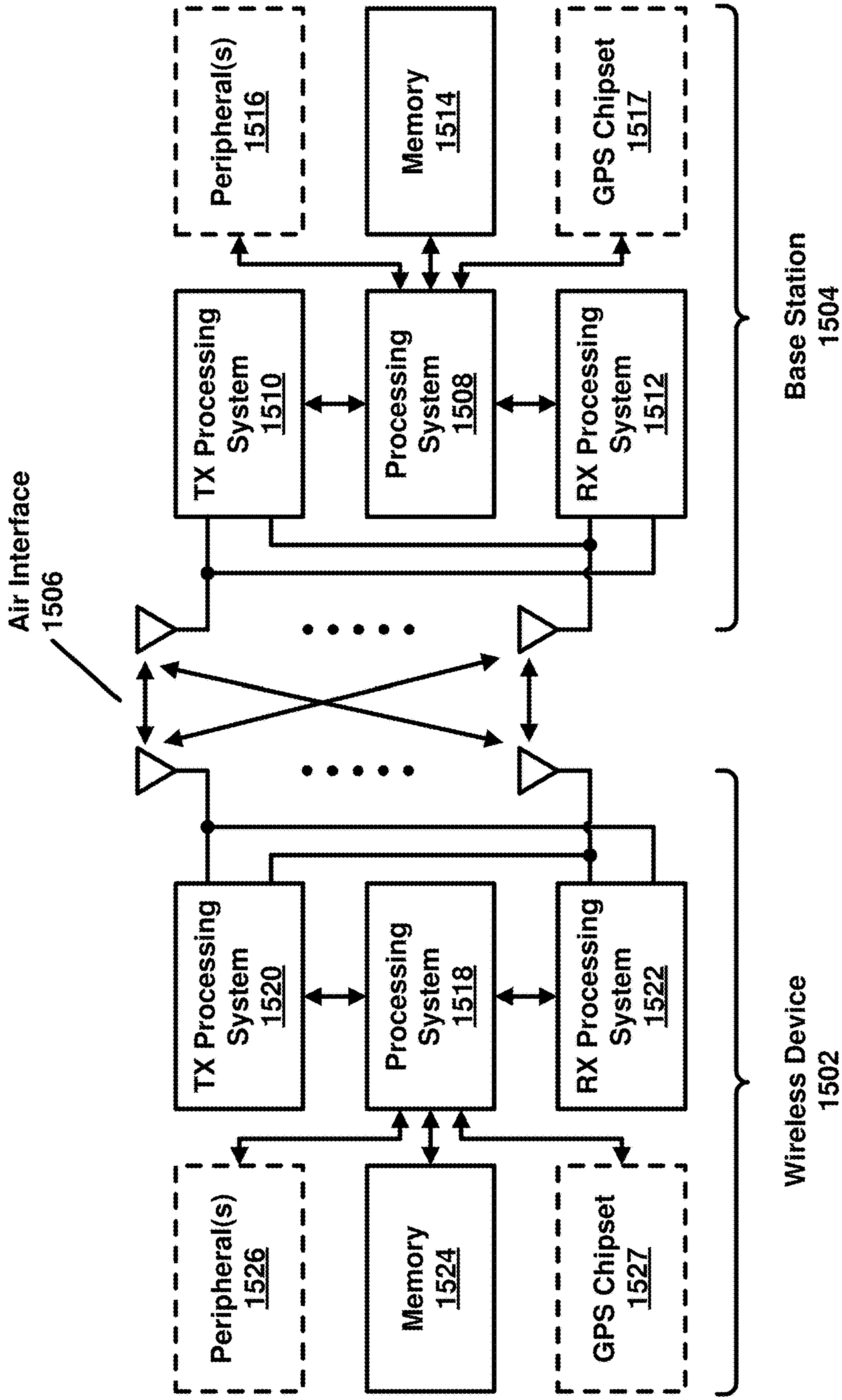


FIG. 14B



Peripheral(s) 1516
Memory 1514
GPS Chipset 1517
TX Processing System 1510
Processing System 1508
RX Processing System 1512
Base Station 1504
Air Interface 1506
TX Processing System 1520
Processing System 1518
RX Processing System 1522
Wireless Device 1502
Peripheral(s) 1526
Memory 1524
GPS Chipset 1527

FIG. 15

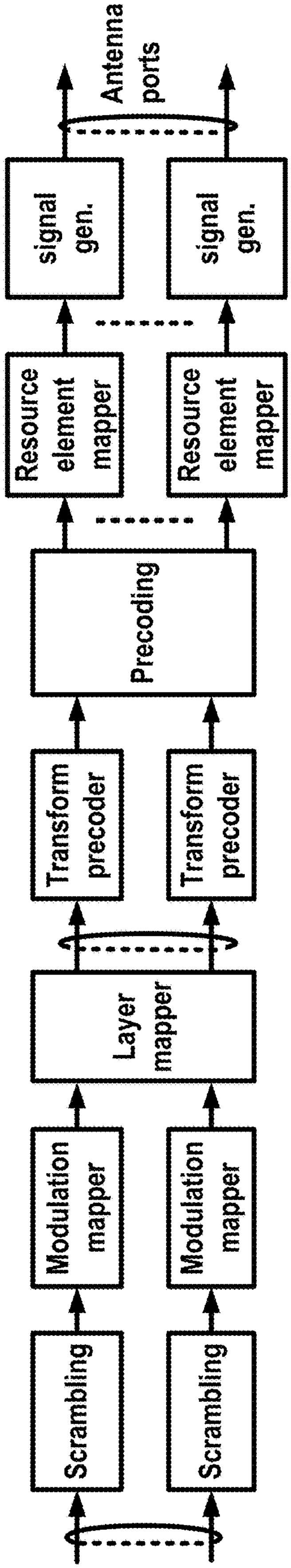


FIG. 16A

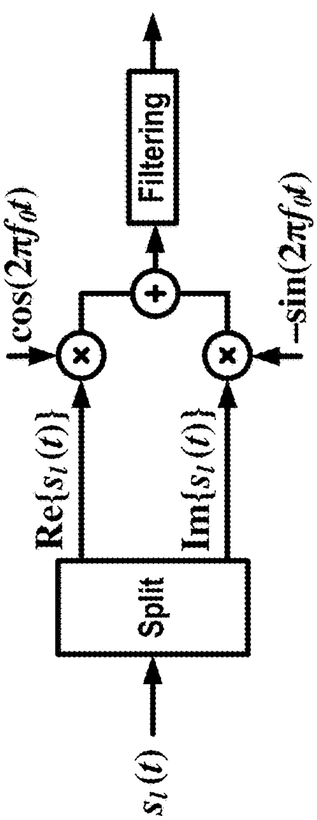


FIG. 16B

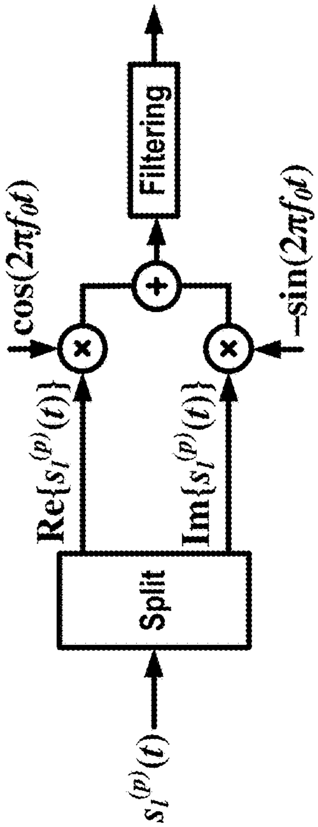


FIG. 16D

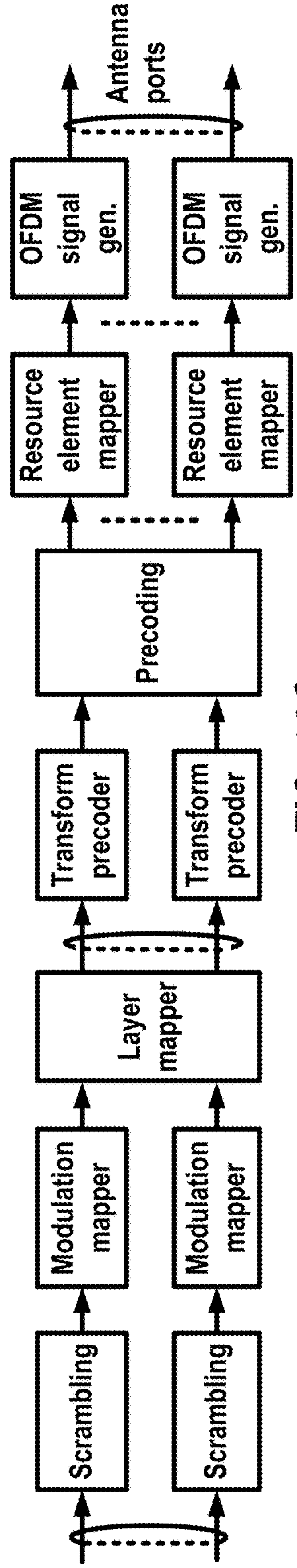


FIG. 16C

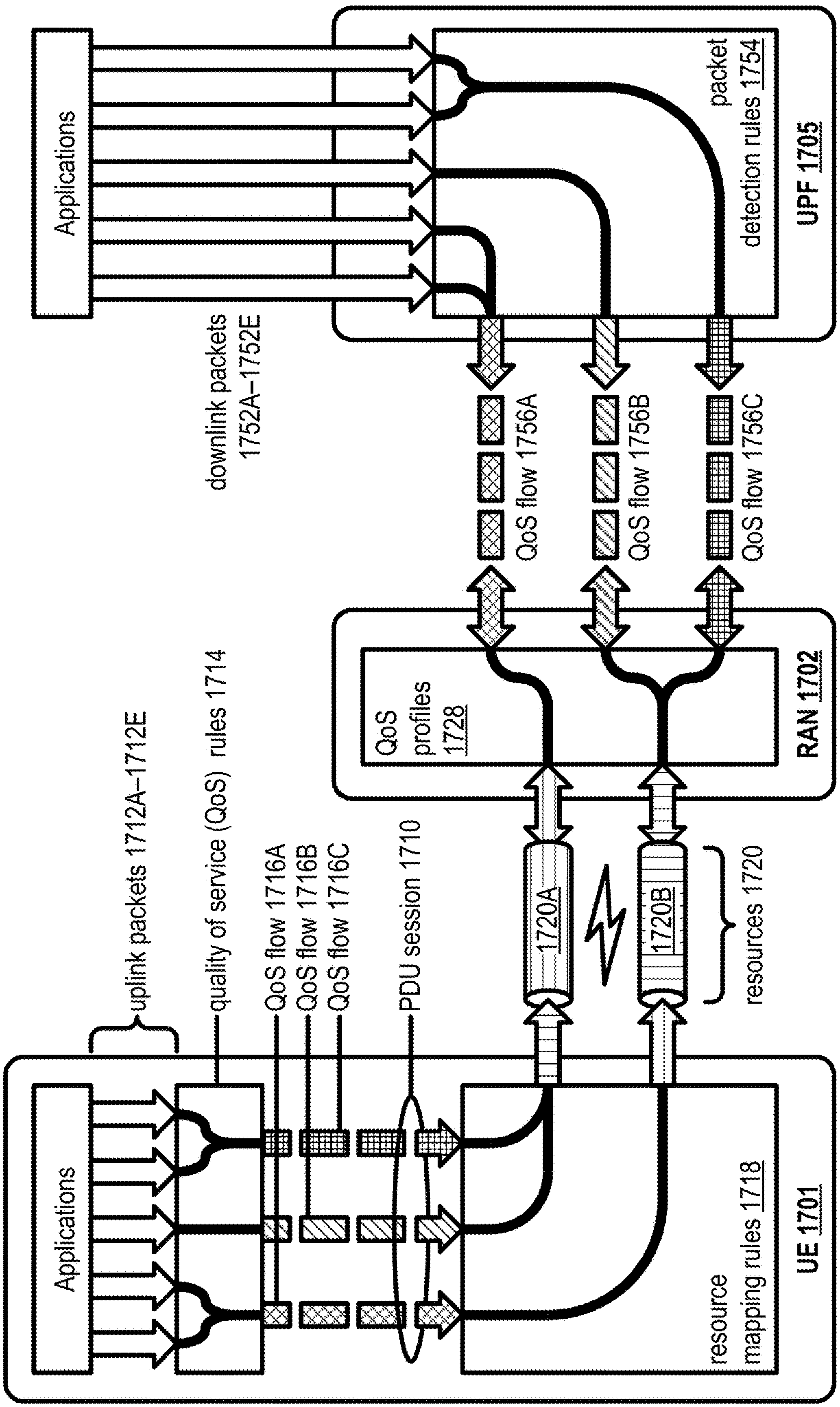

Applications
packet detection rules 1754
UPF 1705
downlink packets 1752A–1752E
QoS flow 1756A
QoS flow 1756B
QoS flow 1756C
QoS profiles 1728
RAN 1702
uplink packets 1712A–1712E
quality of service (QoS) rules 1714
QoS flow 1716A
QoS flow 1716B
QoS flow 1716C
PDU session 1710
1720A
1720B
resources 1720
Applications
resource mapping rules 1718
UE 1701

FIG. 17

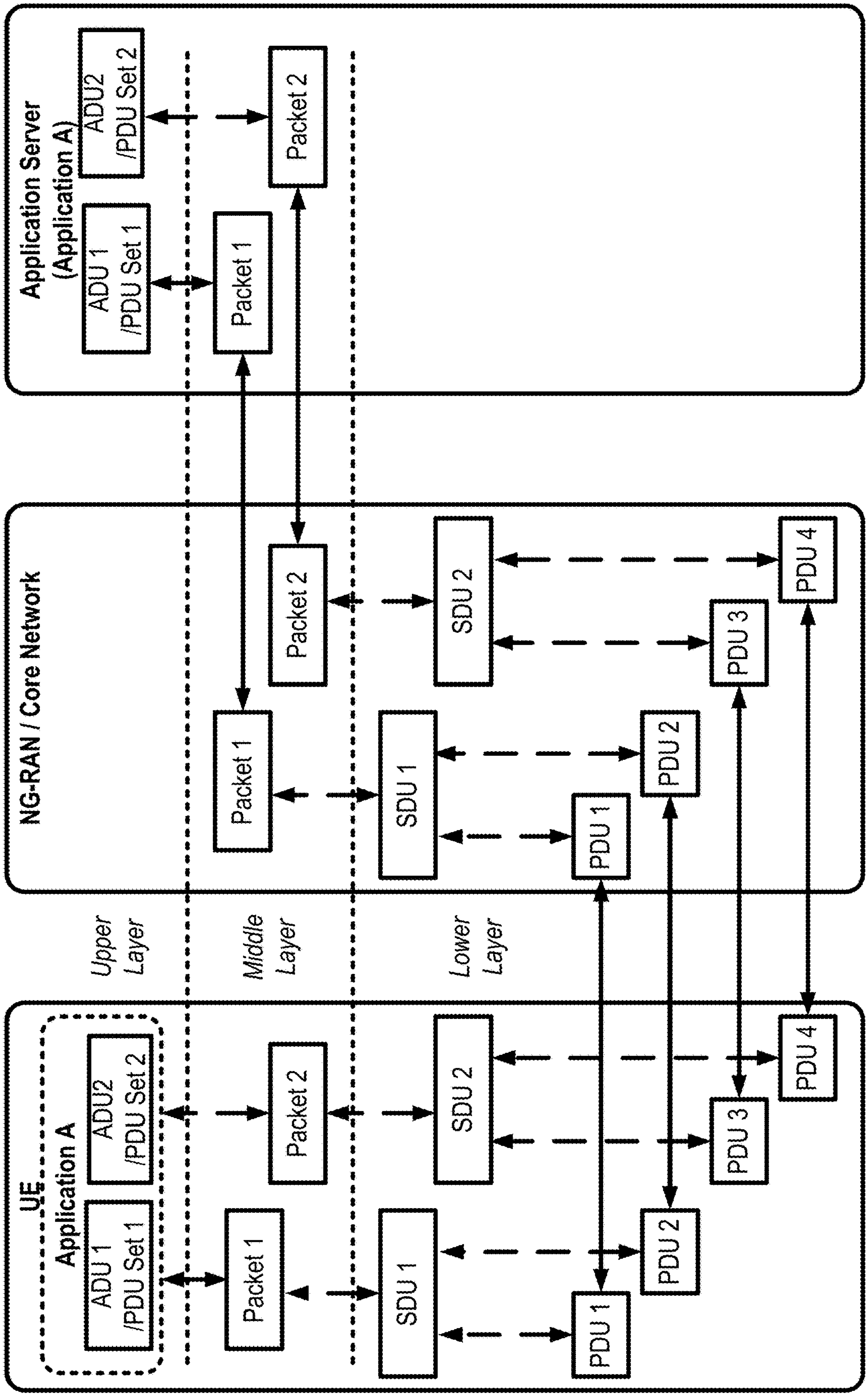

UE
Application A
ADU 1 /PDU Set 1
ADU2 /PDU Set 2
Packet 1
Packet 2
SDU 1
SDU 2
PDU 1
PDU 2
PDU 3
PDU 4
Upper Layer
Middle Layer
Lower Layer
NG-RAN / Core Network
Packet 1
Packet 2
SDU 1
SDU 2
PDU 1
PDU 2
PDU 3
PDU 4
Application Server (Application A)
ADU 1 /PDU Set 1
ADU2 /PDU Set 2
Packet 1
Packet 2

FIG. 18

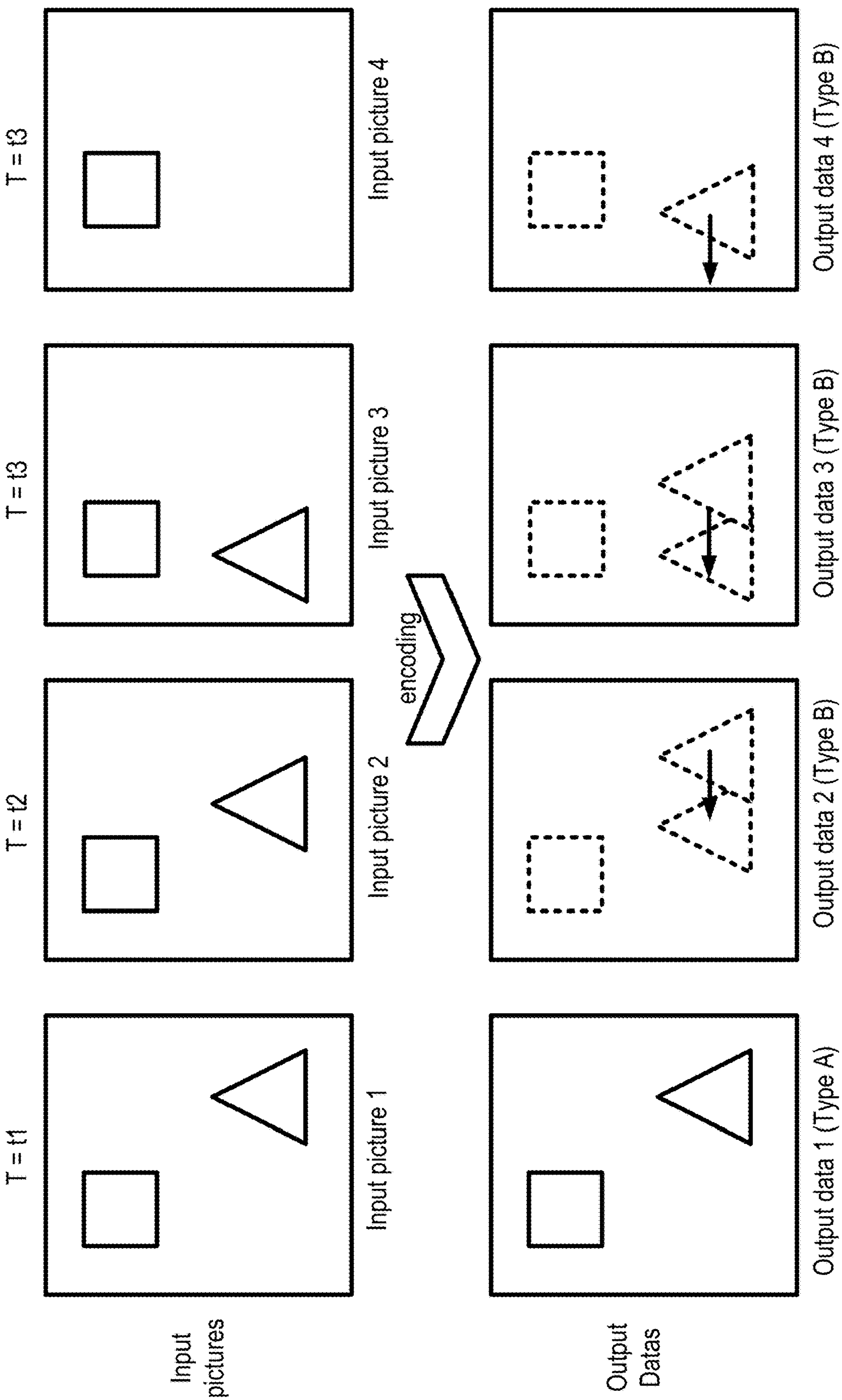

Input pictures
T = t1
T = t2
T = t3
T = t3
Input picture 1
Input picture 2
Input picture 3
Input picture 4
encoding
Output Datas
Output data 1 (Type A)
Output data 2 (Type B)
Output data 3 (Type B)
Output data 4 (Type B)

FIG. 19

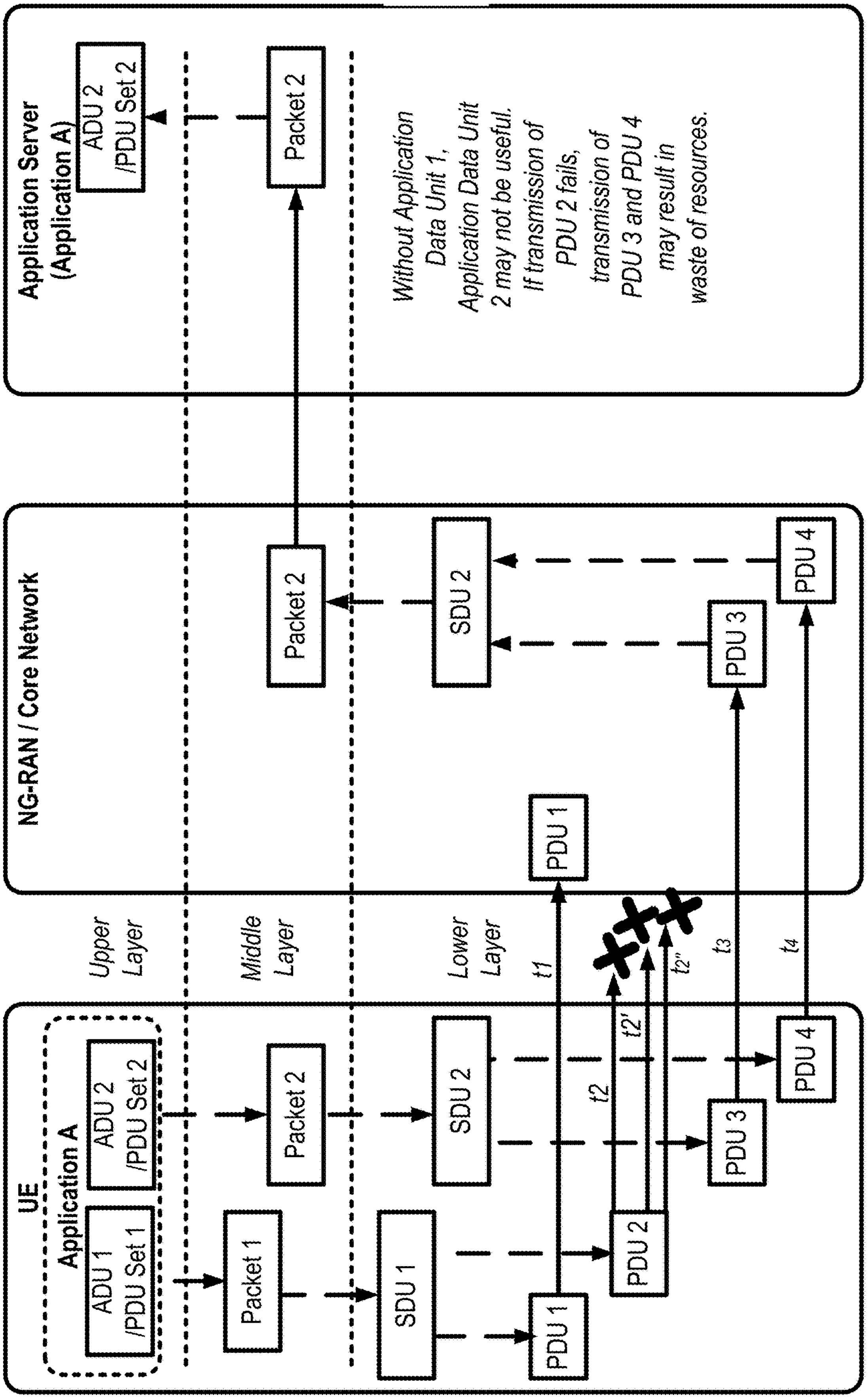

UE
Application A
ADU 1 /PDU Set 1
ADU 2 /PDU Set 2
Packet 1
Packet 2
SDU 1
SDU 2
PDU 1
PDU 2
PDU 3
PDU 4
Upper Layer
Middle Layer
Lower Layer
t1
t2
t2'
t2''
t3
t4
NG-RAN / Core Network
PDU 1
PDU 3
PDU 4
SDU 2
Packet 2
Application Server (Application A)
ADU 2 /PDU Set 2
Packet 2
Without Application Data Unit 1, Application Data Unit 2 may not be useful. If transmission of PDU 2 fails, transmission of PDU 3 and PDU 4 may result in waste of resources.

FIG. 20

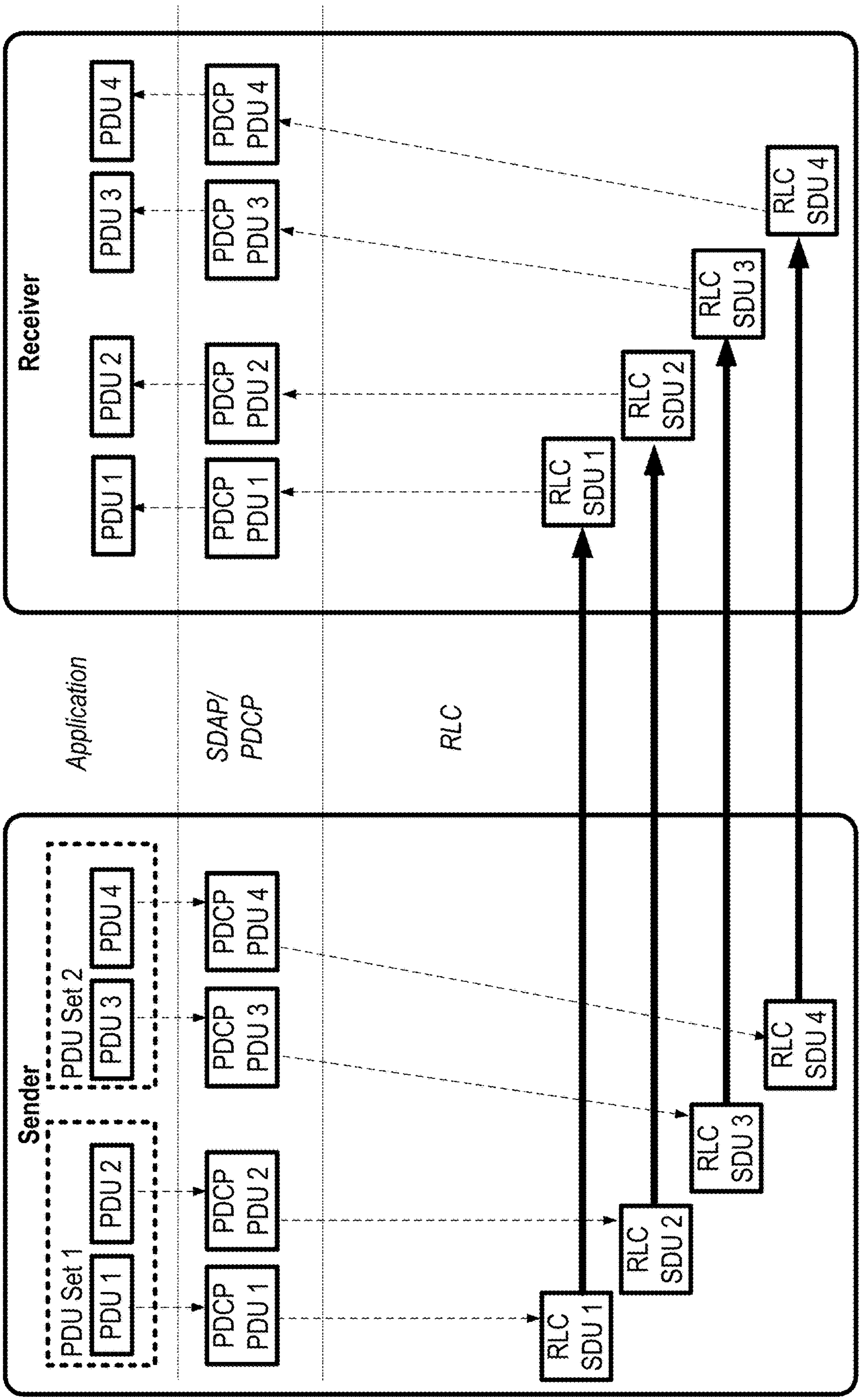

Sender
PDU Set 1
PDU 1
PDU 2
PDU Set 2
PDU 3
PDU 4
PDCP PDU 1
PDCP PDU 2
PDCP PDU 3
PDCP PDU 4
RLC SDU 1
RLC SDU 2
RLC SDU 3
RLC SDU 4
Application
SDAP/ PDCP
RLC
Receiver
PDU 1
PDU 2
PDU 3
PDU 4
PDCP PDU 1
PDCP PDU 2
PDCP PDU 3
PDCP PDU 4
RLC SDU 1
RLC SDU 2
RLC SDU 3
RLC SDU 4

FIG. 21

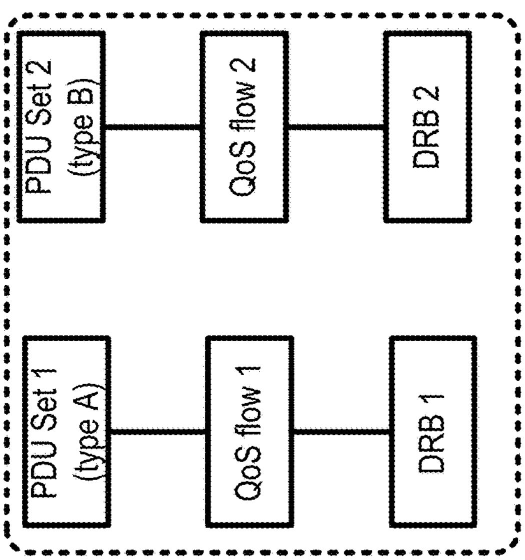


FIG. 22A

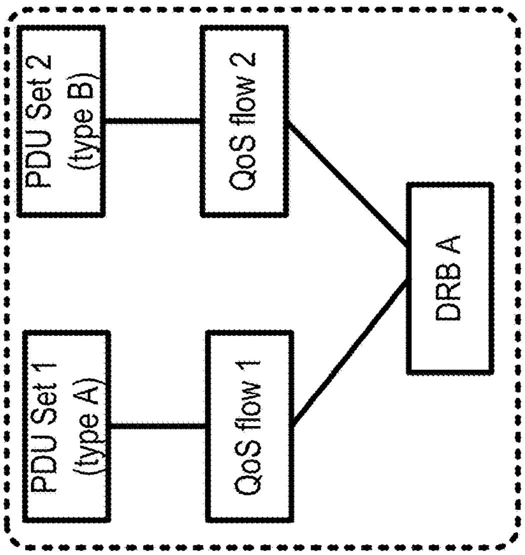


FIG. 22B

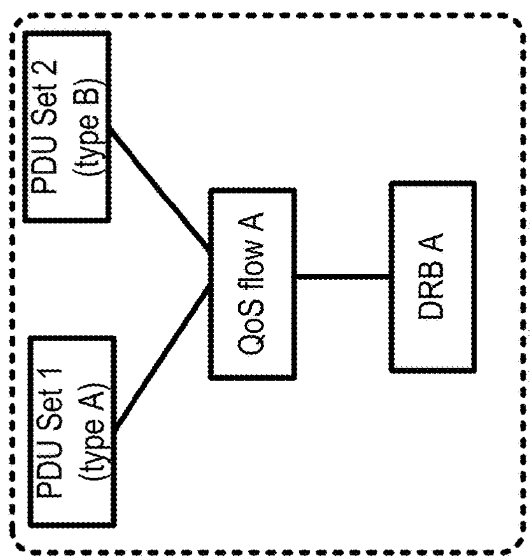


FIG. 22C

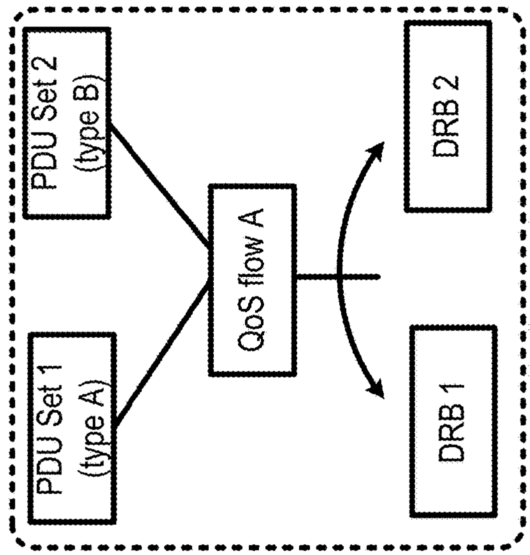


FIG. 22D

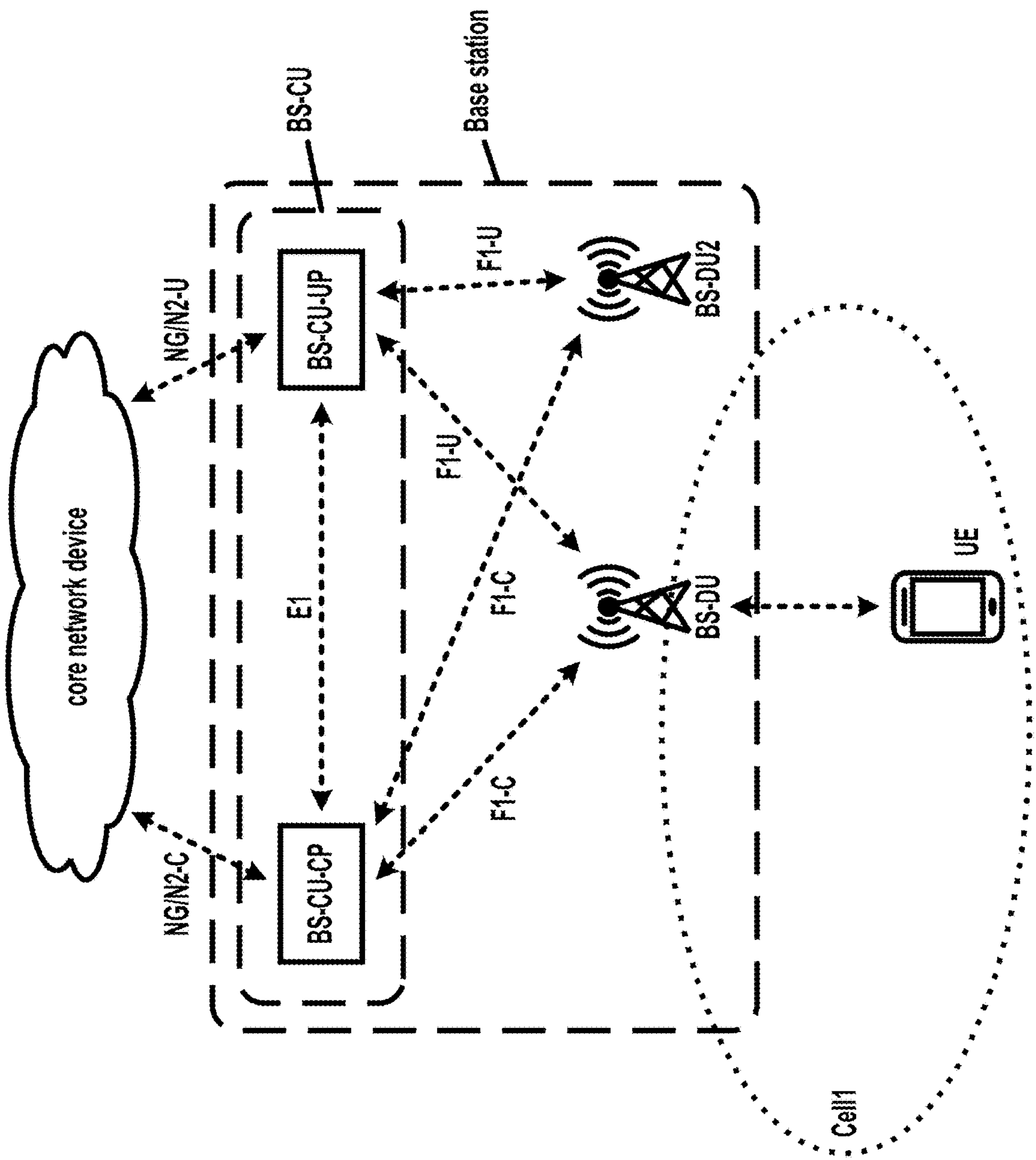

core network device
NG/N2-U
NG/N2-C
BS-CU
Base station
BS-CU-UP
BS-CU-CP
E1
F1-U
F1-U
F1-C
F1-C
BS-DU2
BS-DU
UE
Cell1

FIG. 23

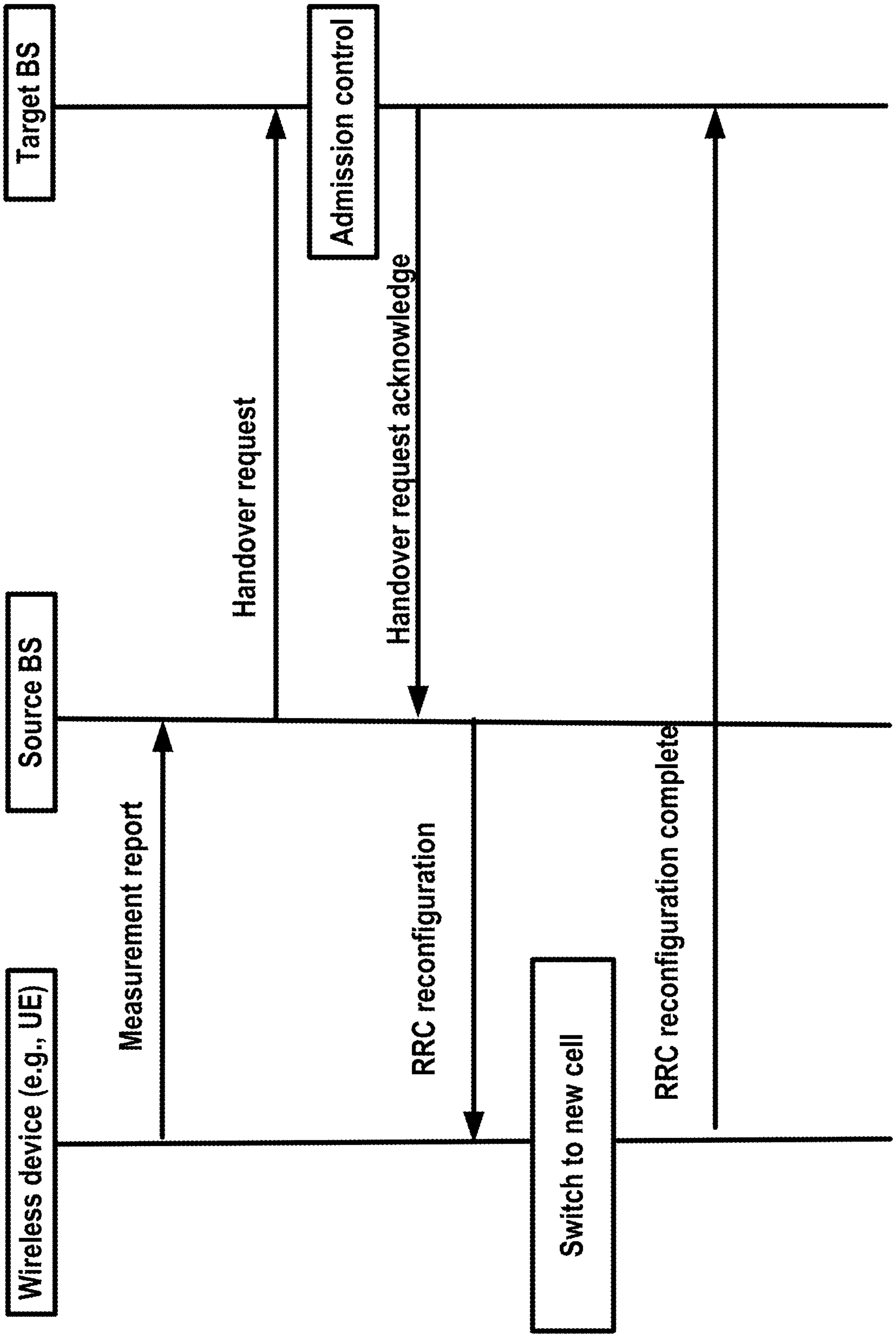

Wireless device (e.g., UE)
Source BS
Target BS
Measurement report
Handover request
Admission control
Handover request acknowledge
RRC reconfiguration
Switch to new cell
RRC reconfiguration complete

FIG. 24

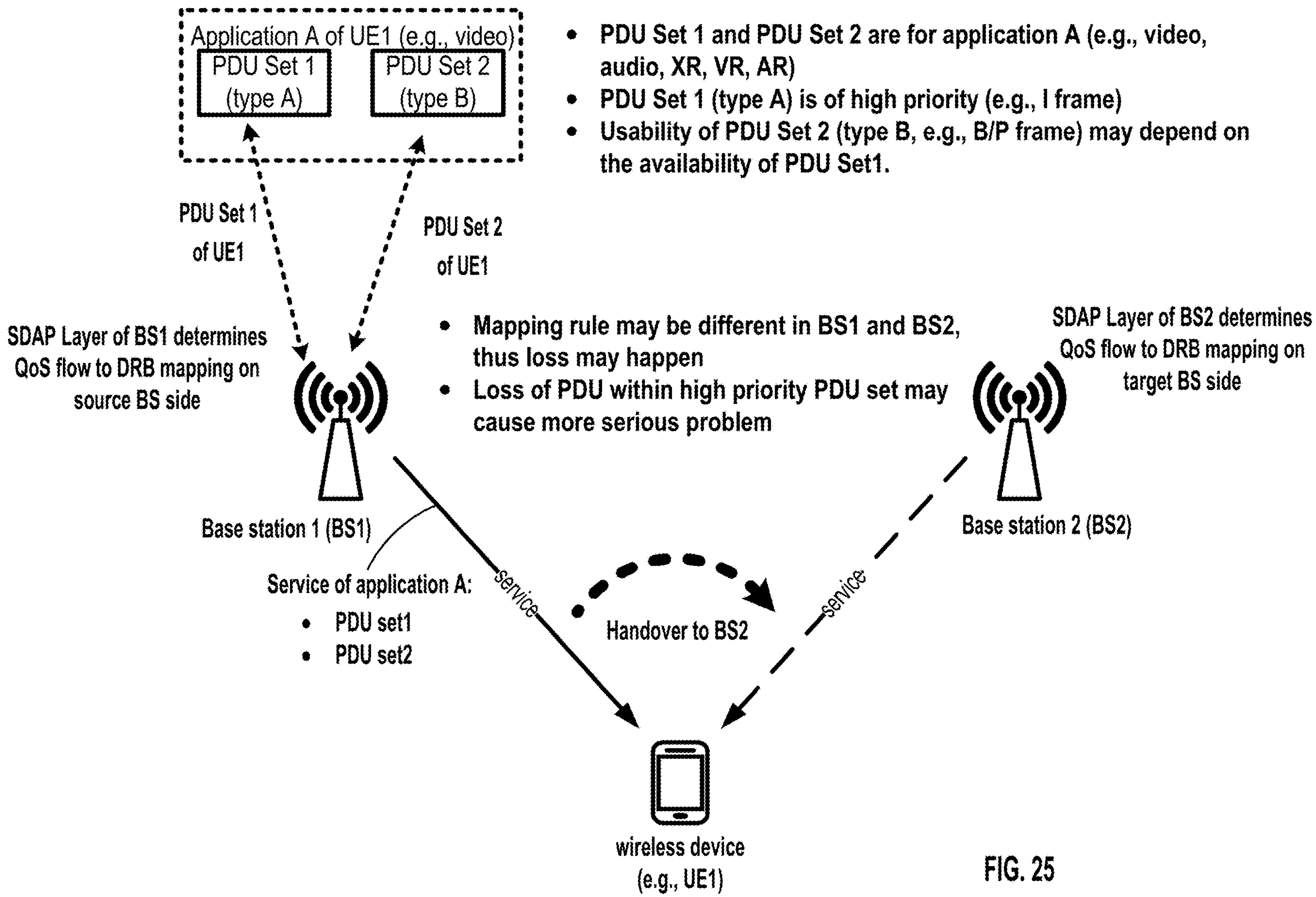
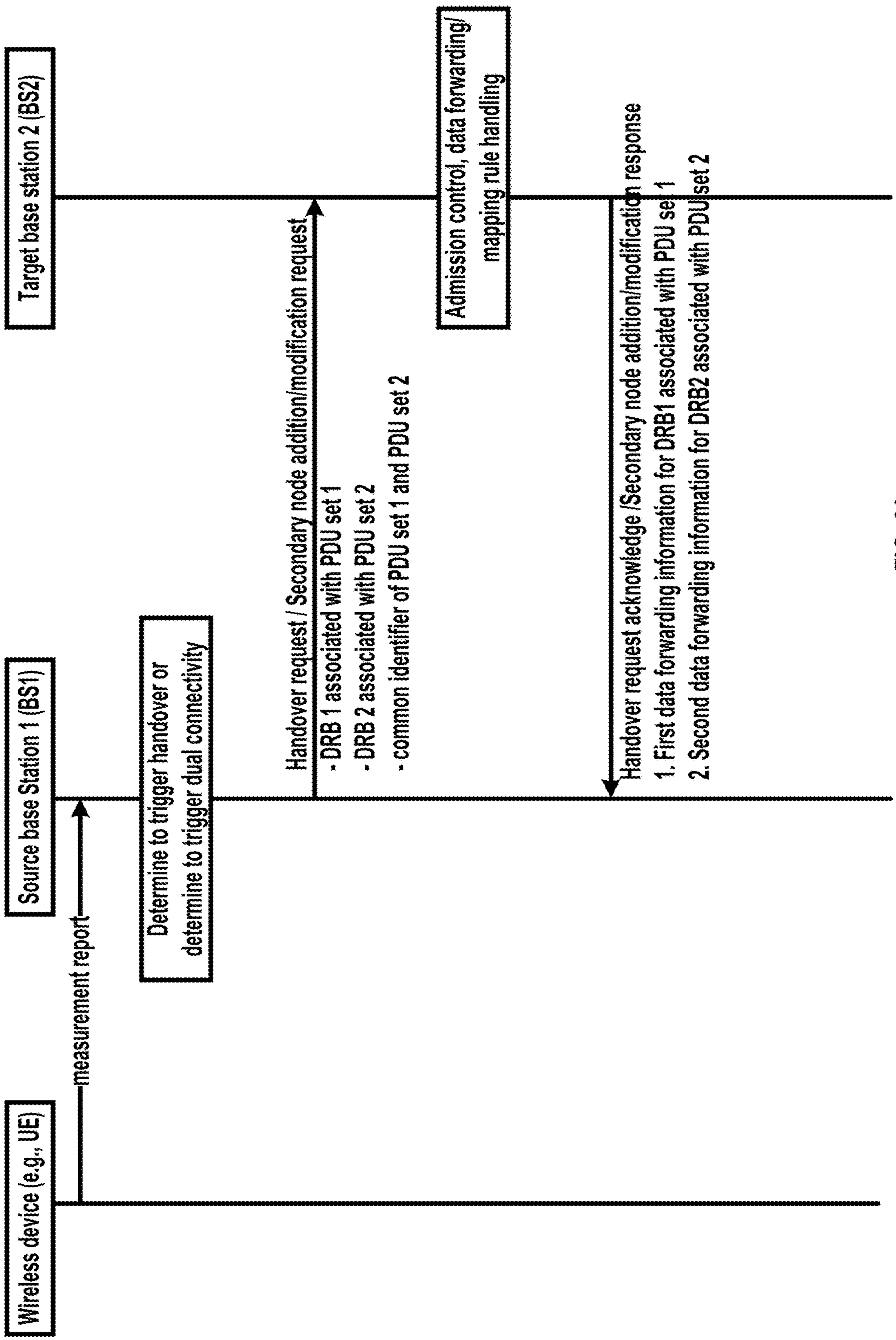

Application A of UE1 (e.g., video)
PDU Set 1 (type A)
PDU Set 2 (type B)
• PDU Set 1 and PDU Set 2 are for application A (e.g., video, audio, XR, VR, AR)
• PDU Set 1 (type A) is of high priority (e.g., I frame)
• Usability of PDU Set 2 (type B, e.g., B/P frame) may depend on the availability of PDU Set1.
PDU Set 1 of UE1
PDU Set 2 of UE1
SDAP Layer of BS1 determines QoS flow to DRB mapping on source BS side
• Mapping rule may be different in BS1 and BS2, thus loss may happen
• Loss of PDU within high priority PDU set may cause more serious problem
SDAP Layer of BS2 determines QoS flow to DRB mapping on target BS side
Base station 1 (BS1)
Base station 2 (BS2)
Service of application A:
• PDU set1
• PDU set2
service
Handover to BS2
service
wireless device (e.g., UE1)

FIG. 25



Wireless device (e.g., UE)
Source base Station 1 (BS1)
Target base station 2 (BS2)
measurement report
Determine to trigger handover or determine to trigger dual connectivity
Handover request / Secondary node addition/modification request
- DRB 1 associated with PDU set 1
- DRB 2 associated with PDU set 2
- common identifier of PDU set 1 and PDU set 2
Admission control, data forwarding/ mapping rule handling
Handover request acknowledge /Secondary node addition/modification response
1. First data forwarding information for DRB1 associated with PDU set 1
2. Second data forwarding information for DRB2 associated with PDU set 2

FIG. 26

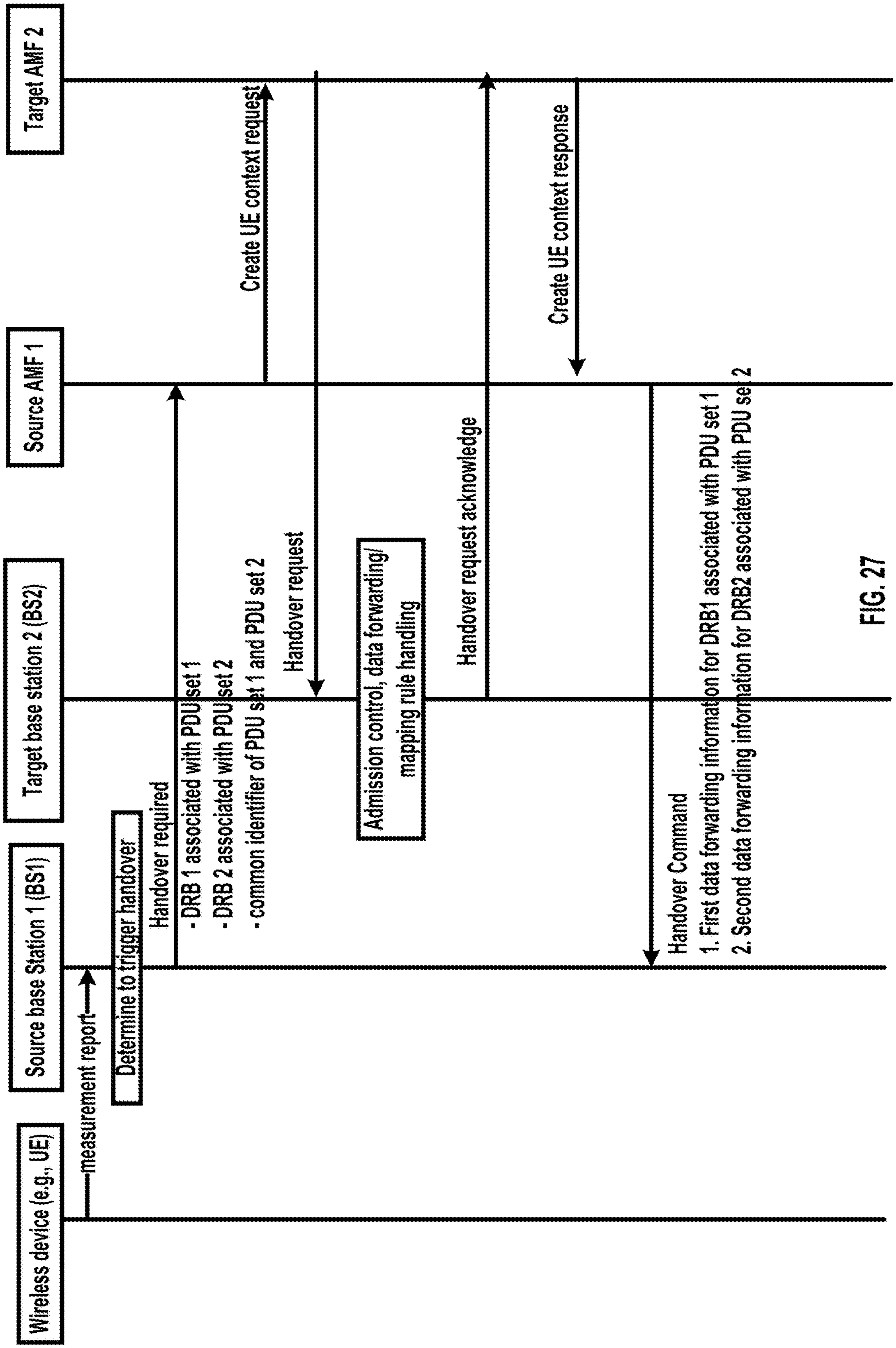

Wireless device (e.g., UE)
Source base Station 1 (BS1)
Target base station 2 (BS2)
Source AMF 1
Target AMF 2
measurement report
Determine to trigger handover
Handover required
- DRB 1 associated with PDU set 1
- DRB 2 associated with PDU set 2
- common identifier of PDU set 1 and PDU set 2
Create UE context request
Handover request
Admission control, data forwarding/ mapping rule handling
Handover request acknowledge
Create UE context response
Handover Command
1. First data forwarding information for DRB1 associated with PDU set 1
2. Second data forwarding information for DRB2 associated with PDU set 2

FIG. 27

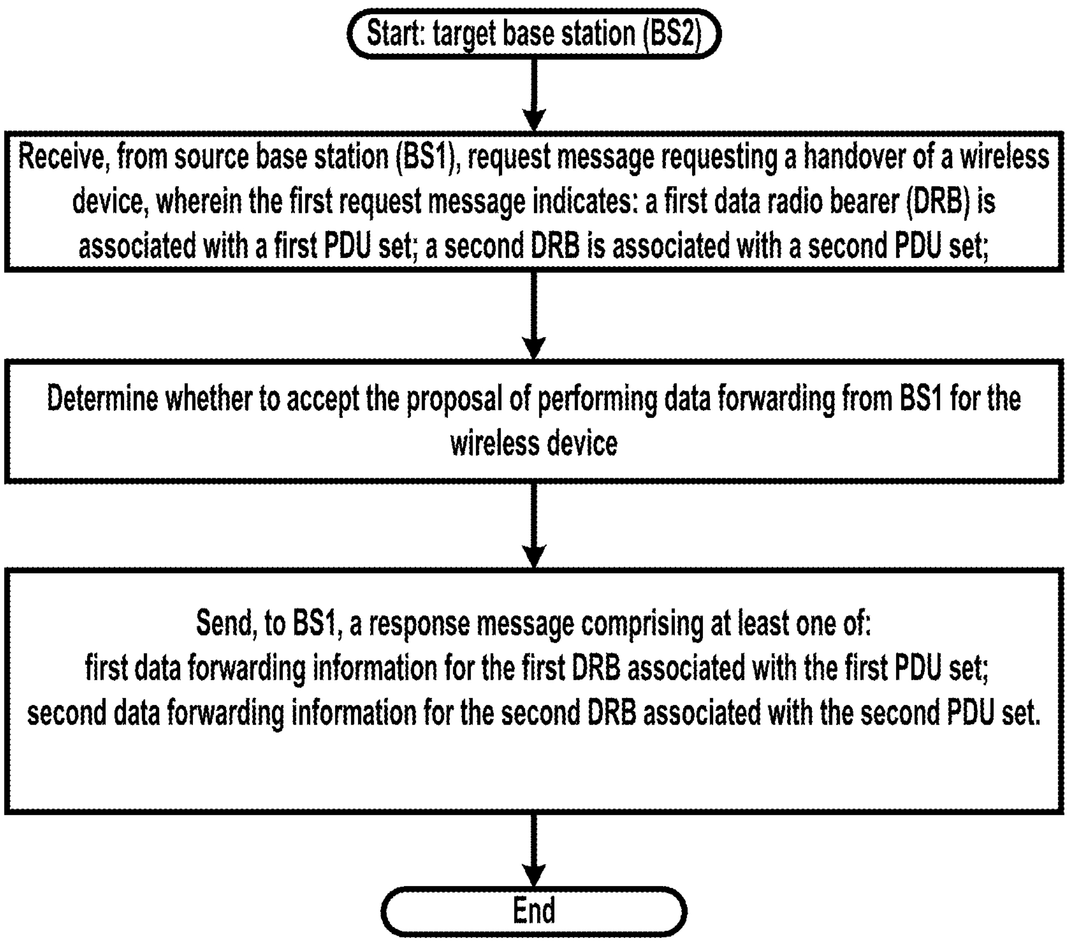

Start: target base station (BS2)
Receive, from source base station (BS1), request message requesting a handover of a wireless device, wherein the first request message indicates: a first data radio bearer (DRB) is associated with a first PDU set; a second DRB is associated with a second PDU set;
Determine whether to accept the proposal of performing data forwarding from BS1 for the wireless device
Send, to BS1, a response message comprising at least one of:
first data forwarding information for the first DRB associated with the first PDU set;
second data forwarding information for the second DRB associated with the second PDU set.
End

FIG. 28

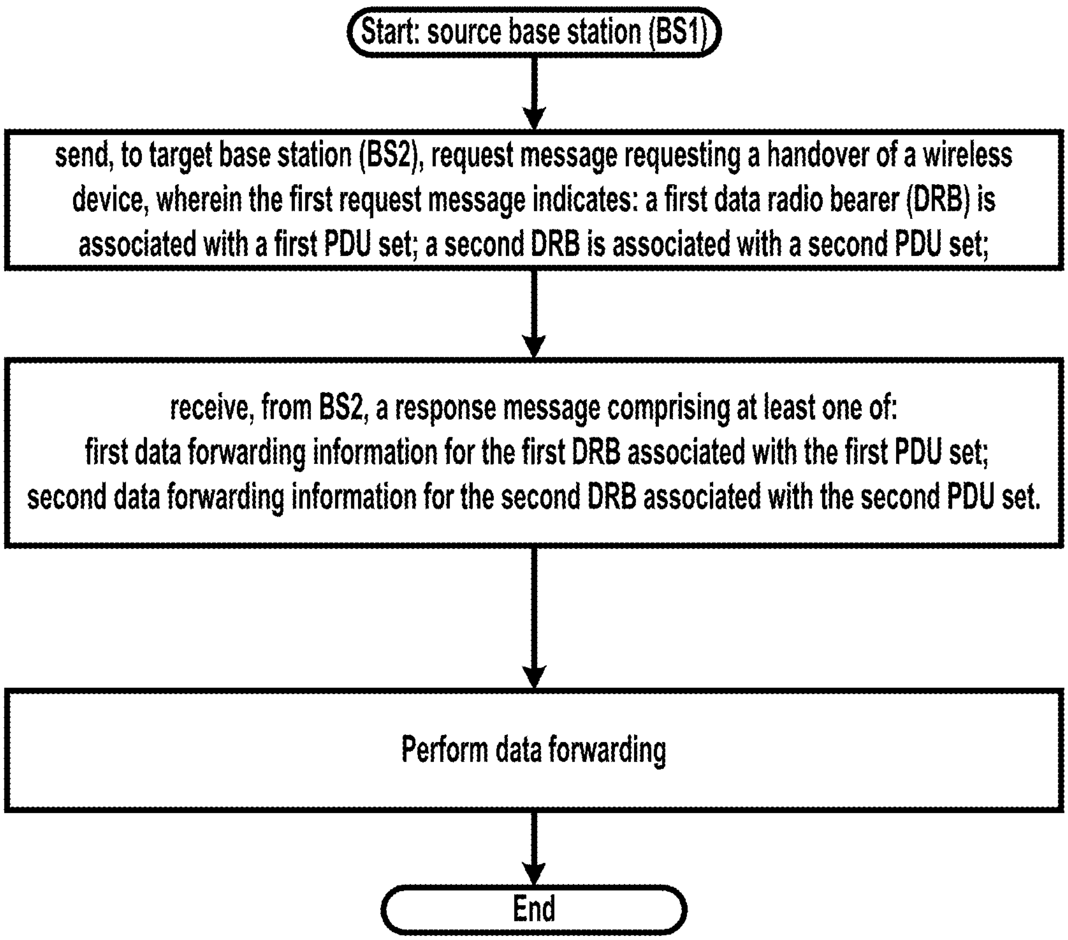

Start: source base station (BS1)
send, to target base station (BS2), request message requesting a handover of a wireless device, wherein the first request message indicates: a first data radio bearer (DRB) is associated with a first PDU set; a second DRB is associated with a second PDU set;
receive, from BS2, a response message comprising at least one of:
first data forwarding information for the first DRB associated with the first PDU set;
second data forwarding information for the second DRB associated with the second PDU set.
Perform data forwarding
End

FIG. 29

EXTENDED REALITY (XR) ENHANCEMENT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of International Application No. PCT/US2023/036598, filed Nov. 1, 2023, which claims the benefit of U.S. Provisional Application No. 63/422,306, filed Nov. 3, 2022, all of which are hereby incorporated by reference in their entireties.

BRIEF DESCRIPTION OF THE DRAWINGS

[0002] Examples of several of the various embodiments of the present disclosure are described herein with reference to the drawings.

[0003] FIG. **1**A and FIG. **1**B illustrate example mobile communication networks in which embodiments of the present disclosure may be implemented.

[0004] FIG. **2**A and FIG. **2**B respectively illustrate a New Radio (NR) user plane and control plane protocol stack.

[0005] FIG. **3** illustrates an example of services provided between protocol layers of the NR user plane protocol stack of FIG. **2**A.

[0006] FIG. **4**A illustrates an example downlink data flow through the NR user plane protocol stack of FIG. **2**A.

[0007] FIG. **4**B illustrates an example format of a MAC subheader in a MAC PDU.

[0008] FIG. **5**A and FIG. **5**B respectively illustrate a mapping between logical channels, transport channels, and physical channels for the downlink and uplink.

[0009] FIG. **6** is an example diagram showing RRC state transitions of a UE.

[0010] FIG. **7** illustrates an example configuration of an NR frame into which OFDM symbols are grouped.

[0011] FIG. **8** illustrates an example configuration of a slot in the time and frequency domain for an NR carrier.

[0012] FIG. **9** illustrates an example of bandwidth adaptation using three configured BWPs for an NR carrier.

[0013] FIG. **10**A illustrates three carrier aggregation configurations with two component carriers.

[0014] FIG. **10**B illustrates an example of how aggregated cells may be configured into one or more PUCCH groups.

[0015] FIG. **11**A illustrates an example of an SS/PBCH block structure and location.

[0016] FIG. **11**B illustrates an example of CSI-RSs that are mapped in the time and frequency domains.

[0017] FIG. **12**A and FIG. **12**B respectively illustrate examples of three downlink and uplink beam management procedures.

[0018] FIG. **13**A, FIG. **13**B, and FIG. **13**C respectively illustrate a four-step contention-based random access procedure, a two-step contention-free random access procedure, and another two-step random access procedure.

[0019] FIG. **14**A illustrates an example of CORESET configurations for a bandwidth part.

[0020] FIG. **14**B illustrates an example of a CCE-to-REG mapping for DCI transmission on a CORESET and PDCCH processing.

[0021] FIG. **15** illustrates an example of a wireless device in communication with a base station.

[0022] FIG. **16**A, FIG. **16**B, FIG. **16**C, and FIG. **16**D illustrate example structures for uplink and downlink transmission.

[0023] FIG. **17** is an example diagram of an aspect of an embodiment of the present disclosure.

[0024] FIG. **18** is an example diagram of an aspect of an embodiment of the present disclosure.

[0025] FIG. **19** is an example diagram of an aspect of an embodiment of the present disclosure.

[0026] FIG. **20** is an example diagram of an aspect of an embodiment of the present disclosure.

[0027] FIG. **21** is an example diagram of an aspect of an embodiment of the present disclosure.

[0028] FIGS. **22**A, **22**B, **22**C, and **22**D are example diagrams of an aspect of an embodiment of the present disclosure.

[0029] FIG. **23** is an example diagram of an aspect of an embodiment of the present disclosure.

[0030] FIG. **24** is an example diagram of an aspect of an embodiment of the present disclosure.

[0031] FIG. **25** is an example diagram of an aspect of an embodiment of the present disclosure.

[0032] FIG. **26** is an example diagram of an aspect of an embodiment of the present disclosure.

[0033] FIG. **27** is an example diagram of an aspect of an embodiment of the present disclosure.

[0034] FIG. **28** is an example diagram of an aspect of an embodiment of the present disclosure.

[0035] FIG. **29** is an example diagram of an aspect of an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0036] In the present disclosure, various embodiments are presented as examples of how the disclosed techniques may be implemented and/or how the disclosed techniques may be practiced in environments and scenarios. It will be apparent to persons skilled in the relevant art that various changes in form and detail can be made therein without departing from the scope. In fact, after reading the description, it will be apparent to one skilled in the relevant art how to implement alternative embodiments. The present embodiments should not be limited by any of the described exemplary embodiments. The embodiments of the present disclosure will be described with reference to the accompanying drawings. Limitations, features, and/or elements from the disclosed example embodiments may be combined to create further embodiments within the scope of the disclosure. Any figures which highlight the functionality and advantages, are presented for example purposes only. The disclosed architecture is sufficiently flexible and configurable, such that it may be utilized in ways other than that shown. For example, the actions listed in any flowchart may be re-ordered or only optionally used in some embodiments.

[0037] Embodiments may be configured to operate as needed. The disclosed mechanism may be performed when certain criteria are met, for example, in a wireless device, a base station, a radio environment, a network, a combination of the above, and/or the like. Example criteria may be based, at least in part, on for example, wireless device or network node configurations, traffic load, initial system set up, packet sizes, traffic characteristics, a combination of the above, and/or the like. When the one or more criteria are met, various example embodiments may be applied. Therefore, it may be possible to implement example embodiments that selectively implement disclosed protocols.

[0038] A base station may communicate with a mix of wireless devices. Wireless devices and/or base stations may support multiple technologies, and/or multiple releases of the same technology. Wireless devices may have some specific capability(ies) depending on wireless device category and/or capability(ies). When this disclosure refers to a base station communicating with a plurality of wireless devices, this disclosure may refer to a subset of the total wireless devices in a coverage area. This disclosure may refer to, for example, a plurality of wireless devices of a given LTE or 5G release with a given capability and in a given sector of the base station. The plurality of wireless devices in this disclosure may refer to a selected plurality of wireless devices, and/or a subset of total wireless devices in a coverage area which perform according to disclosed methods, and/or the like. There may be a plurality of base stations or a plurality of wireless devices in a coverage area that may not comply with the disclosed methods, for example, those wireless devices or base stations may perform based on older releases of LTE or 5G technology.

[0039] In this disclosure, "a" and "an" and similar phrases are to be interpreted as "at least one" and "one or more." Similarly, any term that ends with the suffix "(s)" is to be interpreted as "at least one" and "one or more." In this disclosure, the term "may" is to be interpreted as "may, for example." In other words, the term "may" is indicative that the phrase following the term "may" is an example of one of a multitude of suitable possibilities that may, or may not, be employed by one or more of the various embodiments. The terms "comprises" and "consists of", as used herein, enumerate one or more components of the element being described. The term "comprises" is interchangeable with "includes" and does not exclude unenumerated components from being included in the element being described. By contrast, "consists of" provides a complete enumeration of the one or more components of the element being described. The term "based on", as used herein, should be interpreted as "based at least in part on" rather than, for example, "based solely on". The term "and/or" as used herein represents any possible combination of enumerated elements. For example, "A, B, and/or C" may represent A; B; C; A and B; A and C; B and C; or A, B, and C.

[0040] If A and B are sets and every element of A is an element of B, A is called a subset of B. In this specification, only non-empty sets and subsets are considered. For example, possible subsets of B={cell1, cell2} are: {cell1}, {cell2}, and {cell1, cell2}. The phrase "based on" (or equally "based at least on") is indicative that the phrase following the term "based on" is an example of one of a multitude of suitable possibilities that may, or may not, be employed to one or more of the various embodiments. The phrase "in response to" (or equally "in response at least to") is indicative that the phrase following the phrase "in response to" is an example of one of a multitude of suitable possibilities that may, or may not, be employed to one or more of the various embodiments. The phrase "depending on" (or equally "depending at least to") is indicative that the phrase following the phrase "depending on" is an example of one of a multitude of suitable possibilities that may, or may not, be employed to one or more of the various embodiments. The phrase "employing/using" (or equally "employing/using at least") is indicative that the phrase following the phrase "employing/using" is an example of one of a multitude of suitable possibilities that may, or may not, be employed to one or more of the various embodiments.

[0041] The term configured may relate to the capacity of a device whether the device is in an operational or non-operational state. Configured may refer to specific settings in a device that effect the operational characteristics of the device whether the device is in an operational or non-operational state. In other words, the hardware, software, firmware, registers, memory values, and/or the like may be "configured" within a device, whether the device is in an operational or nonoperational state, to provide the device with specific characteristics. Terms such as "a control message to cause in a device" may mean that a control message has parameters that may be used to configure specific characteristics or may be used to implement certain actions in the device, whether the device is in an operational or non-operational state.

[0042] In this disclosure, parameters (or equally called, fields, or Information elements: IEs) may comprise one or more information objects, and an information object may comprise one or more other objects. For example, if parameter (IE) N comprises parameter (IE) M, and parameter (IE) M comprises parameter (IE) K, and parameter (IE) K comprises parameter (information element) J. Then, for example, N comprises K, and N comprises J. In an example embodiment, when one or more messages comprise a plurality of parameters, it implies that a parameter in the plurality of parameters is in at least one of the one or more messages, but does not have to be in each of the one or more messages.

[0043] Many features presented are described as being optional through the use of "may" or the use of parentheses. For the sake of brevity and legibility, the present disclosure does not explicitly recite each and every permutation that may be obtained by choosing from the set of optional features. The present disclosure is to be interpreted as explicitly disclosing all such permutations. For example, a system described as having three optional features may be embodied in seven ways, namely with just one of the three possible features, with any two of the three possible features or with three of the three possible features.

[0044] Many of the elements described in the disclosed embodiments may be implemented as modules. A module is defined here as an element that performs a defined function and has a defined interface to other elements. The modules described in this disclosure may be implemented in hardware, software in combination with hardware, firmware, wetware (e.g. hardware with a biological element) or a combination thereof, which may be behaviorally equivalent. For example, modules may be implemented as a software routine written in a computer language configured to be executed by a hardware machine (such as C, C++, Fortran, Java, Basic, Matlab or the like) or a modeling/simulation program such as Simulink, Stateflow, GNU Octave, or LabVIEWMathScript. It may be possible to implement modules using physical hardware that incorporates discrete or programmable analog, digital and/or quantum hardware. Examples of programmable hardware comprise: computers, microcontrollers, microprocessors, application-specific integrated circuits (ASICs); field programmable gate arrays (FPGAs); and complex programmable logic devices (CPLDs). Computers, microcontrollers and microprocessors are programmed using languages such as assembly, C, C++ or the like. FPGAs, ASICs and CPLDs are often programmed using hardware description languages (HDL) such as VHSIC hardware description language (VHDL) or Verilog that configure connections between internal hardware modules with lesser functionality on a programmable device. The mentioned technologies are often used in combination to achieve the result of a functional module.

[0045] FIG. **1**A illustrates an example of a mobile communication network **100** in which embodiments of the present disclosure may be implemented. The mobile communication network **100** may be, for example, a public land mobile network (PLMN) run by a network operator. As illustrated in FIG. **1**A, the mobile communication network **100** includes a core network (CN) **102**, a radio access network (RAN) **104**, and a wireless device **106**.

[0046] The CN **102** may provide the wireless device **106** with an interface to one or more data networks (DNs), such as public DNS (e.g., the Internet), private DNs, and/or intra-operator DNs. As part of the interface functionality, the CN **102** may set up end-to-end connections between the wireless device **106** and the one or more DNs, authenticate the wireless device **106**, and provide charging functionality.

[0047] The RAN **104** may connect the CN **102** to the wireless device **106** through radio communications over an air interface. As part of the radio communications, the RAN **104** may provide scheduling, radio resource management, and retransmission protocols. The communication direction from the RAN **104** to the wireless device **106** over the air interface is known as the downlink and the communication direction from the wireless device **106** to the RAN **104** over the air interface is known as the uplink. Downlink transmissions may be separated from uplink transmissions using frequency division duplexing (FDD), time-division duplexing (TDD), and/or some combination of the two duplexing techniques.

[0048] The term wireless device may be used throughout this disclosure to refer to and encompass any mobile device or fixed (non-mobile) device for which wireless communication is needed or usable. For example, a wireless device may be a telephone, smart phone, tablet, computer, laptop, sensor, meter, wearable device, Internet of Things (IoT) device, vehicle road side unit (RSU), relay node, automobile, and/or any combination thereof. The term wireless device encompasses other terminology, including user equipment (UE), user terminal (UT), access terminal (AT), mobile station, handset, wireless transmit and receive unit (WTRU), and/or wireless communication device.

[0049] The RAN **104** may include one or more base stations (not shown). The term base station may be used throughout this disclosure to refer to and encompass a Node B (associated with UMTS and/or 3G standards), an Evolved Node B (eNB, associated with E-UTRA and/or 4G standards), a remote radio head (RRH), a baseband processing unit coupled to one or more RRHs, a repeater node or relay node used to extend the coverage area of a donor node, a Next Generation Evolved Node B (ng-eNB), a Generation Node B (gNB, associated with NR and/or 5G standards), an access point (AP, associated with, for example, WiFi or any other suitable wireless communication standard), and/or any combination thereof. A base station may comprise at least one gNB Central Unit (gNB-CU) and at least one a gNB Distributed Unit (gNB-DU).

[0050] A base station included in the RAN **104** may include one or more sets of antennas for communicating with the wireless device **106** over the air interface. For example, one or more of the base stations may include three sets of antennas to respectively control three cells (or sectors). The size of a cell may be determined by a range at which a receiver (e.g., a base station receiver) can successfully receive the transmissions from a transmitter (e.g., a wireless device transmitter) operating in the cell. Together, the cells of the base stations may provide radio coverage to the wireless device **106** over a wide geographic area to support wireless device mobility.

[0051] In addition to three-sector sites, other implementations of base stations are possible. For example, one or more of the base stations in the RAN **104** may be implemented as a sectored site with more or less than three sectors. One or more of the base stations in the RAN **104** may be implemented as an access point, as a baseband processing unit coupled to several remote radio heads (RRHs), and/or as a repeater or relay node used to extend the coverage area of a donor node. A baseband processing unit coupled to RRHs may be part of a centralized or cloud RAN architecture, where the baseband processing unit may be either centralized in a pool of baseband processing units or virtualized. A repeater node may amplify and rebroadcast a radio signal received from a donor node. A relay node may perform the same/similar functions as a repeater node but may decode the radio signal received from the donor node to remove noise before amplifying and rebroadcasting the radio signal.

[0052] The RAN **104** may be deployed as a homogenous network of macrocell base stations that have similar antenna patterns and similar high-level transmit powers. The RAN **104** may be deployed as a heterogeneous network. In heterogeneous networks, small cell base stations may be used to provide small coverage areas, for example, coverage areas that overlap with the comparatively larger coverage areas provided by macrocell base stations. The small coverage areas may be provided in areas with high data traffic (or so-called “hotspots”) or in areas with weak macrocell coverage. Examples of small cell base stations include, in order of decreasing coverage area, microcell base stations, picocell base stations, and femtocell base stations or home base stations.

[0053] The Third-Generation Partnership Project (3GPP) was formed in 1998 to provide global standardization of specifications for mobile communication networks similar to the mobile communication network **100** in FIG. **1**A. To date, 3GPP has produced specifications for three generations of mobile networks: a third generation (3G) network known as Universal Mobile Telecommunications System (UMTS), a fourth generation (4G) network known as Long-Term Evolution (LTE), and a fifth generation (5G) network known as 5G System (5GS). Embodiments of the present disclosure are described with reference to the RAN of a 3GPP 5G network, referred to as next-generation RAN (NG-RAN). Embodiments may be applicable to RANs of other mobile communication networks, such as the RAN **104** in FIG. **1**A, the RANs of earlier 3G and 4G networks, and those of future networks yet to be specified (e.g., a 3GPP 6G network). NG-RAN implements 5G radio access technology known as New Radio (NR) and may be provisioned to implement 4G radio access technology or other radio access technologies, including non-3GPP radio access technologies.

[0054] FIG. **1**B illustrates another example mobile communication network **150** in which embodiments of the present disclosure may be implemented. Mobile communication network **150** may be, for example, a PLMN run by a network operator. As illustrated in FIG. **1**B, mobile communication network **150** includes a 5G core network (5G-CN) **152**, an NG-RAN **154**, and UEs **156**A and **156**B (collectively UEs **156**). These components may be implemented and operate in the same or similar manner as corresponding components described with respect to FIG. **1**A.

[0055] The 5G-CN **152** provides the UEs **156** with an interface to one or more DNs, such as public DNS (e.g., the Internet), private DNs, and/or intra-operator DNs. As part of the interface functionality, the 5G-CN **152** may set up end-to-end connections between the UEs **156** and the one or more DNs, authenticate the UEs **156**, and provide charging functionality. Compared to the CN of a 3GPP 4G network, the basis of the 5G-CN **152** may be a service-based architecture. This means that the architecture of the nodes making up the 5G-CN **152** may be defined as network functions that offer services via interfaces to other network functions. The network functions of the 5G-CN **152** may be implemented in several ways, including as network elements on dedicated or shared hardware, as software instances running on dedicated or shared hardware, or as virtualized functions instantiated on a platform (e.g., a cloud-based platform).

[0056] As illustrated in FIG. **1**B, the 5G-CN **152** includes an Access and Mobility Management Function (AMF) **158**A and a User Plane Function (UPF) **158**B, which are shown as one component AMF/UPF **158** in FIG. **1**B for ease of illustration. The UPF **158**B may serve as a gateway between the NG-RAN **154** and the one or more DNs. The UPF **158**B may perform functions such as packet routing and forwarding, packet inspection and user plane policy rule enforcement, traffic usage reporting, uplink classification to support routing of traffic flows to the one or more DNS, quality of service (QOS) handling for the user plane (e.g., packet filtering, gating, uplink/downlink rate enforcement, and uplink traffic verification), downlink packet buffering, and downlink data notification triggering. The UPF **158**B may serve as an anchor point for intra-/inter-Radio Access Technology (RAT) mobility, an external protocol (or packet) data unit (PDU) session point of interconnect to the one or more DNs, and/or a branching point to support a multi-homed PDU session. The UEs **156** may be configured to receive services through a PDU session, which is a logical connection between a UE and a DN.

[0057] The AMF **158**A may perform functions such as Non-Access Stratum (NAS) signaling termination, NAS signaling security, Access Stratum (AS) security control, inter-CN node signaling for mobility between 3GPP access networks, idle mode UE reachability (e.g., control and execution of paging retransmission), registration area management, intra-system and inter-system mobility support, access authentication, access authorization including checking of roaming rights, mobility management control (subscription and policies), network slicing support, and/or session management function (SMF) selection. NAS may refer to the functionality operating between a CN and a UE, and AS may refer to the functionality operating between the UE and a RAN.

[0058] The 5G-CN **152** may include one or more additional network functions that are not shown in FIG. **1**B for the sake of clarity. For example, the 5G-CN **152** may include one or more of a Session Management Function (SMF), an NR Repository Function (NRF), a Policy Control Function (PCF), a Network Exposure Function (NEF), a Unified Data Management (UDM), an Application Function (AF), and/or an Authentication Server Function (AUSF).

[0059] The NG-RAN **154** may connect the 5G-CN **152** to the UEs **156** through radio communications over the air interface. The NG-RAN **154** may include one or more gNBs, illustrated as gNB **160**A and gNB **160**B (collectively gNBs **160**) and/or one or more ng-eNBs, illustrated as ng-eNB **162**A and ng-eNB **162**B (collectively ng-eNBs **162**). The gNBs **160** and ng-eNBs **162** may be more generically referred to as base stations. The gNBs **160** and ng-eNBs **162** may include one or more sets of antennas for communicating with the UEs **156** over an air interface. For example, one or more of the gNBs **160** and/or one or more of the ng-eNBs **162** may include three sets of antennas to respectively control three cells (or sectors). Together, the cells of the gNBs **160** and the ng-eNBs **162** may provide radio coverage to the UEs **156** over a wide geographic area to support UE mobility.

[0060] As shown in FIG. **1**B, the gNBs **160** and/or the ng-eNBs **162** may be connected to the 5G-CN **152** by means of an NG interface and to other base stations by an Xn interface. The NG and Xn interfaces may be established using direct physical connections and/or indirect connections over an underlying transport network, such as an internet protocol (IP) transport network. The gNBs **160** and/or the ng-eNBs **162** may be connected to the UEs **156** by means of a Uu interface. For example, as illustrated in FIG. **1**B, gNB **160**A may be connected to the UE **156**A by means of a Uu interface. The NG, Xn, and Uu interfaces are associated with a protocol stack. The protocol stacks associated with the interfaces may be used by the network elements in FIG. **1**B to exchange data and signaling messages and may include two planes: a user plane and a control plane. The user plane may handle data of interest to a user. The control plane may handle signaling messages of interest to the network elements.

[0061] The gNBs **160** and/or the ng-eNBs **162** may be connected to one or more AMF/UPF functions of the 5G-CN **152**, such as the AMF/UPF **158**, by means of one or more NG interfaces. For example, the gNB **160**A may be connected to the UPF **158**B of the AMF/UPF **158** by means of an NG-User plane (NG-U) interface. The NG-U interface may provide delivery (e.g., non-guaranteed delivery) of user plane PDUs between the gNB **160**A and the UPF **158**B. The gNB **160**A may be connected to the AMF **158**A by means of an NG-Control plane (NG-C) interface. The NG-C interface may provide, for example, NG interface management, UE context management, UE mobility management, transport of NAS messages, paging, PDU session management, and configuration transfer and/or warning message transmission.

[0062] The gNBs **160** may provide NR user plane and control plane protocol terminations towards the UEs **156** over the Uu interface. For example, the gNB **160**A may provide NR user plane and control plane protocol terminations toward the UE **156**A over a Uu interface associated with a first protocol stack. The ng-eNBs **162** may provide Evolved UMTS Terrestrial Radio Access (E-UTRA) user plane and control plane protocol terminations towards the UEs **156** over a Uu interface, where E-UTRA refers to the 3GPP 4G radio-access technology. For example, the ng-eNB **162**B may provide E-UTRA user plane and control plane protocol terminations towards the UE **156**B over a Uu interface associated with a second protocol stack.

[0063] The 5G-CN **152** was described as being configured to handle NR and 4G radio accesses. It will be appreciated by one of ordinary skill in the art that it may be possible for NR to connect to a 4G core network in a mode known as "non-standalone operation." In non-standalone operation, a 4G core network is used to provide (or at least support) control-plane functionality (e.g., initial access, mobility, and paging). Although only one AMF/UPF **158** is shown in FIG. **1**B, one gNB or ng-eNB may be connected to multiple AMF/UPF nodes to provide redundancy and/or to load share across the multiple AMF/UPF nodes.

[0064] As discussed, an interface (e.g., Uu, Xn, and NG interfaces) between the network elements in FIG. **1**B may be associated with a protocol stack that the network elements use to exchange data and signaling messages. A protocol stack may include two planes: a user plane and a control plane. The user plane may handle data of interest to a user, and the control plane may handle signaling messages of interest to the network elements.

[0065] FIG. **2**A and FIG. **2**B respectively illustrate examples of NR user plane and NR control plane protocol stacks for the Uu interface that lies between a UE **210** and a gNB **220**. The protocol stacks illustrated in FIG. **2**A and FIG. **2**B may be the same or similar to those used for the Uu interface between, for example, the UE **156**A and the gNB **160**A shown in FIG. **1**B.

[0066] FIG. **2**A illustrates a NR user plane protocol stack comprising five layers implemented in the UE **210** and the gNB **220**. At the bottom of the protocol stack, physical layers (PHYs) **211** and **221** may provide transport services to the higher layers of the protocol stack and may correspond to layer 1 of the Open Systems Interconnection (OSI) model. The next four protocols above PHYs **211** and **221** comprise media access control layers (MACs) **212** and **222**, radio link control layers (RLCs) **213** and **223**, packet data convergence protocol layers (PDCPs) **214** and **224**, and service data application protocol layers (SDAPs) **215** and **225**. Together, these four protocols may make up layer 2, or the data link layer, of the OSI model.

[0067] FIG. **3** illustrates an example of services provided between protocol layers of the NR user plane protocol stack. Starting from the top of FIG. **2**A and FIG. **3**, the SDAPs **215** and **225** may perform QoS flow handling. The UE **210** may receive services through a PDU session, which may be a logical connection between the UE **210** and a DN. The PDU session may have one or more QoS flows. A UPF of a CN (e.g., the UPF **158**B) may map IP packets to the one or more QoS flows of the PDU session based on QoS requirements (e.g., in terms of delay, data rate, and/or error rate). The SDAPs **215** and **225** may perform mapping/de-mapping between the one or more QoS flows and one or more data radio bearers. The mapping/de-mapping between the QoS flows and the data radio bearers may be determined by the SDAP **225** at the gNB **220**. The SDAP **215** at the UE **210** may be informed of the mapping between the QoS flows and the data radio bearers through reflective mapping or control signaling received from the gNB **220**. For reflective mapping, the SDAP **225** at the gNB **220** may mark the downlink packets with a QoS flow indicator (QFI), which may be observed by the SDAP **215** at the UE **210** to determine the mapping/de-mapping between the QoS flows and the data radio bearers.

[0068] The PDCPs **214** and **224** may perform header compression/decompression to reduce the amount of data that needs to be transmitted over the air interface, ciphering/deciphering to prevent unauthorized decoding of data transmitted over the air interface, and integrity protection (to ensure control messages originate from intended sources. The PDCPs **214** and **224** may perform retransmissions of undelivered packets, in-sequence delivery and reordering of packets, and removal of packets received in duplicate due to, for example, an intra-gNB handover. The PDCPs **214** and **224** may perform packet duplication to improve the likelihood of the packet being received and, at the receiver, remove any duplicate packets. Packet duplication may be useful for services that require high reliability.

[0069] Although not shown in FIG. **3**, PDCPs **214** and **224** may perform mapping/de-mapping between a split radio bearer and RLC channels in a dual connectivity scenario. Dual connectivity is a technique that allows a UE to connect to two cells or, more generally, two cell groups: a master cell group (MCG) and a secondary cell group (SCG). A split bearer is when a single radio bearer, such as one of the radio bearers provided by the PDCPs **214** and **224** as a service to the SDAPs **215** and **225**, is handled by cell groups in dual connectivity. The PDCPs **214** and **224** may map/de-map the split radio bearer between RLC channels belonging to cell groups.

[0070] The RLCs **213** and **223** may perform segmentation, retransmission through Automatic Repeat Request (ARQ), and removal of duplicate data units received from MACs **212** and **222**, respectively. The RLCs **213** and **223** may support three transmission modes: transparent mode (TM); unacknowledged mode (UM); and acknowledged mode (AM). Based on the transmission mode an RLC is operating, the RLC may perform one or more of the noted functions. The RLC configuration may be per logical channel with no dependency on numerologies and/or Transmission Time Interval (TTI) durations. As shown in FIG. **3**, the RLCs **213** and **223** may provide RLC channels as a service to PDCPs **214** and **224**, respectively.

[0071] The MACs **212** and **222** may perform multiplexing/demultiplexing of logical channels and/or mapping between logical channels and transport channels. The multiplexing/demultiplexing may include multiplexing/demultiplexing of data units, belonging to the one or more logical channels, into/from Transport Blocks (TBs) delivered to/from the PHYs **211** and **221**. The MAC **222** may be configured to perform scheduling, scheduling information reporting, and priority handling between UEs by means of dynamic scheduling. Scheduling may be performed in the gNB **220** (at the MAC **222**) for downlink and uplink. The MACs **212** and **222** may be configured to perform error correction through Hybrid Automatic Repeat Request (HARQ) (e.g., one HARQ entity per carrier in case of Carrier Aggregation (CA)), priority handling between logical channels of the UE **210** by means of logical channel prioritization, and/or padding. The MACs **212** and **222** may support one or more numerologies and/or transmission timings. In an example, mapping restrictions in a logical channel prioritization may control which numerology and/or transmission timing a logical channel may use. As shown in FIG. **3**, the MACs **212** and **222** may provide logical channels as a service to the RLCs **213** and **223**.

[0072] The PHYs **211** and **221** may perform mapping of transport channels to physical channels and digital and analog signal processing functions for sending and receiving information over the air interface. These digital and analog signal processing functions may include, for example, coding/decoding and modulation/demodulation. The PHYs **211** and **221** may perform multi-antenna mapping. As shown in FIG. **3**, the PHYs **211** and **221** may provide one or more transport channels as a service to the MACs **212** and **222**.

[0073] FIG. **4**A illustrates an example downlink data flow through the NR user plane protocol stack. FIG. **4**A illustrates a downlink data flow of three IP packets (n, n+1, and m) through the NR user plane protocol stack to generate two TBs at the gNB **220**. An uplink data flow through the NR user plane protocol stack may be similar to the downlink data flow depicted in FIG. **4**A.

[0074] The downlink data flow of FIG. **4**A begins when SDAP **225** receives the three IP packets from one or more QoS flows and maps the three packets to radio bearers. In FIG. **4**A, the SDAP **225** maps IP packets n and n+1 to a first radio bearer **402** and maps IP packet m to a second radio bearer **404**. An SDAP header (labeled with an "H" in FIG. **4**A) is added to an IP packet. The data unit from/to a higher protocol layer is referred to as a service data unit (SDU) of the lower protocol layer and the data unit to/from a lower protocol layer is referred to as a protocol data unit (PDU) of the higher protocol layer. As shown in FIG. **4**A, the data unit from the SDAP **225** is an SDU of lower protocol layer PDCP **224** and is a PDU of the SDAP **225**.

[0075] The remaining protocol layers in FIG. **4**A may perform their associated functionality (e.g., with respect to FIG. **3**), add corresponding headers, and forward their respective outputs to the next lower layer. For example, the PDCP **224** may perform IP-header compression and ciphering and forward its output to the RLC **223**. The RLC **223** may optionally perform segmentation (e.g., as shown for IP packet m in FIG. **4**A) and forward its output to the MAC **222**. The MAC **222** may multiplex a number of RLC PDUs and may attach a MAC subheader to an RLC PDU to form a transport block. In NR, the MAC subheaders may be distributed across the MAC PDU, as illustrated in FIG. **4**A. In LTE, the MAC subheaders may be entirely located at the beginning of the MAC PDU. The NR MAC PDU structure may reduce processing time and associated latency because the MAC PDU subheaders may be computed before the full MAC PDU is assembled.

[0076] FIG. **4**B illustrates an example format of a MAC subheader in a MAC PDU. The MAC subheader includes: an SDU length field for indicating the length (e.g., in bytes) of the MAC SDU to which the MAC subheader corresponds; a logical channel identifier (LCID) field for identifying the logical channel from which the MAC SDU originated to aid in the demultiplexing process; a flag (F) for indicating the size of the SDU length field; and a reserved bit (R) field for future use.

[0077] FIG. **4**B further illustrates MAC control elements (CEs) inserted into the MAC PDU by a MAC, such as MAC **223** or MAC **222**. For example, FIG. **4**B illustrates two MAC CEs inserted into the MAC PDU. MAC CEs may be inserted at the beginning of a MAC PDU for downlink transmissions (as shown in FIG. **4**B) and at the end of a MAC PDU for uplink transmissions. MAC CEs may be used for in-band control signaling. Example MAC CEs include: scheduling-related MAC CEs, such as buffer status reports and power headroom reports; activation/deactivation MAC CEs, such as those for activation/deactivation of PDCP duplication detection, channel state information (C SI) reporting, sounding reference signal (SRS) transmission, and prior configured components; discontinuous reception (DRX) related MAC CEs; timing advance MAC CEs; and random access related MAC CEs. A MAC CE may be preceded by a MAC subheader with a similar format as described for MAC SDUs and may be identified with a reserved value in the LCID field that indicates the type of control information included in the MAC CE.

[0078] Before describing the NR control plane protocol stack, logical channels, transport channels, and physical channels are first described as well as a mapping between the channel types. One or more of the channels may be used to carry out functions associated with the NR control plane protocol stack described later below.

[0079] FIG. **5**A and FIG. **5**B illustrate, for downlink and uplink respectively, a mapping between logical channels, transport channels, and physical channels. Information is passed through channels between the RLC, the MAC, and the PHY of the NR protocol stack. A logical channel may be used between the RLC and the MAC and may be classified as a control channel that carries control and configuration information in the NR control plane or as a traffic channel that carries data in the NR user plane. A logical channel may be classified as a dedicated logical channel that is dedicated to a specific UE or as a common logical channel that may be used by more than one UE. A logical channel may also be defined by the type of information it carries. The set of logical channels defined by NR include, for example:

- **[0080]** a paging control channel (PCCH) for carrying paging messages used to page a UE whose location is not-known to the network on a cell level;
- **[0081]** a broadcast control channel (BCCH) for carrying system information messages in the form of a master information block (MIB) and several system information blocks (SIBs), wherein the system information messages may be used by the UEs to obtain information about how a cell is configured and how to operate within the cell;
- **[0082]** a common control channel (CCCH) for carrying control messages together with random access;
- **[0083]** a dedicated control channel (DCCH) for carrying control messages to/from a specific the UE to configure the UE; and
- **[0084]** a dedicated traffic channel (DTCH) for carrying user data to/from a specific the UE.

[0085] Transport channels are used between the MAC and PHY layers and may be defined by how the information they carry is transmitted over the air interface. The set of transport channels defined by NR include, for example:

- **[0086]** a paging channel (PCH) for carrying paging messages that originated from the PCCH;
- **[0087]** a broadcast channel (BCH) for carrying the MIB from the BCCH;
- **[0088]** a downlink shared channel (DL-SCH) for carrying downlink data and signaling messages, including the SIBs from the BCCH;
- **[0089]** an uplink shared channel (UL-SCH) for carrying uplink data and signaling messages; and
- **[0090]** a random access channel (RACH) for allowing a UE to contact the network without any prior scheduling.

[0091] The PHY may use physical channels to pass information between processing levels of the PHY. A physical channel may have an associated set of time-frequency resources for carrying the information of one or more transport channels. The PHY may generate control information to support the low-level operation of the PHY and provide the control information to the lower levels of the PHY via physical control channels, known as L1/L2 control channels. The set of physical channels and physical control channels defined by NR include, for example:

[0092] a physical broadcast channel (PBCH) for carrying the MIB from the BCH;

[0093] a physical downlink shared channel (PDSCH) for carrying downlink data and signaling messages from the DL-SCH, as well as paging messages from the PCH;

[0094] a physical downlink control channel (PDCCH) for carrying downlink control information (DCI), which may include downlink scheduling commands, uplink scheduling grants, and uplink power control commands;

[0095] a physical uplink shared channel (PUSCH) for carrying uplink data and signaling messages from the UL-SCH and in some instances uplink control information (UCI) as described below;

[0096] a physical uplink control channel (PUCCH) for carrying UCI, which may include HARQ acknowledgments, channel quality indicators (CQI), pre-coding matrix indicators (PMI), rank indicators (RI), and scheduling requests (SR); and

[0097] a physical random access channel (PRACH) for random access.

[0098] Similar to the physical control channels, the physical layer generates physical signals to support the low-level operation of the physical layer. As shown in FIG. **5**A and FIG. **5**B, the physical layer signals defined by NR include: primary synchronization signals (PSS), secondary synchronization signals (SSS), channel state information reference signals (CSI-RS), demodulation reference signals (DMRS), sounding reference signals (SRS), and phase-tracking reference signals (PT-RS). These physical layer signals will be described in greater detail below.

[0099] FIG. **2**B illustrates an example NR control plane protocol stack. As shown in FIG. **2**B, the NR control plane protocol stack may use the same/similar first four protocol layers as the example NR user plane protocol stack. These four protocol layers include the PHYs **211** and **221**, the MACs **212** and **222**, the RLCs **213** and **223**, and the PDCPs **214** and **224**. Instead of having the SDAPs **215** and **225** at the top of the stack as in the NR user plane protocol stack, the NR control plane stack has radio resource controls (RRCs) **216** and **226** and NAS protocols **217** and **237** at the top of the NR control plane protocol stack.

[0100] The NAS protocols **217** and **237** may provide control plane functionality between the UE **210** and the AMF **230** (e.g., the AMF **158**A) or, more generally, between the UE **210** and the CN. The NAS protocols **217** and **237** may provide control plane functionality between the UE **210** and the AMF **230** via signaling messages, referred to as NAS messages. There is no direct path between the UE **210** and the AMF **230** through which the NAS messages can be transported. The NAS messages may be transported using the AS of the Uu and NG interfaces. NAS protocols **217** and **237** may provide control plane functionality such as authentication, security, connection setup, mobility management, and session management.

[0101] The RRCs **216** and **226** may provide control plane functionality between the UE **210** and the gNB **220** or, more generally, between the UE **210** and the RAN. The RRCs **216** and **226** may provide control plane functionality between the UE **210** and the gNB **220** via signaling messages, referred to as RRC messages. RRC messages may be transmitted between the UE **210** and the RAN using signaling radio bearers and the same/similar PDCP, RLC, MAC, and PHY protocol layers. The MAC may multiplex control-plane and user-plane data into the same transport block (TB). The RRCs **216** and **226** may provide control plane functionality such as: broadcast of system information related to AS and NAS; paging initiated by the CN or the RAN; establishment, maintenance and release of an RRC connection between the UE **210** and the RAN; security functions including key management; establishment, configuration, maintenance and release of signaling radio bearers and data radio bearers; mobility functions; QoS management functions; the UE measurement reporting and control of the reporting; detection of and recovery from radio link failure (RLF); and/or NAS message transfer. As part of establishing an RRC connection, RRCs **216** and **226** may establish an RRC context, which may involve configuring parameters for communication between the UE **210** and the RAN.

[0102] FIG. **6** is an example diagram showing RRC state transitions of a UE. The UE may be the same or similar to the wireless device **106** depicted in FIG. **1**A, the UE **210** depicted in FIG. **2**A and FIG. **2**B, or any other wireless device described in the present disclosure. As illustrated in FIG. **6**, a UE may be in at least one of three RRC states: RRC connected **602** (e.g., RRC_CONNECTED), RRC idle **604** (e.g., RRC_IDLE), and RRC inactive **606** (e.g., RRC_INACTIVE).

[0103] In RRC connected **602**, the UE has an established RRC context and may have at least one RRC connection with a base station. The base station may be similar to one of the one or more base stations included in the RAN **104** depicted in FIG. **1**A, one of the gNBs **160** or ng-eNBs **162** depicted in FIG. **1**B, the gNB **220** depicted in FIG. **2**A and FIG. **2**B, or any other base station described in the present disclosure. The base station with which the UE is connected may have the RRC context for the UE. The RRC context, referred to as the UE context, may comprise parameters for communication between the UE and the base station. These parameters may include, for example: one or more AS contexts; one or more radio link configuration parameters; bearer configuration information (e.g., relating to a data radio bearer, signaling radio bearer, logical channel, QoS flow, and/or PDU session); security information; and/or PHY, MAC, RLC, PDCP, and/or SDAP layer configuration information. While in RRC connected **602**, mobility of the UE may be managed by the RAN (e.g., the RAN **104** or the NG-RAN **154**). The UE may measure the signal levels (e.g., reference signal levels) from a serving cell and neighboring cells and report these measurements to the base station currently serving the UE. The UE's serving base station may request a handover to a cell of one of the neighboring base stations based on the reported measurements. The RRC state may transition from RRC connected **602** to RRC idle **604** through a connection release procedure **608** or to RRC inactive **606** through a connection inactivation procedure **610**.

[0104] In RRC idle **604**, an RRC context may not be established for the UE. In RRC idle **604**, the UE may not have an RRC connection with the base station. While in RRC idle **604**, the UE may be in a sleep state for the majority of the time (e.g., to conserve battery power). The UE may wake up periodically (e.g., once in every discontinuous reception cycle) to monitor for paging messages from the RAN. Mobility of the UE may be managed by the UE through a procedure known as cell reselection. The RRC state may transition from RRC idle **604** to RRC connected **602** through a connection establishment procedure **612**, which may involve a random access procedure as discussed in greater detail below.

[0105] In RRC inactive **606**, the RRC context previously established is maintained in the UE and the base station. This allows for a fast transition to RRC connected **602** with reduced signaling overhead as compared to the transition from RRC idle **604** to RRC connected **602**. While in RRC inactive **606**, the UE may be in a sleep state and mobility of the UE may be managed by the UE through cell reselection. The RRC state may transition from RRC inactive **606** to RRC connected **602** through a connection resume procedure **614** or to RRC idle **604** though a connection release procedure **616** that may be the same as or similar to connection release procedure **608**.

[0106] An RRC state may be associated with a mobility management mechanism. In RRC idle **604** and RRC inactive **606**, mobility is managed by the UE through cell reselection. The purpose of mobility management in RRC idle **604** and RRC inactive **606** is to allow the network to be able to notify the UE of an event via a paging message without having to broadcast the paging message over the entire mobile communications network. The mobility management mechanism used in RRC idle **604** and RRC inactive **606** may allow the network to track the UE on a cell-group level so that the paging message may be broadcast over the cells of the cell group that the UE currently resides within instead of the entire mobile communication network. The mobility management mechanisms for RRC idle **604** and RRC inactive **606** track the UE on a cell-group level. They may do so using different granularities of grouping. For example, there may be three levels of cell-grouping granularity: individual cells; cells within a RAN area identified by a RAN area identifier (RAI); and cells within a group of RAN areas, referred to as a tracking area and identified by a tracking area identifier (TAI).

[0107] Tracking areas may be used to track the UE at the CN level. The CN (e.g., the CN **102** or the 5G-CN **152**) may provide the UE with a list of TAIs associated with a UE registration area. If the UE moves, through cell reselection, to a cell associated with a TAI not included in the list of TAIs associated with the UE registration area, the UE may perform a registration update with the CN to allow the CN to update the UE's location and provide the UE with a new the UE registration area.

[0108] RAN areas may be used to track the UE at the RAN level. For a UE in RRC inactive **606** state, the UE may be assigned a RAN notification area. A RAN notification area may comprise one or more cell identities, a list of RAIs, or a list of TAIs. In an example, a base station may belong to one or more RAN notification areas. In an example, a cell may belong to one or more RAN notification areas. If the UE moves, through cell reselection, to a cell not included in the RAN notification area assigned to the UE, the UE may perform a notification area update with the RAN to update the UE's RAN notification area.

[0109] A base station storing an RRC context for a UE or a last serving base station of the UE may be referred to as an anchor base station. An anchor base station may maintain an RRC context for the UE at least during a period of time that the UE stays in a RAN notification area of the anchor base station and/or during a period of time that the UE stays in RRC inactive **606**.

[0110] A gNB, such as gNBs **160** in FIG. **1**B, may be split in two parts: a central unit (gNB-CU), and one or more distributed units (gNB-DU). A gNB-CU may be coupled to one or more gNB-DUs using an F1 interface. The gNB-CU may comprise the RRC, the PDCP, and the SDAP. A gNB-DU may comprise the RLC, the MAC, and the PHY.

[0111] In NR, the physical signals and physical channels (discussed with respect to FIG. **5**A and FIG. **5**B) may be mapped onto orthogonal frequency divisional multiplexing (OFDM) symbols. OFDM is a multicarrier communication scheme that transmits data over F orthogonal subcarriers (or tones). Before transmission, the data may be mapped to a series of complex symbols (e.g., M-quadrature amplitude modulation (M-QAM) or M-phase shift keying (M-PSK) symbols), referred to as source symbols, and divided into F parallel symbol streams. The F parallel symbol streams may be treated as though they are in the frequency domain and used as inputs to an Inverse Fast Fourier Transform (IFFT) block that transforms them into the time domain. The IFFT block may take in F source symbols at a time, one from each of the F parallel symbol streams, and use each source symbol to modulate the amplitude and phase of one of F sinusoidal basis functions that correspond to the F orthogonal subcarriers. The output of the IFFT block may be F time-domain samples that represent the summation of the F orthogonal subcarriers. The F time-domain samples may form a single OFDM symbol. After some processing (e.g., addition of a cyclic prefix) and up-conversion, an OFDM symbol provided by the IFFT block may be transmitted over the air interface on a carrier frequency. The F parallel symbol streams may be mixed using an FFT block before being processed by the IFFT block. This operation produces Discrete Fourier Transform (DFT)-precoded OFDM symbols and may be used by UEs in the uplink to reduce the peak to average power ratio (PAPR). Inverse processing may be performed on the OFDM symbol at a receiver using an FFT block to recover the data mapped to the source symbols.

[0112] FIG. **7** illustrates an example configuration of an NR frame into which OFDM symbols are grouped. An NR frame may be identified by a system frame number (SFN). The SFN may repeat with a period of 1024 frames. As illustrated, one NR frame may be 10 milliseconds (ms) in duration and may include 10 subframes that are 1 ms in duration. A subframe may be divided into slots that include, for example, 14 OFDM symbols per slot.

[0113] The duration of a slot may depend on the numerology used for the OFDM symbols of the slot. In NR, a flexible numerology is supported to accommodate different cell deployments (e.g., cells with carrier frequencies below 1 GHZ up to cells with carrier frequencies in the mm-wave range). A numerology may be defined in terms of subcarrier spacing and cyclic prefix duration. For a numerology in NR, subcarrier spacings may be scaled up by powers of two from a baseline subcarrier spacing of 15 kHz, and cyclic prefix durations may be scaled down by powers of two from a baseline cyclic prefix duration of 4.7 μs. For example, NR defines numerologies with the following subcarrier spacing/

cyclic prefix duration combinations: 15 kHz/4.7 μs; 30 KHz/2.3 μs; 60 KHz/1.2 μs; 120 KHz/0.59 μs; and 240 kHz/0.29 μs.

[0114] A slot may have a fixed number of OFDM symbols (e.g., 14 OFDM symbols). A numerology with a higher subcarrier spacing has a shorter slot duration and, correspondingly, more slots per subframe. FIG. **7** illustrates this numerology-dependent slot duration and slots-per-subframe transmission structure (the numerology with a subcarrier spacing of 240 KHz is not shown in FIG. **7** for ease of illustration). A subframe in NR may be used as a numerology-independent time reference, while a slot may be used as the unit upon which uplink and downlink transmissions are scheduled. To support low latency, scheduling in NR may be decoupled from the slot duration and start at any OFDM symbol and last for as many symbols as needed for a transmission. These partial slot transmissions may be referred to as mini-slot or subslot transmissions.

[0115] FIG. **8** illustrates an example configuration of a slot in the time and frequency domain for an NR carrier. The slot includes resource elements (REs) and resource blocks (RBs). An RE is the smallest physical resource in NR. An RE spans one OFDM symbol in the time domain by one subcarrier in the frequency domain as shown in FIG. **8**. An RB spans twelve consecutive REs in the frequency domain as shown in FIG. **8**. An NR carrier may be limited to a width of 275 RBs or 275×12=3300 subcarriers. Such a limitation, if used, may limit the NR carrier to 50, 100, 200, and 400 MHz for subcarrier spacings of 15, 30, 60, and 120 kHz, respectively, where the 400 MHz bandwidth may be set based on a 400 MHz per carrier bandwidth limit.

[0116] FIG. **8** illustrates a single numerology being used across the entire bandwidth of the NR carrier. In other example configurations, multiple numerologies may be supported on the same carrier.

[0117] NR may support wide carrier bandwidths (e.g., up to 400 MHz for a subcarrier spacing of 120 kHz). Not all UEs may be able to receive the full carrier bandwidth (e.g., due to hardware limitations). Also, receiving the full carrier bandwidth may be prohibitive in terms of UE power consumption. In an example, to reduce power consumption and/or for other purposes, a UE may adapt the size of the UE's receive bandwidth based on the amount of traffic the UE is scheduled to receive. This is referred to as bandwidth adaptation.

[0118] NR defines bandwidth parts (BWPs) to support UEs not capable of receiving the full carrier bandwidth and to support bandwidth adaptation. In an example, a BWP may be defined by a subset of contiguous RBs on a carrier. A UE may be configured (e.g., via RRC layer) with one or more downlink BWPs and one or more uplink BWPs per serving cell (e.g., up to four downlink BWPs and up to four uplink BWPs per serving cell). At a given time, one or more of the configured BWPs for a serving cell may be active. These one or more BWPs may be referred to as active BWPs of the serving cell. When a serving cell is configured with a secondary uplink carrier, the serving cell may have one or more first active BWPs in the uplink carrier and one or more second active BWPs in the secondary uplink carrier.

[0119] For unpaired spectra, a downlink BWP from a set of configured downlink BWPs may be linked with an uplink BWP from a set of configured uplink BWPs if a downlink BWP index of the downlink BWP and an uplink BWP index of the uplink BWP are the same. For unpaired spectra, a UE may expect that a center frequency for a downlink BWP is the same as a center frequency for an uplink BWP.

[0120] For a downlink BWP in a set of configured downlink BWPs on a primary cell (PCell), a base station may configure a UE with one or more control resource sets (CORESETs) for at least one search space. A search space is a set of locations in the time and frequency domains where the UE may find control information. The search space may be a UE-specific search space or a common search space (potentially usable by a plurality of UEs). For example, a base station may configure a UE with a common search space, on a PCell or on a primary secondary cell (PSCell), in an active downlink BWP.

[0121] For an uplink BWP in a set of configured uplink BWPs, a BS may configure a UE with one or more resource sets for one or more PUCCH transmissions. A UE may receive downlink receptions (e.g., PDCCH or PDSCH) in a downlink BWP according to a configured numerology (e.g., subcarrier spacing and cyclic prefix duration) for the downlink BWP. The UE may transmit uplink transmissions (e.g., PUCCH or PUSCH) in an uplink BWP according to a configured numerology (e.g., subcarrier spacing and cyclic prefix length for the uplink BWP).

[0122] One or more BWP indicator fields may be provided in Downlink Control Information (DCI). A value of a BWP indicator field may indicate which BWP in a set of configured BWPs is an active downlink BWP for one or more downlink receptions. The value of the one or more BWP indicator fields may indicate an active uplink BWP for one or more uplink transmissions.

[0123] A base station may semi-statically configure a UE with a default downlink BWP within a set of configured downlink BWPs associated with a PCell. If the base station does not provide the default downlink BWP to the UE, the default downlink BWP may be an initial active downlink BWP. The UE may determine which BWP is the initial active downlink BWP based on a CORESET configuration obtained using the PBCH.

[0124] A base station may configure a UE with a BWP inactivity timer value for a PCell. The UE may start or restart a BWP inactivity timer at any appropriate time. For example, the UE may start or restart the BWP inactivity timer (a) when the UE detects a DCI indicating an active downlink BWP other than a default downlink BWP for a paired spectra operation; or (b) when a UE detects a DCI indicating an active downlink BWP or active uplink BWP other than a default downlink BWP or uplink BWP for an unpaired spectra operation. If the UE does not detect DCI during an interval of time (e.g., 1 ms or 0.5 ms), the UE may run the BWP inactivity timer toward expiration (for example, increment from zero to the BWP inactivity timer value, or decrement from the BWP inactivity timer value to zero). When the BWP inactivity timer expires, the UE may switch from the active downlink BWP to the default downlink BWP.

[0125] In an example, a base station may semi-statically configure a UE with one or more BWPs. A UE may switch an active BWP from a first BWP to a second BWP in response to receiving a DCI indicating the second BWP as an active BWP and/or in response to an expiry of the BWP inactivity timer (e.g., if the second BWP is the default BWP).

[0126] Downlink and uplink BWP switching (where BWP switching refers to switching from a currently active BWP to a not currently active BWP) may be performed independently in paired spectra. In unpaired spectra, downlink and uplink BWP switching may be performed simultaneously. Switching between configured BWPs may occur based on RRC signaling, DCI, expiration of a BWP inactivity timer, and/or an initiation of random access.

[0127] FIG. **9** illustrates an example of bandwidth adaptation using three configured BWPs for an NR carrier. A UE configured with the three BWPs may switch from one BWP to another BWP at a switching point. In the example illustrated in FIG. **9**, the BWPs include: a BWP **902** with a bandwidth of 40 MHz and a subcarrier spacing of 15 kHz; a BWP **904** with a bandwidth of 10 MHz and a subcarrier spacing of 15 kHz; and a BWP **906** with a bandwidth of 20 MHz and a subcarrier spacing of 60 KHz. The BWP **902** may be an initial active BWP, and the BWP **904** may be a default BWP. The UE may switch between BWPs at switching points. In the example of FIG. **9**, the UE may switch from the BWP **902** to the BWP **904** at a switching point **908**. The switching at the switching point **908** may occur for any suitable reason, for example, in response to an expiry of a BWP inactivity timer (indicating switching to the default BWP) and/or in response to receiving a DCI indicating BWP **904** as the active BWP. The UE may switch at a switching point **910** from active BWP **904** to BWP **906** in response receiving a DCI indicating BWP **906** as the active BWP. The UE may switch at a switching point **912** from active BWP **906** to BWP **904** in response to an expiry of a BWP inactivity timer and/or in response receiving a DCI indicating BWP **904** as the active BWP. The UE may switch at a switching point **914** from active BWP **904** to BWP **902** in response receiving a DCI indicating BWP **902** as the active BWP.

[0128] If a UE is configured for a secondary cell with a default downlink BWP in a set of configured downlink BWPs and a timer value, UE procedures for switching BWPs on a secondary cell may be the same/similar as those on a primary cell. For example, the UE may use the timer value and the default downlink BWP for the secondary cell in the same/similar manner as the UE would use these values for a primary cell.

[0129] To provide for greater data rates, two or more carriers can be aggregated and simultaneously transmitted to/from the same UE using carrier aggregation (CA). The aggregated carriers in CA may be referred to as component carriers (CCs). When CA is used, there are a number of serving cells for the UE, one for a CC. The CCs may have three configurations in the frequency domain.

[0130] FIG. **10**A illustrates the three CA configurations with two CCs. In the intraband, contiguous configuration **1002**, the two CCs are aggregated in the same frequency band (frequency band A) and are located directly adjacent to each other within the frequency band. In the intraband, non-contiguous configuration **1004**, the two CCs are aggregated in the same frequency band (frequency band A) and are separated in the frequency band by a gap. In the interband configuration **1006**, the two CCs are located in frequency bands (frequency band A and frequency band B).

[0131] In an example, up to 32 CCs may be aggregated. The aggregated CCs may have the same or different bandwidths, subcarrier spacing, and/or duplexing schemes (TDD or FDD). A serving cell for a UE using CA may have a downlink CC. For FDD, one or more uplink CCs may be optionally configured for a serving cell. The ability to aggregate more downlink carriers than uplink carriers may be useful, for example, when the UE has more data traffic in the downlink than in the uplink.

[0132] When CA is used, one of the aggregated cells for a UE may be referred to as a primary cell (PCell). The PCell may be the serving cell that the UE initially connects to at RRC connection establishment, reestablishment, and/or handover. The PCell may provide the UE with NAS mobility information and the security input. UEs may have different PCells. In the downlink, the carrier corresponding to the PCell may be referred to as the downlink primary CC (DL PCC). In the uplink, the carrier corresponding to the PCell may be referred to as the uplink primary CC (UL PCC). The other aggregated cells for the UE may be referred to as secondary cells (SCells). In an example, the SCells may be configured after the PCell is configured for the UE. For example, an SCell may be configured through an RRC Connection Reconfiguration procedure. In the downlink, the carrier corresponding to an SCell may be referred to as a downlink secondary CC (DL SCC). In the uplink, the carrier corresponding to the SCell may be referred to as the uplink secondary CC (UL SCC).

[0133] Configured SCells for a UE may be activated and deactivated based on, for example, traffic and channel conditions. Deactivation of an SCell may mean that PDCCH and PDSCH reception on the SCell is stopped and PUSCH, SRS, and CQI transmissions on the SCell are stopped. Configured SCells may be activated and deactivated using a MAC CE with respect to FIG. **4**B. For example, a MAC CE may use a bitmap (e.g., one bit per SCell) to indicate which SCells (e.g., in a subset of configured SCells) for the UE are activated or deactivated. Configured SCells may be deactivated in response to an expiration of an SCell deactivation timer (e.g., one SCell deactivation timer per SCell).

[0134] Downlink control information, such as scheduling assignments and scheduling grants, for a cell may be transmitted on the cell corresponding to the assignments and grants, which is known as self-scheduling. The DCI for the cell may be transmitted on another cell, which is known as cross-carrier scheduling. Uplink control information (e.g., HARQ acknowledgments and channel state feedback, such as CQI, PMI, and/or RI) for aggregated cells may be transmitted on the PUCCH of the PCell. For a larger number of aggregated downlink CCs, the PUCCH of the PCell may become overloaded. Cells may be divided into multiple PUCCH groups.

[0135] FIG. **10**B illustrates an example of how aggregated cells may be configured into one or more PUCCH groups. A PUCCH group **1010** and a PUCCH group **1050** may include one or more downlink CCs, respectively. In the example of FIG. **10**B, the PUCCH group **1010** includes three downlink CCs: a PCell **1011**, an SCell **1012**, and an SCell **1013**. The PUCCH group **1050** includes three downlink CCs in the present example: a PCell **1051**, an SCell **1052**, and an SCell **1053**. One or more uplink CCs may be configured as a PCell **1021**, an SCell **1022**, and an SCell **1023**. One or more other uplink CCs may be configured as a primary Scell (PSCell) **1061**, an SCell **1062**, and an SCell **1063**. Uplink control information (UCI) related to the downlink CCs of the PUCCH group **1010**, shown as UCI **1031**, UCI **1032**, and UCI **1033**, may be transmitted in the uplink of the PCell **1021**. Uplink control information (UCI) related to the downlink CCs of the PUCCH group **1050**, shown as UCI **1071**, UCI **1072**, and UCI **1073**, may be transmitted in the uplink of the PSCell **1061**. In an example, if the aggregated cells depicted in FIG. **10**B were not divided into the PUCCH group **1010** and the PUCCH group **1050**, a single uplink PCell to transmit UCI relating to the downlink CCs, and the PCell may become overloaded. By dividing transmissions of UCI between the PCell **1021** and the PSCell **1061**, overloading may be prevented.

[0136] A cell, comprising a downlink carrier and optionally an uplink carrier, may be assigned with a physical cell ID and a cell index. The physical cell ID or the cell index may identify a downlink carrier and/or an uplink carrier of the cell, for example, depending on the context in which the physical cell ID is used. A physical cell ID may be determined using a synchronization signal transmitted on a downlink component carrier. A cell index may be determined using RRC messages. In the disclosure, a physical cell ID may be referred to as a carrier ID, and a cell index may be referred to as a carrier index. For example, when the disclosure refers to a first physical cell ID for a first downlink carrier, the disclosure may mean the first physical cell ID is for a cell comprising the first downlink carrier. The same/similar concept may apply to, for example, a carrier activation. When the disclosure indicates that a first carrier is activated, the specification may mean that a cell comprising the first carrier is activated.

[0137] In CA, a multi-carrier nature of a PHY may be exposed to a MAC. In an example, a HARQ entity may operate on a serving cell. A transport block may be generated per assignment/grant per serving cell. A transport block and potential HARQ retransmissions of the transport block may be mapped to a serving cell.

[0138] In the downlink, a base station may transmit (e.g., unicast, multicast, and/or broadcast) one or more Reference Signals (RSs) to a UE (e.g., PSS, SSS, CSI-RS, DMRS, and/or PT-RS, as shown in FIG. **5**A). In the uplink, the UE may transmit one or more RSs to the base station (e.g., DMRS, PT-RS, and/or SRS, as shown in FIG. **5**B). The PSS and the SSS may be transmitted by the base station and used by the UE to synchronize the UE to the base station. The PSS and the SSS may be provided in a synchronization signal (SS)/physical broadcast channel (PBCH) block that includes the PSS, the SSS, and the PBCH. The base station may periodically transmit a burst of SS/PBCH blocks.

[0139] FIG. **11**A illustrates an example of an SS/PBCH block's structure and location. A burst of SS/PBCH blocks may include one or more SS/PBCH blocks (e.g., 4 SS/PBCH blocks, as shown in FIG. **11**A). Bursts may be transmitted periodically (e.g., every 2 frames or 20 ms). A burst may be restricted to a half-frame (e.g., a first half-frame having a duration of 5 ms). It will be understood that FIG. **11**A is an example, and that these parameters (number of SS/PBCH blocks per burst, periodicity of bursts, position of burst within the frame) may be configured based on, for example: a carrier frequency of a cell in which the SS/PBCH block is transmitted; a numerology or subcarrier spacing of the cell; a configuration by the network (e.g., using RRC signaling); or any other suitable factor. In an example, the UE may assume a subcarrier spacing for the SS/PBCH block based on the carrier frequency being monitored, unless the radio network configured the UE to assume a different subcarrier spacing.

[0140] The SS/PBCH block may span one or more OFDM symbols in the time domain (e.g., 4 OFDM symbols, as shown in the example of FIG. **11**A) and may span one or more subcarriers in the frequency domain (e.g., **240** contiguous subcarriers). The PSS, the SSS, and the PBCH may have a common center frequency. The PSS may be transmitted first and may span, for example, 1 OFDM symbol and 127 subcarriers. The SSS may be transmitted after the PSS (e.g., two symbols later) and may span 1 OFDM symbol and 127 subcarriers. The PBCH may be transmitted after the PSS (e.g., across the next 3 OFDM symbols) and may span 240 subcarriers.

[0141] The location of the SS/PBCH block in the time and frequency domains may not be known to the UE (e.g., if the UE is searching for the cell). To find and select the cell, the UE may monitor a carrier for the PSS. For example, the UE may monitor a frequency location within the carrier. If the PSS is not found after a certain duration (e.g., 20 ms), the UE may search for the PSS at a different frequency location within the carrier, as indicated by a synchronization raster. If the PSS is found at a location in the time and frequency domains, the UE may determine, based on a known structure of the SS/PBCH block, the locations of the SSS and the PBCH, respectively. The SS/PBCH block may be a cell-defining SS block (CD-SSB). In an example, a primary cell may be associated with a CD-SSB. The CD-SSB may be located on a synchronization raster. In an example, a cell selection/search and/or reselection may be based on the CD-SSB

[0142] The SS/PBCH block may be used by the UE to determine one or more parameters of the cell. For example, the UE may determine a physical cell identifier (PCI) of the cell based on the sequences of the PSS and the SSS, respectively. The UE may determine a location of a frame boundary of the cell based on the location of the SS/PBCH block. For example, the SS/PBCH block may indicate that it has been transmitted in accordance with a transmission pattern, wherein a SS/PBCH block in the transmission pattern is a known distance from the frame boundary.

[0143] The PBCH may use a QPSK modulation and may use forward error correction (FEC). The FEC may use polar coding. One or more symbols spanned by the PBCH may carry one or more DMRSs for demodulation of the PBCH. The PBCH may include an indication of a current system frame number (SFN) of the cell and/or a SS/PBCH block timing index. These parameters may facilitate time synchronization of the UE to the base station. The PBCH may include a master information block (MIB) used to provide the UE with one or more parameters. The MIB may be used by the UE to locate remaining minimum system information (RMSI) associated with the cell. The RMSI may include a System Information Block Type 1 (SIB1). The SIB1 may contain information needed by the UE to access the cell. The UE may use one or more parameters of the MIB to monitor PDCCH, which may be used to schedule PDSCH. The PDSCH may include the SIB1. The SIB1 may be decoded using parameters provided in the MIB. The PBCH may indicate an absence of SIB1. Based on the PBCH indicating the absence of SIB1, the UE may be pointed to a frequency. The UE may search for an SS/PBCH block at the frequency to which the UE is pointed.

[0144] The UE may assume that one or more SS/PBCH blocks transmitted with a same SS/PBCH block index are quasi co-located (QCLed) (e.g., having the same/similar Doppler spread, Doppler shift, average gain, average delay, and/or spatial Rx parameters). The UE may not assume QCL for SS/PBCH block transmissions having different SS/PBCH block indices.

[0145] SS/PBCH blocks (e.g., those within a half-frame) may be transmitted in spatial directions (e.g., using different beams that span a coverage area of the cell). In an example, a first SS/PBCH block may be transmitted in a first spatial direction using a first beam, and a second SS/PBCH block may be transmitted in a second spatial direction using a second beam.

[0146] In an example, within a frequency span of a carrier, a base station may transmit a plurality of SS/PBCH blocks. In an example, a first PCI of a first SS/PBCH block of the plurality of SS/PBCH blocks may be different from a second PCI of a second SS/PBCH block of the plurality of SS/PBCH blocks. The PCIs of SS/PBCH blocks transmitted in different frequency locations may be different or the same.

[0147] The CSI-RS may be transmitted by the base station and used by the UE to acquire channel state information (CSI). The base station may configure the UE with one or more CSI-RSs for channel estimation or any other suitable purpose. The base station may configure a UE with one or more of the same/similar CSI-RSs. The UE may measure the one or more CSI-RSs. The UE may estimate a downlink channel state and/or generate a CSI report based on the measuring of the one or more downlink CSI-RSs. The UE may provide the CSI report to the base station. The base station may use feedback provided by the UE (e.g., the estimated downlink channel state) to perform link adaptation.

[0148] The base station may semi-statically configure the UE with one or more CSI-RS resource sets. A CSI-RS resource may be associated with a location in the time and frequency domains and a periodicity. The base station may selectively activate and/or deactivate a CSI-RS resource. The base station may indicate to the UE that a CSI-RS resource in the CSI-RS resource set is activated and/or deactivated.

[0149] The base station may configure the UE to report CSI measurements. The base station may configure the UE to provide CSI reports periodically, aperiodically, or semi-persistently. For periodic CSI reporting, the UE may be configured with a timing and/or periodicity of a plurality of CSI reports. For aperiodic CSI reporting, the base station may request a CSI report. For example, the base station may command the UE to measure a configured CSI-RS resource and provide a CSI report relating to the measurements. For semi-persistent CSI reporting, the base station may configure the UE to transmit periodically, and selectively activate or deactivate the periodic reporting. The base station may configure the UE with a CSI-RS resource set and CSI reports using RRC signaling.

[0150] The CSI-RS configuration may comprise one or more parameters indicating, for example, up to 32 antenna ports. The UE may be configured to employ the same OFDM symbols for a downlink CSI-RS and a control resource set (CORESET) when the downlink CSI-RS and CORESET are spatially QCLed and resource elements associated with the downlink CSI-RS are outside of the physical resource blocks (PRBs) configured for the CORESET. The UE may be configured to employ the same OFDM symbols for downlink CSI-RS and SS/PBCH blocks when the downlink CSI-RS and SS/PBCH blocks are spatially QCLed and resource elements associated with the downlink CSI-RS are outside of PRBs configured for the SS/PBCH blocks.

[0151] Downlink DMRSs may be transmitted by a base station and used by a UE for channel estimation. For example, the downlink DMRS may be used for coherent demodulation of one or more downlink physical channels (e.g., PDSCH). An NR network may support one or more variable and/or configurable DMRS patterns for data demodulation. At least one downlink DMRS configuration may support a front-loaded DMRS pattern. A front-loaded DMRS may be mapped over one or more OFDM symbols (e.g., one or two adjacent OFDM symbols). A base station may semi-statically configure the UE with a number (e.g. a maximum number) of front-loaded DMRS symbols for PDSCH. A DMRS configuration may support one or more DMRS ports. For example, for single user-MIMO, a DMRS configuration may support up to eight orthogonal downlink DMRS ports per UE. For multiuser-MIMO, a DMRS configuration may support up to 4 orthogonal downlink DMRS ports per UE. A radio network may support (e.g., at least for CP-OFDM) a common DMRS structure for downlink and uplink, wherein a DMRS location, a DMRS pattern, and/or a scrambling sequence may be the same or different. The base station may transmit a downlink DMRS and a corresponding PDSCH using the same precoding matrix. The UE may use the one or more downlink DMRSs for coherent demodulation/channel estimation of the PDSCH.

[0152] In an example, a transmitter (e.g., a base station) may use a precoder matrices for a part of a transmission bandwidth. For example, the transmitter may use a first precoder matrix for a first bandwidth and a second precoder matrix for a second bandwidth. The first precoder matrix and the second precoder matrix may be different based on the first bandwidth being different from the second bandwidth. The UE may assume that a same precoding matrix is used across a set of PRBs. The set of PRBs may be denoted as a precoding resource block group (PRG).

[0153] A PDSCH may comprise one or more layers. The UE may assume that at least one symbol with DMRS is present on a layer of the one or more layers of the PDSCH. A higher layer may configure up to 3 DMRSs for the PDSCH.

[0154] Downlink PT-RS may be transmitted by a base station and used by a UE for phase-noise compensation. Whether a downlink PT-RS is present or not may depend on an RRC configuration. The presence and/or pattern of the downlink PT-RS may be configured on a UE-specific basis using a combination of RRC signaling and/or an association with one or more parameters employed for other purposes (e.g., modulation and coding scheme (MCS), which may be indicated by DCI. When configured, a dynamic presence of a downlink PT-RS may be associated with one or more DCI parameters comprising at least MCS. An NR network may support a plurality of PT-RS densities defined in the time and/or frequency domains. When present, a frequency domain density may be associated with at least one configuration of a scheduled bandwidth. The UE may assume a same precoding for a DMRS port and a PT-RS port. A number of PT-RS ports may be fewer than a number of DMRS ports in a scheduled resource. Downlink PT-RS may be confined in the scheduled time/frequency duration for the UE. Downlink PT-RS may be transmitted on symbols to facilitate phase tracking at the receiver.

[0155] The UE may transmit an uplink DMRS to a base station for channel estimation. For example, the base station may use the uplink DMRS for coherent demodulation of one or more uplink physical channels. For example, the UE may transmit an uplink DMRS with a PUSCH and/or a PUCCH. The uplink DM-RS may span a range of frequencies that is similar to a range of frequencies associated with the corresponding physical channel. The base station may configure the UE with one or more uplink DMRS configurations. At least one DMRS configuration may support a front-loaded DMRS pattern. The front-loaded DMRS may be mapped over one or more OFDM symbols (e.g., one or two adjacent OFDM symbols). One or more uplink DMRSs may be configured to transmit at one or more symbols of a PUSCH and/or a PUCCH. The base station may semi-statically configure the UE with a number (e.g. maximum number) of front-loaded DMRS symbols for the PUSCH and/or the PUCCH, which the UE may use to schedule a single-symbol DMRS and/or a double-symbol DMRS. An NR network may support (e.g., for cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) a common DMRS structure for downlink and uplink, wherein a DMRS location, a DMRS pattern, and/or a scrambling sequence for the DMRS may be the same or different.

[0156] A PUSCH may comprise one or more layers, and the UE may transmit at least one symbol with DMRS present on a layer of the one or more layers of the PUSCH. In an example, a higher layer may configure up to three DMRSs for the PUSCH.

[0157] Uplink PT-RS (which may be used by a base station for phase tracking and/or phase-noise compensation) may or may not be present depending on an RRC configuration of the UE. The presence and/or pattern of uplink PT-RS may be configured on a UE-specific basis by a combination of RRC signaling and/or one or more parameters employed for other purposes (e.g., Modulation and Coding Scheme (MCS), which may be indicated by DCI. When configured, a dynamic presence of uplink PT-RS may be associated with one or more DCI parameters comprising at least MCS. A radio network may support a plurality of uplink PT-RS densities defined in time/frequency domain. When present, a frequency domain density may be associated with at least one configuration of a scheduled bandwidth. The UE may assume a same precoding for a DMRS port and a PT-RS port. A number of PT-RS ports may be fewer than a number of DMRS ports in a scheduled resource. For example, uplink PT-RS may be confined in the scheduled time/frequency duration for the UE.

[0158] SRS may be transmitted by a UE to a base station for channel state estimation to support uplink channel dependent scheduling and/or link adaptation. SRS transmitted by the UE may allow a base station to estimate an uplink channel state at one or more frequencies. A scheduler at the base station may employ the estimated uplink channel state to assign one or more resource blocks for an uplink PUSCH transmission from the UE. The base station may semi-statically configure the UE with one or more SRS resource sets. For an SRS resource set, the base station may configure the UE with one or more SRS resources. An SRS resource set applicability may be configured by a higher layer (e.g., RRC) parameter. For example, when a higher layer parameter indicates beam management, an SRS resource in a SRS resource set of the one or more SRS resource sets (e.g., with the same/similar time domain behavior, periodic, aperiodic, and/or the like) may be transmitted at a time instant (e.g., simultaneously). The UE may transmit one or more SRS resources in SRS resource sets. An NR network may support aperiodic, periodic and/or semi-persistent SRS transmissions. The UE may transmit SRS resources based on one or more trigger types, wherein the one or more trigger types may comprise higher layer signaling (e.g., RRC) and/or one or more DCI formats. In an example, at least one DCI format may be employed for the UE to select at least one of one or more configured SRS resource sets. An SRS trigger type 0 may refer to an SRS triggered based on a higher layer signaling. An SRS trigger type 1 may refer to an SRS triggered based on one or more DCI formats. In an example, when PUSCH and SRS are transmitted in a same slot, the UE may be configured to transmit SRS after a transmission of a PUSCH and a corresponding uplink DMRS.

[0159] The base station may semi-statically configure the UE with one or more SRS configuration parameters indicating at least one of following: a SRS resource configuration identifier; a number of SRS ports; time domain behavior of an SRS resource configuration (e.g., an indication of periodic, semi-persistent, or aperiodic SRS); slot, mini-slot, and/or subframe level periodicity; offset for a periodic and/or an aperiodic SRS resource; a number of OFDM symbols in an SRS resource; a starting OFDM symbol of an SRS resource; an SRS bandwidth; a frequency hopping bandwidth; a cyclic shift; and/or an SRS sequence ID.

[0160] 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. If a first symbol and a second symbol are transmitted on the same antenna port, the receiver may infer the channel (e.g., fading gain, multipath delay, and/or the like) for conveying the second symbol on the antenna port, from the channel for conveying the first symbol on the antenna port. A first antenna port and a second antenna port may be referred to as quasi co-located (QCLed) if one or more large-scale properties of the channel over which a first symbol on the first antenna port is conveyed may be inferred from the channel over which a second symbol on a second antenna port is conveyed. The one or more large-scale properties may comprise at least one of: a delay spread; a Doppler spread; a Doppler shift; an average gain; an average delay; and/or spatial Receiving (Rx) parameters.

[0161] Channels that use beamforming require beam management. Beam management may comprise beam measurement, beam selection, and beam indication. A beam may be associated with one or more reference signals. For example, a beam may be identified by one or more beamformed reference signals. The UE may perform downlink beam measurement based on downlink reference signals (e.g., a channel state information reference signal (CSI-RS)) and generate a beam measurement report. The UE may perform the downlink beam measurement procedure after an RRC connection is set up with a base station.

[0162] FIG. **11**B illustrates an example of channel state information reference signals (CSI-RSs) that are mapped in the time and frequency domains. A square shown in FIG. **11**B may span a resource block (RB) within a bandwidth of a cell. A base station may transmit one or more RRC messages comprising CSI-RS resource configuration parameters indicating one or more CSI-RSs. One or more of the following parameters may be configured by higher layer signaling (e.g., RRC and/or MAC signaling) for a CSI-RS resource configuration: a CSI-RS resource configuration identity, a number of CSI-RS ports, a CSI-RS configuration (e.g., symbol and resource element (RE) locations in a subframe), a CSI-RS subframe configuration (e.g., subframe location, offset, and periodicity in a radio frame), a CSI-RS power parameter, a CSI-RS sequence parameter, a code division multiplexing (CDM) type parameter, a frequency density, a transmission comb, quasi co-location (QCL) parameters (e.g., QCL-scramblingidentity, crs-portscount, mbsfn-subframeconfiglist, csi-rs-configZPid, qcl-csi-rs-configNZPid), and/or other radio resource parameters.

[0163] The three beams illustrated in FIG. **11**B may be configured for a UE in a UE-specific configuration. Three beams are illustrated in FIG. **11**B (beam #1, beam #2, and beam #3), more or fewer beams may be configured. Beam #1 may be allocated with CSI-RS 1101 that may be transmitted in one or more subcarriers in an RB of a first symbol. Beam #2 may be allocated with CSI-RS 1102 that may be transmitted in one or more subcarriers in an RB of a second symbol. Beam #3 may be allocated with CSI-RS 1103 that may be transmitted in one or more subcarriers in an RB of a third symbol. By using frequency division multiplexing (FDM), a base station may use other subcarriers in a same RB (for example, those that are not used to transmit CSI-RS 1101) to transmit another CSI-RS associated with a beam for another UE. By using time domain multiplexing (TDM), beams used for the UE may be configured such that beams for the UE use symbols from beams of other UEs.

[0164] CSI-RSs such as those illustrated in FIG. **11**B (e.g., CSI-RS 1101, 1102, 1103) may be transmitted by the base station and used by the UE for one or more measurements. For example, the UE may measure a reference signal received power (RSRP) of configured CSI-RS resources. The base station may configure the UE with a reporting configuration and the UE may report the RSRP measurements to a network (for example, via one or more base stations) based on the reporting configuration. In an example, the base station may determine, based on the reported measurement results, one or more transmission configuration indication (TCI) states comprising a number of reference signals. In an example, the base station may indicate one or more TCI states to the UE (e.g., via RRC signaling, a MAC CE, and/or a DCI). The UE may receive a downlink transmission with a receive (Rx) beam determined based on the one or more TCI states. In an example, the UE may or may not have a capability of beam correspondence. If the UE has the capability of beam correspondence, the UE may determine a spatial domain filter of a transmit (Tx) beam based on a spatial domain filter of the corresponding Rx beam. If the UE does not have the capability of beam correspondence, the UE may perform an uplink beam selection procedure to determine the spatial domain filter of the Tx beam. The UE may perform the uplink beam selection procedure based on one or more sounding reference signal (SRS) resources configured to the UE by the base station. The base station may select and indicate uplink beams for the UE based on measurements of the one or more SRS resources transmitted by the UE.

[0165] In a beam management procedure, a UE may assess (e.g., measure) a channel quality of one or more beam pair links, a beam pair link comprising a transmitting beam transmitted by a base station and a receiving beam received by the UE. Based on the assessment, the UE may transmit a beam measurement report indicating one or more beam pair quality parameters comprising, e.g., one or more beam identifications (e.g., a beam index, a reference signal index, or the like), RSRP, a precoding matrix indicator (PMI), a channel quality indicator (CQI), and/or a rank indicator (RI).

[0166] FIG. **12**A illustrates examples of three downlink beam management procedures: P1, P2, and P3. Procedure P1 may enable a UE measurement on transmit (Tx) beams of a transmission reception point (TRP) (or multiple TRPs), e.g., to support a selection of one or more base station Tx beams and/or UE Rx beams (shown as ovals in the top row and bottom row, respectively, of P1). Beamforming at a TRP may comprise a Tx beam sweep for a set of beams (shown, in the top rows of P1 and P2, as ovals rotated in a counter-clockwise direction indicated by the dashed arrow). Beamforming at a UE may comprise an Rx beam sweep for a set of beams (shown, in the bottom rows of P1 and P3, as ovals rotated in a clockwise direction indicated by the dashed arrow). Procedure P2 may be used to enable a UE measurement on Tx beams of a TRP (shown, in the top row of P2, as ovals rotated in a counter-clockwise direction indicated by the dashed arrow). The UE and/or the base station may perform procedure P2 using a smaller set of beams than is used in procedure P1, or using narrower beams than the beams used in procedure P1. This may be referred to as beam refinement. The UE may perform procedure P3 for Rx beam determination by using the same Tx beam at the base station and sweeping an Rx beam at the UE.

[0167] FIG. **12**B illustrates examples of three uplink beam management procedures: U1, U2, and U3. Procedure U1 may be used to enable a base station to perform a measurement on Tx beams of a UE, e.g., to support a selection of one or more UE Tx beams and/or base station Rx beams (shown as ovals in the top row and bottom row, respectively, of U1). Beamforming at the UE may include, e.g., a Tx beam sweep from a set of beams (shown in the bottom rows of U1 and U3 as ovals rotated in a clockwise direction indicated by the dashed arrow). Beamforming at the base station may include, e.g., an Rx beam sweep from a set of beams (shown, in the top rows of U1 and U2, as ovals rotated in a counter-clockwise direction indicated by the dashed arrow). Procedure U2 may be used to enable the base station to adjust its Rx beam when the UE uses a fixed Tx beam. The UE and/or the base station may perform procedure U2 using a smaller set of beams than is used in procedure P1, or using narrower beams than the beams used in procedure P1. This may be referred to as beam refinement The UE may perform procedure U3 to adjust its Tx beam when the base station uses a fixed Rx beam.

[0168] A UE may initiate a beam failure recovery (BFR) procedure based on detecting a beam failure. The UE may transmit a BFR request (e.g., a preamble, a UCI, an SR, a MAC CE, and/or the like) based on the initiating of the BFR procedure. The UE may detect the beam failure based on a determination that a quality of beam pair link(s) of an associated control channel is unsatisfactory (e.g., having an error rate higher than an error rate threshold, a received signal power lower than a received signal power threshold, an expiration of a timer, and/or the like).

[0169] The UE may measure a quality of a beam pair link using one or more reference signals (RSs) comprising one or more SS/PBCH blocks, one or more CSI-RS resources, and/or one or more demodulation reference signals (DMRSs). A quality of the beam pair link may be based on one or more of a block error rate (BLER), an RSRP value, a signal to interference plus noise ratio (SINR) value, a reference signal received quality (RSRQ) value, and/or a CSI value measured on RS resources. The base station may indicate that an RS resource is quasi co-located (QCLed) with one or more DM-RSs of a channel (e.g., a control channel, a shared data channel, and/or the like). The RS resource and the one or more DMRSs of the channel may be QCLed when the channel characteristics (e.g., Doppler shift, Doppler spread, average delay, delay spread, spatial Rx parameter, fading, and/or the like) from a transmission via the RS resource to the UE are similar or the same as the channel characteristics from a transmission via the channel to the UE.

[0170] A network (e.g., a gNB and/or an ng-eNB of a network) and/or the UE may initiate a random access procedure. A UE in an RRC_IDLE state and/or an RRC_INACTIVE state may initiate the random access procedure to request a connection setup to a network. The UE may initiate the random access procedure from an RRC_CONNECTED state. The UE may initiate the random access procedure to request uplink resources (e.g., for uplink transmission of an SR when there is no PUCCH resource available) and/or acquire uplink timing (e.g., when uplink synchronization status is non-synchronized). The UE may initiate the random access procedure to request one or more system information blocks (SIBs) (e.g., other system information such as SIB2, SIB3, and/or the like). The UE may initiate the random access procedure for a beam failure recovery request. A network may initiate a random access procedure for a handover and/or for establishing time alignment for an SCell addition.

[0171] FIG. **13**A illustrates a four-step contention-based random access procedure. Prior to initiation of the procedure, a base station may transmit a configuration message **1310** to the UE. The procedure illustrated in FIG. **13**A comprises transmission of four messages: a Msg 1 **1311**, a Msg 2 **1312**, a Msg 3 **1313**, and a Msg 4 **1314**. The Msg 1 **1311** may include and/or be referred to as a preamble (or a random access preamble). The Msg 2 **1312** may include and/or be referred to as a random access response (RAR).

[0172] The configuration message **1310** may be transmitted, for example, using one or more RRC messages. The one or more RRC messages may indicate one or more random access channel (RACH) parameters to the UE. The one or more RACH parameters may comprise at least one of following: general parameters for one or more random access procedures (e.g., RACH-configGeneral); cell-specific parameters (e.g., RACH-ConfigCommon); and/or dedicated parameters (e.g., RACH-configDedicated). The base station may broadcast or multicast the one or more RRC messages to one or more UEs. The one or more RRC messages may be UE-specific (e.g., dedicated RRC messages transmitted to a UE in an RRC_CONNECTED state and/or in an RRC_INACTIVE state). The UE may determine, based on the one or more RACH parameters, a time-frequency resource and/or an uplink transmit power for transmission of the Msg 1 **1311** and/or the Msg 3 **1313**. Based on the one or more RACH parameters, the UE may determine a reception timing and a downlink channel for receiving the Msg 2 **1312** and the Msg 4 **1314**.

[0173] The one or more RACH parameters provided in the configuration message **1310** may indicate one or more Physical RACH (PRACH) occasions available for transmission of the Msg 1 **1311**. The one or more PRACH occasions may be predefined. The one or more RACH parameters may indicate one or more available sets of one or more PRACH occasions (e.g., prach-ConfigIndex). The one or more RACH parameters may indicate an association between (a) one or more PRACH occasions and (b) one or more reference signals. The one or more RACH parameters may indicate an association between (a) one or more preambles and (b) one or more reference signals. The one or more reference signals may be SS/PBCH blocks and/or CSI-RSs. For example, the one or more RACH parameters may indicate a number of SS/PBCH blocks mapped to a PRACH occasion and/or a number of preambles mapped to a SS/PBCH blocks.

[0174] The one or more RACH parameters provided in the configuration message **1310** may be used to determine an uplink transmit power of Msg 1 **1311** and/or Msg 3 **1313**. For example, the one or more RACH parameters may indicate a reference power for a preamble transmission (e.g., a received target power and/or an initial power of the preamble transmission). There may be one or more power offsets indicated by the one or more RACH parameters. For example, the one or more RACH parameters may indicate: a power ramping step; a power offset between SSB and CSI-RS; a power offset between transmissions of the Msg 1 **1311** and the Msg 3 **1313**; and/or a power offset value between preamble groups. The one or more RACH parameters may indicate one or more thresholds based on which the UE may determine at least one reference signal (e.g., an SSB and/or CSI-RS) and/or an uplink carrier (e.g., a normal uplink (NUL) carrier and/or a supplemental uplink (SUL) carrier).

[0175] The Msg 1 **1311** may include one or more preamble transmissions (e.g., a preamble transmission and one or more preamble retransmissions). An RRC message may be used to configure one or more preamble groups (e.g., group A and/or group B). A preamble group may comprise one or more preambles. The UE may determine the preamble group based on a pathloss measurement and/or a size of the Msg 3 **1313**. The UE may measure an RSRP of one or more reference signals (e.g., SSBs and/or CSI-RSs) and determine at least one reference signal having an RSRP above an RSRP threshold (e.g., rsrp-ThresholdSSB and/or rsrp-ThresholdCSI-RS). The UE may select at least one preamble associated with the one or more reference signals and/or a selected preamble group, for example, if the association between the one or more preambles and the at least one reference signal is configured by an RRC message.

[0176] The UE may determine the preamble based on the one or more RACH parameters provided in the configuration message **1310**. For example, the UE may determine the preamble based on a pathloss measurement, an RSRP measurement, and/or a size of the Msg 3 **1313**. As another example, the one or more RACH parameters may indicate: a preamble format; a maximum number of preamble transmissions; and/or one or more thresholds for determining one or more preamble groups (e.g., group A and group B). A base station may use the one or more RACH parameters to configure the UE with an association between one or more preambles and one or more reference signals (e.g., SSBs and/or CSI-RSs). If the association is configured, the UE may determine the preamble to include in Msg 1 **1311** based on the association. The Msg 1 **1311** may be transmitted to the base station via one or more PRACH occasions. The UE may use one or more reference signals (e.g., SSBs and/or CSI-RSs) for selection of the preamble and for determining of the PRACH occasion. One or more RACH parameters (e.g., ra-ssb-OccasionMskIndex and/or ra-OccasionList) may indicate an association between the PRACH occasions and the one or more reference signals.

[0177] The UE may perform a preamble retransmission if no response is received following a preamble transmission. The UE may increase an uplink transmit power for the preamble retransmission. The UE may select an initial preamble transmit power based on a pathloss measurement and/or a target received preamble power configured by the network. The UE may determine to retransmit a preamble and may ramp up the uplink transmit power. The UE may receive one or more RACH parameters (e.g., PREAMBLE_POWER_RAMPING_STEP) indicating a ramping step for the preamble retransmission. The ramping step may be an amount of incremental increase in uplink transmit power for a retransmission. The UE may ramp up the uplink transmit power if the UE determines a reference signal (e.g., SSB and/or CSI-RS) that is the same as a previous preamble transmission. The UE may count a number of preamble transmissions and/or retransmissions (e.g., PREAMBLE_TRANSMISSION_COUNTER). The UE may determine that a random access procedure completed unsuccessfully, for example, if the number of preamble transmissions exceeds a threshold configured by the one or more RACH parameters (e.g., preambleTransMax).

[0178] The Msg 2 **1312** received by the UE may include an RAR. In some scenarios, the Msg 2 **1312** may include multiple RARs corresponding to multiple UEs. The Msg 2 **1312** may be received after or in response to the transmitting of the Msg 1 **1311**. The Msg 2 **1312** may be scheduled on the DL-SCH and indicated on a PDCCH using a random access RNTI (RA-RNTI). The Msg 2 **1312** may indicate that the Msg 1 **1311** was received by the base station. The Msg 2 **1312** may include a time-alignment command that may be used by the UE to adjust the UE's transmission timing, a scheduling grant for transmission of the Msg 3 **1313**, and/or a Temporary Cell RNTI (TC-RNTI). After transmitting a preamble, the UE may start a time window (e.g., ra-ResponseWindow) to monitor a PDCCH for the Msg 2 **1312**. The UE may determine when to start the time window based on a PRACH occasion that the UE uses to transmit the preamble. For example, the UE may start the time window one or more symbols after a last symbol of the preamble (e.g., at a first PDCCH occasion from an end of a preamble transmission). The one or more symbols may be determined based on a numerology. The PDCCH may be in a common search space (e.g., a Type1-PDCCH common search space) configured by an RRC message. The UE may identify the RAR based on a Radio Network Temporary Identifier (RNTI). RNTIs may be used depending on one or more events initiating the random access procedure. The UE may use random access RNTI (RA-RNTI). The RA-RNTI may be associated with PRACH occasions in which the UE transmits a preamble. For example, the UE may determine the RA-RNTI based on: an OFDM symbol index; a slot index; a frequency domain index; and/or a UL carrier indicator of the PRACH occasions. An example of RA-RNTI may be as follows:

$$RA\text{-}RNTI = 1 + s\_id + 14 \times t\_id + 14 \times 80 \times f\_id + 14 \times 80 \times 8 \times ul\_carrier\_id$$

[0179] where s_id may be an index of a first OFDM symbol of the PRACH occasion (e.g., $0 \le s\_id < 14$), t_id may be an index of a first slot of the PRACH occasion in a system frame (e.g., $0 \le t\_id < 80$), f_id may be an index of the PRACH occasion in the frequency domain (e.g., $0 \le f\_id < 8$), and ul_carrier_id may be a UL carrier used for a preamble transmission (e.g., 0 for an NUL carrier, and 1 for an SUL carrier).

[0180] The UE may transmit the Msg 3 **1313** in response to a successful reception of the Msg 2 **1312** (e.g., using resources identified in the Msg 2 **1312**). The Msg 3 **1313** may be used for contention resolution in, for example, the contention-based random access procedure illustrated in FIG. **13**A. In some scenarios, a plurality of UEs may transmit a same preamble to a base station and the base station may provide an RAR that corresponds to a UE. Collisions may occur if the plurality of UEs interpret the RAR as corresponding to themselves. Contention resolution (e.g., using the Msg 3 **1313** and the Msg 4 **1314**) may be used to increase the likelihood that the UE does not incorrectly use an identity of another the UE. To perform contention resolution, the UE may include a device identifier in the Msg 3 **1313** (e.g., a C-RNTI if assigned, a TC-RNTI included in the Msg 2 **1312**, and/or any other suitable identifier).

[0181] The Msg 4 **1314** may be received after or in response to the transmitting of the Msg 3 **1313**. If a C-RNTI was included in the Msg 3 **1313**, the base station will address the UE on the PDCCH using the C-RNTI. If the UE's unique C-RNTI is detected on the PDCCH, the random access procedure is determined to be successfully completed. If a TC-RNTI is included in the Msg 3 **1313** (e.g., if the UE is in an RRC_IDLE state or not otherwise connected to the base station), Msg 4 **1314** will be received using a DL-SCH associated with the TC-RNTI. If a MAC PDU is successfully decoded and a MAC PDU comprises the UE contention resolution identity MAC CE that matches or otherwise corresponds with the CCCH SDU sent (e.g., transmitted) in Msg 3 **1313**, the UE may determine that the contention resolution is successful and/or the UE may determine that the random access procedure is successfully completed.

[0182] The UE may be configured with a supplementary uplink (SUL) carrier and a normal uplink (NUL) carrier. An initial access (e.g., random access procedure) may be supported in an uplink carrier. For example, a base station may configure the UE with two separate RACH configurations: one for an SUL carrier and the other for an NUL carrier. For random access in a cell configured with an SUL carrier, the network may indicate which carrier to use (NUL or SUL). The UE may determine the SUL carrier, for example, if a measured quality of one or more reference signals is lower than a broadcast threshold. Uplink transmissions of the random access procedure (e.g., the Msg 1 **1311** and/or the Msg 3 **1313**) may remain on the selected carrier. The UE may switch an uplink carrier during the random access procedure (e.g., between the Msg 1 **1311** and the Msg 3 **1313**) in one or more cases. For example, the UE may determine and/or switch an uplink carrier for the Msg 1 **1311** and/or the Msg 3 **1313** based on a channel clear assessment (e.g., a listen-before-talk).

[0183] FIG. **13**B illustrates a two-step contention-free random access procedure. Similar to the four-step contention-based random access procedure illustrated in FIG. **13**A, a base station may, prior to initiation of the procedure, transmit a configuration message **1320** to the UE. The configuration message **1320** may be analogous in some respects to the configuration message **1310**. The procedure illustrated in FIG. **13**B comprises transmission of two messages: a Msg 1 **1321** and a Msg 2 **1322**. The Msg 1 **1321** and the Msg 2 **1322** may be analogous in some respects to the Msg 1 **1311** and a Msg 2 **1312** illustrated in FIG. **13**A, respectively. As will be understood from FIGS. **13**A and **13**B, the contention-free random access procedure may not include messages analogous to the Msg 3 **1313** and/or the Msg 4 **1314**.

[0184] The contention-free random access procedure illustrated in FIG. **13**B may be initiated for a beam failure recovery, other SI request, SCell addition, and/or handover. For example, a base station may indicate or assign to the UE the preamble to be used for the Msg 1 **1321**. The UE may receive, from the base station via PDCCH and/or RRC, an indication of a preamble (e.g., ra-PreambleIndex).

[0185] After transmitting a preamble, the UE may start a time window (e.g., ra-ResponseWindow) to monitor a PDCCH for the RAR. In the event of a beam failure recovery request, the base station may configure the UE with a separate time window and/or a separate PDCCH in a search space indicated by an RRC message (e.g., recoverySearchSpaceld). The UE may monitor for a PDCCH transmission addressed to a Cell RNTI (C-RNTI) on the search space. In the contention-free random access procedure illustrated in FIG. **13**B, the UE may determine that a random access procedure successfully completes after or in response to transmission of Msg 1 **1321** and reception of a corresponding Msg 2 **1322**. The UE may determine that a random access procedure successfully completes, for example, if a PDCCH transmission is addressed to a C-RNTI. The UE may determine that a random access procedure successfully completes, for example, if the UE receives an RAR comprising a preamble identifier corresponding to a preamble transmitted by the UE and/or the RAR comprises a MAC sub-PDU with the preamble identifier. The UE may determine the response as an indication of an acknowledgement for an SI request.

[0186] FIG. **13**C illustrates another two-step random access procedure. Similar to the random access procedures illustrated in FIGS. **13**A and **13**B, a base station may, prior to initiation of the procedure, transmit a configuration message **1330** to the UE. The configuration message **1330** may be analogous in some respects to the configuration message **1310** and/or the configuration message **1320**. The procedure illustrated in FIG. **13**C comprises transmission of two messages: a Msg A **1331** and a Msg B **1332**.

[0187] Msg A **1331** may be transmitted in an uplink transmission by the UE. Msg A **1331** may comprise one or more transmissions of a preamble **1341** and/or one or more transmissions of a transport block **1342**. The transport block **1342** may comprise contents that are similar and/or equivalent to the contents of the Msg 3 **1313** illustrated in FIG. **13**A. The transport block **1342** may comprise UCI (e.g., an SR, a HARQ ACK/NACK, and/or the like). The UE may receive the Msg B **1332** after or in response to transmitting the Msg A **1331**. The Msg B **1332** may comprise contents that are similar and/or equivalent to the contents of the Msg 2 **1312** (e.g., an RAR) illustrated in FIGS. **13**A and **13**B and/or the Msg 4 **1314** illustrated in FIG. **13**A.

[0188] The UE may initiate the two-step random access procedure in FIG. **13**C for licensed spectrum and/or unlicensed spectrum. The UE may determine, based on one or more factors, whether to initiate the two-step random access procedure. The one or more factors may be: a radio access technology in use (e.g., LTE, NR, and/or the like); whether the UE has valid TA or not; a cell size; the UE's RRC state; a type of spectrum (e.g., licensed vs. unlicensed); and/or any other suitable factors.

[0189] The UE may determine, based on two-step RACH parameters included in the configuration message **1330**, a radio resource and/or an uplink transmit power for the preamble **1341** and/or the transport block **1342** included in the Msg A **1331**. The RACH parameters may indicate a modulation and coding schemes (MCS), a time-frequency resource, and/or a power control for the preamble **1341** and/or the transport block **1342**. A time-frequency resource for transmission of the preamble **1341** (e.g., a PRACH) and a time-frequency resource for transmission of the transport block **1342** (e.g., a PUSCH) may be multiplexed using FDM, TDM, and/or CDM. The RACH parameters may enable the UE to determine a reception timing and a downlink channel for monitoring for and/or receiving Msg B **1332**.

[0190] The transport block **1342** may comprise data (e.g., delay-sensitive data), an identifier of the UE, security information, and/or device information (e.g., an International Mobile Subscriber Identity (IMSI). The base station may transmit the Msg B **1332** as a response to the Msg A **1331**. The Msg B **1332** may comprise at least one of following: a preamble identifier; a timing advance command; a power control command; an uplink grant (e.g., a radio resource assignment and/or an MCS); a UE identifier for contention resolution; and/or an RNTI (e.g., a C-RNTI or a TC-RNTI). The UE may determine that the two-step random access procedure is successfully completed if: a preamble identifier in the Msg B **1332** is matched to a preamble transmitted by the UE; and/or the identifier of the UE in Msg B **1332** is matched to the identifier of the UE in the Msg A **1331** (e.g., the transport block **1342**).

[0191] A UE and a base station may exchange control signaling. The control signaling may be referred to as L1/L2 control signaling and may originate from the PHY layer (e.g., layer 1) and/or the MAC layer (e.g., layer 2). The control signaling may comprise downlink control signaling transmitted from the base station to the UE and/or uplink control signaling transmitted from the UE to the base station.

[0192] The downlink control signaling may comprise: a downlink scheduling assignment; an uplink scheduling grant indicating uplink radio resources and/or a transport format; a slot format information; a preemption indication; a power control command; and/or any other suitable signaling. The UE may receive the downlink control signaling in a payload transmitted by the base station on a physical downlink control channel (PDCCH). The payload transmitted on the PDCCH may be referred to as downlink control information (DCI). In some scenarios, the PDCCH may be a group common PDCCH (GC-PDCCH) that is common to a group of UEs.

[0193] A base station may attach one or more cyclic redundancy check (CRC) parity bits to a DCI in order to facilitate detection of transmission errors. When the DCI is intended for a UE (or a group of the UEs), the base station may scramble the CRC parity bits with an identifier of the UE (or an identifier of the group of the UEs). Scrambling the CRC parity bits with the identifier may comprise Modulo-2 addition (or an exclusive OR operation) of the identifier value and the CRC parity bits. The identifier may comprise a 16-bit value of a radio network temporary identifier (RNTI).

[0194] DCIs may be used for different purposes. A purpose may be indicated by the type of RNTI used to scramble the CRC parity bits. For example, a DCI having CRC parity bits scrambled with a paging RNTI (P-RNTI) may indicate paging information and/or a system information change notification. The P-RNTI may be predefined as "FFFE" in hexadecimal. A DCI having CRC parity bits scrambled with a system information RNTI (SI-RNTI) may indicate a broadcast transmission of the system information. The SI-RNTI may be predefined as "FFFF" in hexadecimal. A DCI having CRC parity bits scrambled with a random access RNTI (RA-RNTI) may indicate a random access response (RAR). A DCI having CRC parity bits scrambled with a cell RNTI (C-RNTI) may indicate a dynamically scheduled unicast transmission and/or a triggering of PDCCH-ordered random access. A DCI having CRC parity bits scrambled with a temporary cell RNTI (TC-RNTI) may indicate a contention resolution (e.g., a Msg 3 analogous to the Msg 3 **1313** illustrated in FIG. **13**A). Other RNTIs configured to the UE by a base station may comprise a Configured Scheduling RNTI (CS-RNTI), a Transmit Power Control-PUCCH RNTI (TPC-PUCCH-RNTI), a Transmit Power Control-PUSCH RNTI (TPC-PUSCH-RNTI), a Transmit Power Control-SRS RNTI (TPC-SRS-RNTI), an Interruption RNTI (INT-RNTI), a Slot Format Indication RNTI (SFI-RNTI), a Semi-Persistent CSI RNTI (SP-CSI-RNTI), a Modulation and Coding Scheme Cell RNTI (MCS-C-RNTI), and/or the like.

[0195] Depending on the purpose and/or content of a DCI, the base station may transmit the DCIs with one or more DCI formats. For example, DCI format 0_0 may be used for scheduling of PUSCH in a cell. DCI format 0_0 may be a fallback DCI format (e.g., with compact DCI payloads). DCI format 0_1 may be used for scheduling of PUSCH in a cell (e.g., with more DCI payloads than DCI format 0_0). DCI format 1_0 may be used for scheduling of PDSCH in a cell. DCI format 1_0 may be a fallback DCI format (e.g., with compact DCI payloads). DCI format 1_1 may be used for scheduling of PDSCH in a cell (e.g., with more DCI payloads than DCI format 1_0). DCI format 2_0 may be used for providing a slot format indication to a group of UEs. DCI format 2_1 may be used for notifying a group of UEs of a physical resource block and/or OFDM symbol where the UE may assume no transmission is intended to the UE. DCI format 2_2 may be used for transmission of a transmit power control (TPC) command for PUCCH or PUSCH. DCI format 2_3 may be used for transmission of a group of TPC commands for SRS transmissions by one or more UEs. DCI format(s) for new functions may be defined in future releases. DCI formats may have different DCI sizes, or may share the same DCI size.

[0196] After scrambling a DCI with a RNTI, the base station may process the DCI with channel coding (e.g., polar coding), rate matching, scrambling and/or QPSK modulation. A base station may map the coded and modulated DCI on resource elements used and/or configured for a PDCCH. Based on a payload size of the DCI and/or a coverage of the base station, the base station may transmit the DCI via a PDCCH occupying a number of contiguous control channel elements (CCEs). The number of the contiguous CCEs (referred to as aggregation level) may be 1, 2, 4, 8, 16, and/or any other suitable number. A CCE may comprise a number (e.g., 6) of resource-element groups (REGs). A REG may comprise a resource block in an OFDM symbol. The mapping of the coded and modulated DCI on the resource elements may be based on mapping of CCEs and REGs (e.g., CCE-to-REG mapping).

[0197] FIG. **14**A illustrates an example of CORESET configurations for a bandwidth part. The base station may transmit a DCI via a PDCCH on one or more control resource sets (CORESETs). A CORESET may comprise a time-frequency resource in which the UE tries to decode a DCI using one or more search spaces. The base station may configure a CORESET in the time-frequency domain. In the example of FIG. **14**A, a first CORESET **1401** and a second CORESET **1402** occur at the first symbol in a slot. The first CORESET **1401** overlaps with the second CORESET **1402** in the frequency domain. A third CORESET **1403** occurs at a third symbol in the slot. A fourth CORESET **1404** occurs at the seventh symbol in the slot. CORESETs may have a different number of resource blocks in frequency domain.

[0198] FIG. **14**B illustrates an example of a CCE-to-REG mapping for DCI transmission on a CORESET and PDCCH processing. The CCE-to-REG mapping may be an interleaved mapping (e.g., for the purpose of providing frequency diversity) or a non-interleaved mapping (e.g., for the purposes of facilitating interference coordination and/or frequency-selective transmission of control channels). The base station may perform different or same CCE-to-REG mapping on different CORESETs. A CORESET may be associated with a CCE-to-REG mapping by RRC configuration. A CORESET may be configured with an antenna port quasi co-location (QCL) parameter. The antenna port QCL parameter may indicate QCL information of a demodulation reference signal (DMRS) for PDCCH reception in the CORESET.

[0199] The base station may transmit, to the UE, RRC messages comprising configuration parameters of one or more CORESETs and one or more search space sets. The configuration parameters may indicate an association between a search space set and a CORESET. A search space set may comprise a set of PDCCH candidates formed by CCEs at a given aggregation level. The configuration parameters may indicate: a number of PDCCH candidates to be monitored per aggregation level; a PDCCH monitoring periodicity and a PDCCH monitoring pattern; one or more DCI formats to be monitored by the UE; and/or whether a search space set is a common search space set or a UE-specific search space set. A set of CCEs in the common search space set may be predefined and known to the UE. A set of CCEs in the UE-specific search space set may be configured based on the UE's identity (e.g., C-RNTI).

[0200] As shown in FIG. **14**B, the UE may determine a time-frequency resource for a CORESET based on RRC messages. The UE may determine a CCE-to-REG mapping (e.g., interleaved or non-interleaved, and/or mapping parameters) for the CORESET based on configuration parameters of the CORESET. The UE may determine a number (e.g., at most 10) of search space sets configured on the CORESET based on the RRC messages. The UE may monitor a set of PDCCH candidates according to configuration parameters of a search space set. The UE may monitor a set of PDCCH candidates in one or more CORESETs for detecting one or more DCIs. Monitoring may comprise decoding one or more PDCCH candidates of the set of the PDCCH candidates according to the monitored DCI formats. Monitoring may comprise decoding a DCI content of one or more PDCCH candidates with possible (or configured) PDCCH locations, possible (or configured) PDCCH formats (e.g., number of CCEs, number of PDCCH candidates in common search spaces, and/or number of PDCCH candidates in the UE-specific search spaces) and possible (or configured) DCI formats. The decoding may be referred to as blind decoding. The UE may determine a DCI as valid for the UE, in response to CRC checking (e.g., scrambled bits for CRC parity bits of the DCI matching a RNTI value). The UE may process information contained in the DCI (e.g., a scheduling assignment, an uplink grant, power control, a slot format indication, a downlink preemption, and/or the like).

[0201] The UE may transmit uplink control signaling (e.g., uplink control information (UCI) to a base station. The uplink control signaling may comprise hybrid automatic repeat request (HARQ) acknowledgements for received DL-SCH transport blocks. The UE may transmit the HARQ acknowledgements after receiving a DL-SCH transport block. Uplink control signaling may comprise channel state information (CSI) indicating channel quality of a physical downlink channel. The UE may transmit the CSI to the base station. The base station, based on the received CSI, may determine transmission format parameters (e.g., comprising multi-antenna and beamforming schemes) for a downlink transmission. Uplink control signaling may comprise scheduling requests (SR). The UE may transmit an SR indicating that uplink data is available for transmission to the base station. The UE may transmit a UCI (e.g., HARQ acknowledgements (HARQ-ACK), CSI report, SR, and the like) via a physical uplink control channel (PUCCH) or a physical uplink shared channel (PUSCH). The UE may transmit the uplink control signaling via a PUCCH using one of several PUCCH formats.

[0202] There may be five PUCCH formats and the UE may determine a PUCCH format based on a size of the UCI (e.g., a number of uplink symbols of UCI transmission and a number of UCI bits). PUCCH format 0 may have a length of one or two OFDM symbols and may include two or fewer bits. The UE may transmit UCI in a PUCCH resource using PUCCH format 0 if the transmission is over one or two symbols and the number of HARQ-ACK information bits with positive or negative SR (HARQ-ACK/SR bits) is one or two. PUCCH format 1 may occupy a number between four and fourteen OFDM symbols and may include two or fewer bits. The UE may use PUCCH format 1 if the transmission is four or more symbols and the number of HARQ-ACK/SR bits is one or two. PUCCH format 2 may occupy one or two OFDM symbols and may include more than two bits. The UE may use PUCCH format 2 if the transmission is over one or two symbols and the number of UCI bits is two or more. PUCCH format 3 may occupy a number between four and fourteen OFDM symbols and may include more than two bits. The UE may use PUCCH format 3 if the transmission is four or more symbols, the number of UCI bits is two or more and PUCCH resource does not include an orthogonal cover code. PUCCH format 4 may occupy a number between four and fourteen OFDM symbols and may include more than two bits. The UE may use PUCCH format 4 if the transmission is four or more symbols, the number of UCI bits is two or more and the PUCCH resource includes an orthogonal cover code.

[0203] The base station may transmit configuration parameters to the UE for a plurality of PUCCH resource sets using, for example, an RRC message. The plurality of PUCCH resource sets (e.g., up to four sets) may be configured on an uplink BWP of a cell. A PUCCH resource set may be configured with a PUCCH resource set index, a plurality of PUCCH resources with a PUCCH resource being identified by a PUCCH resource identifier (e.g., pucch-Resourceid), and/or a number (e.g. a maximum number) of UCI information bits the UE may transmit using one of the plurality of PUCCH resources in the PUCCH resource set. When configured with a plurality of PUCCH resource sets, the UE may select one of the plurality of PUCCH resource sets based on a total bit length of the UCI information bits (e.g., HARQ-ACK, SR, and/or CSI). If the total bit length of UCI information bits is two or fewer, the UE may select a first PUCCH resource set having a PUCCH resource set index equal to "0". If the total bit length of UCI information bits is greater than two and less than or equal to a first configured value, the UE may select a second PUCCH resource set having a PUCCH resource set index equal to "1". If the total bit length of UCI information bits is greater than the first configured value and less than or equal to a second configured value, the UE may select a third PUCCH resource set having a PUCCH resource set index equal to "2". If the total bit length of UCI information bits is greater than the second configured value and less than or equal to a third value (e.g., 1406), the UE may select a fourth PUCCH resource set having a PUCCH resource set index equal to "3".

[0204] After determining a PUCCH resource set from a plurality of PUCCH resource sets, the UE may determine a PUCCH resource from the PUCCH resource set for UCI (HARQ-ACK, CSI, and/or SR) transmission. The UE may determine the PUCCH resource based on a PUCCH resource indicator in a DCI (e.g., with a DCI format 1_0 or DCI for 1_1) received on a PDCCH. A three-bit PUCCH resource indicator in the DCI may indicate one of eight PUCCH resources in the PUCCH resource set. Based on the PUCCH resource indicator, the UE may transmit the UCI (HARQ-ACK, CSI and/or SR) using a PUCCH resource indicated by the PUCCH resource indicator in the DCI.

[0205] FIG. **15** illustrates an example of a wireless device **1502** in communication with a base station **1504** in accordance with embodiments of the present disclosure. The wireless device **1502** and base station **1504** may be part of a mobile communication network, such as the mobile communication network **100** illustrated in FIG. **1**A, the mobile communication network **150** illustrated in FIG. **1**B, or any other communication network. Only one wireless device **1502** and one base station **1504** are illustrated in FIG. **15**, but it will be understood that a mobile communication network may include more than one UE and/or more than one base station, with the same or similar configuration as those shown in FIG. **15**.

[0206] The base station **1504** may connect the wireless device **1502** to a core network (not shown) through radio communications over the air interface (or radio interface) **1506**. The communication direction from the base station **1504** to the wireless device **1502** over the air interface **1506** is known as the downlink, and the communication direction from the wireless device **1502** to the base station **1504** over the air interface is known as the uplink. Downlink transmissions may be separated from uplink transmissions using FDD, TDD, and/or some combination of the two duplexing techniques.

[0207] In the downlink, data to be sent to the wireless device **1502** from the base station **1504** may be provided to the processing system **1508** of the base station **1504**. The data may be provided to the processing system **1508** by, for example, a core network. In the uplink, data to be sent to the base station **1504** from the wireless device **1502** may be provided to the processing system **1518** of the wireless device **1502**. The processing system **1508** and the processing system **1518** may implement layer 3 and layer 2 OSI functionality to process the data for transmission. Layer 2 may include an SDAP layer, a PDCP layer, an RLC layer, and a MAC layer, for example, with respect to FIG. **2**A, FIG. **2**B, FIG. **3**, and FIG. **4**A. Layer 3 may include an RRC layer as with respect to FIG. **2**B.

[0208] After being processed by processing system **1508**, the data to be sent to the wireless device **1502** may be provided to a transmission processing system **1510** of base station **1504**. Similarly, after being processed by the processing system **1518**, the data to be sent to base station **1504** may be provided to a transmission processing system **1520** of the wireless device **1502**. The transmission processing system **1510** and the transmission processing system **1520** may implement layer 1 OSI functionality. Layer 1 may include a PHY layer with respect to FIG. **2**A, FIG. **2**B, FIG. **3**, and FIG. **4**A. For transmit processing, the PHY layer may perform, for example, forward error correction coding of transport channels, interleaving, rate matching, mapping of transport channels to physical channels, modulation of physical channel, multiple-input multiple-output (MIMO) or multi-antenna processing, and/or the like.

[0209] At the base station **1504**, a reception processing system **1512** may receive the uplink transmission from the wireless device **1502**. At the wireless device **1502**, a reception processing system **1522** may receive the downlink transmission from base station **1504**. The reception processing system **1512** and the reception processing system **1522** may implement layer 1 OSI functionality. Layer 1 may include a PHY layer with respect to FIG. **2**A, FIG. **2**B, FIG. **3**, and FIG. **4**A. For receive processing, the PHY layer may perform, for example, error detection, forward error correction decoding, deinterleaving, demapping of transport channels to physical channels, demodulation of physical channels, MIMO or multi-antenna processing, and/or the like.

[0210] As shown in FIG. **15**, a wireless device **1502** and the base station **1504** may include multiple antennas. The multiple antennas may be used to perform one or more MIMO or multi-antenna techniques, such as spatial multiplexing (e.g., single-user MIMO or multi-user MIMO), transmit/receive diversity, and/or beamforming. In other examples, the wireless device **1502** and/or the base station **1504** may have a single antenna.

[0211] The processing system **1508** and the processing system **1518** may be associated with a memory **1514** and a memory **1524**, respectively. Memory **1514** and memory **1524** (e.g., one or more non-transitory computer readable mediums) may store computer program instructions or code that may be executed by the processing system **1508** and/or the processing system **1518** to carry out one or more of the functionalities discussed in the present application. Although not shown in FIG. **15**, the transmission processing system **1510**, the transmission processing system **1520**, the reception processing system **1512**, and/or the reception processing system **1522** may be coupled to a memory (e.g., one or more non-transitory computer readable mediums) storing computer program instructions or code that may be executed to carry out one or more of their respective functionalities.

[0212] The processing system **1508** and/or the processing system **1518** may comprise one or more controllers and/or one or more processors. The one or more controllers and/or one or more processors may comprise, for example, a general-purpose processor, a digital signal processor (DSP), a microcontroller, an application specific integrated circuit (ASIC), a field programmable gate array (FPGA) and/or other programmable logic device, discrete gate and/or transistor logic, discrete hardware components, an on-board unit, or any combination thereof. The processing system **1508** and/or the processing system **1518** may perform at least one of signal coding/processing, data processing, power control, input/output processing, and/or any other functionality that may enable the wireless device **1502** and the base station **1504** to operate in a wireless environment.

[0213] The processing system **1508** and/or the processing system **1518** may be connected to one or more peripherals **1516** and one or more peripherals **1526**, respectively. The one or more peripherals **1516** and the one or more peripherals **1526** may include software and/or hardware that provide features and/or functionalities, for example, a speaker, a microphone, a keypad, a display, a touchpad, a power source, a satellite transceiver, a universal serial bus (USB) port, a hands-free headset, a frequency modulated (FM) radio unit, a media player, an Internet browser, an electronic control unit (e.g., for a motor vehicle), and/or one or more sensors (e.g., an accelerometer, a gyroscope, a temperature sensor, a radar sensor, a lidar sensor, an ultrasonic sensor, a light sensor, a camera, and/or the like). The processing system **1508** and/or the processing system **1518** may receive user input data from and/or provide user output data to the one or more peripherals **1516** and/or the one or more peripherals **1526**. The processing system **1518** in the wireless device **1502** may receive power from a power source and/or may be configured to distribute the power to the other components in the wireless device **1502**. The power source may comprise one or more sources of power, for example, a battery, a solar cell, a fuel cell, or any combination thereof. The processing system **1508** and/or the processing system **1518** may be connected to a GPS chipset **1517** and a GPS chipset **1527**, respectively. The GPS chipset **1517** and the GPS chipset **1527** may be configured to provide geographic location information of the wireless device **1502** and the base station **1504**, respectively.

[0214] FIG. **16**A illustrates an example structure for uplink transmission. A baseband signal representing a physical uplink shared channel may perform one or more functions. The one or more functions may comprise at least one of: scrambling; modulation of scrambled bits to generate complex-valued symbols; mapping of the complex-valued modulation symbols onto one or several transmission layers; transform precoding to generate complex-valued symbols;

precoding of the complex-valued symbols; mapping of precoded complex-valued symbols to resource elements; generation of complex-valued time-domain Single Carrier-Frequency Division Multiple Access (SC-FDMA) or CP-OFDM signal for an antenna port; and/or the like. In an example, when transform precoding is enabled, a SC-FDMA signal for uplink transmission may be generated. In an example, when transform precoding is not enabled, an CP-OFDM signal for uplink transmission may be generated by FIG. **16**A. These functions are illustrated as examples and it is anticipated that other mechanisms may be implemented in various embodiments.

[0215] FIG. **16**B illustrates an example structure for modulation and up-conversion of a baseband signal to a carrier frequency. The baseband signal may be a complex-valued SC-FDMA or CP-OFDM baseband signal for an antenna port and/or a complex-valued Physical Random Access Channel (PRACH) baseband signal. Filtering may be employed prior to transmission.

[0216] FIG. **16**C illustrates an example structure for downlink transmissions. A baseband signal representing a physical downlink channel may perform one or more functions. The one or more functions may comprise: scrambling of coded bits in a codeword to be transmitted on a physical channel; modulation of scrambled bits to generate complex-valued modulation symbols; mapping of the complex-valued modulation symbols onto one or several transmission layers; precoding of the complex-valued modulation symbols on a layer for transmission on the antenna ports; mapping of complex-valued modulation symbols for an antenna port to resource elements; generation of complex-valued time-domain OFDM signal for an antenna port; and/or the like. These functions are illustrated as examples and it is anticipated that other mechanisms may be implemented in various embodiments.

[0217] FIG. **16**D illustrates another example structure for modulation and up-conversion of a baseband signal to a carrier frequency. The baseband signal may be a complex-valued OFDM baseband signal for an antenna port. Filtering may be employed prior to transmission.

[0218] A wireless device may receive from a base station one or more messages (e.g. RRC messages) comprising configuration parameters of a plurality of cells (e.g. primary cell, secondary cell). The wireless device may communicate with at least one base station (e.g. two or more base stations in dual-connectivity) via the plurality of cells. The one or more messages (e.g. as a part of the configuration parameters) may comprise parameters of physical, MAC, RLC, PCDP, SDAP, RRC layers for configuring the wireless device. For example, the configuration parameters may comprise parameters for configuring physical and MAC layer channels, bearers, etc. For example, the configuration parameters may comprise parameters indicating values of timers for physical, MAC, RLC, PCDP, SDAP, RRC layers, and/or communication channels.

[0219] A timer may begin running once it is started and continue running until it is stopped or until it expires. A timer may be started if it is not running or restarted if it is running. A timer may be associated with a value (e.g. the timer may be started or restarted from a value or may be started from zero and expire once it reaches the value). The duration of a timer may not be updated until the timer is stopped or expires (e.g., due to BWP switching). A timer may be used to measure a time period/window for a process. When the specification refers to an implementation and procedure related to one or more timers, it will be understood that there are multiple ways to implement the one or more timers. For example, it will be understood that one or more of the multiple ways to implement a timer may be used to measure a time period/window for the procedure. For example, a random access response window timer may be used for measuring a window of time for receiving a random access response. In an example, instead of starting and expiry of a random access response window timer, the time difference between two time stamps may be used. When a timer is restarted, a process for measurement of time window may be restarted. Other example implementations may be provided to restart a measurement of a time window.

[0220] FIG. **17** illustrates an example of a quality of service (QOS) model for differentiated data exchange. In the QoS model of FIG. **17**, there are a UE **1701**, a RAN **1702**, and a UPF **1705**. The QoS model facilitates prioritization of certain packet or protocol data units (PDUs), also referred to as packets. For example, higher-priority packets may be exchanged faster and/or more reliably than lower-priority packets. The network may devote more resources to exchange of high-QoS packets.

[0221] In the example of FIG. **17**, a PDU session **1710** is established between UE **1701** and UPF **1705**. The PDU session **1710** may be a logical connection enabling the UE **1701** to exchange data with a particular data network (for example, the Internet). The UE **1701** may request establishment of the PDU session **1710**. At the time that the PDU session **1710** is established, the UE **1701** may, for example, identify the targeted data network based on its data network name (DNN). The PDU session **1710** may be managed, for example, by a session management function (SMF, not shown). In order to facilitate exchange of data associated with the PDU session **1710**, between the UE **1701** and the data network, the SMF may select the UPF **1705** (and optionally, one or more other UPFs, not shown).

[0222] One or more applications associated with UE **1701** may generate uplink packets **1712**A-**1712**E associated with the PDU session **1710**. In order to work within the QoS model, UE **1701** may apply QoS rules **1714** to uplink packets **1712**A-**1712**E. The QoS rules **1714** may be associated with PDU session **1710** and may be determined and/or provided to the UE **1701** when PDU session **1710** is established and/or modified. Based on QoS rules **1714**, UE **1701** may classify uplink packets **1712**A-**1712**E, map each of the uplink packets **1712**A-**1712**E to a QoS flow, and/or mark uplink packets **1712**A-**1712**E with a QoS flow indicator (QFI). As a packet travels through the network, and potentially mixes with other packets from other UEs having potentially different priorities, the QFI indicates how the packet should be handled in accordance with the QoS model. In the present illustration, uplink packets **1712**A, **1712**B are mapped to QoS flow **1716**A, uplink packet **1712**C is mapped to QoS flow **1716**B, and the remaining packets are mapped to QoS flow **1716**C.

[0223] The QoS flows may be the finest granularity of QoS differentiation in a PDU session. In the figure, three QoS flows **1716**A-**1716**C are illustrated. However, it will be understood that there may be any number of QoS flows. Some QoS flows may be associated with a guaranteed bit rate (GBR QoS flows) and others may have bit rates that are not guaranteed (non-GBR QoS flows). QoS flows may also be subject to per-UE and per-session aggregate bit rates. One of the QoS flows may be a default QoS flow. The QoS flows may have different priorities. For example, QoS flow **1716**A may have a higher priority than QoS flow **1716**B, which may have a higher priority than QoS flow **1716**C. Different priorities may be reflected by different QoS flow characteristics. For example, QoS flows may be associated with flow bit rates. A particular QoS flow may be associated with a guaranteed flow bit rate (GFBR) and/or a maximum flow bit rate (MFBR). QoS flows may be associated with specific packet delay budgets (PDBs), packet error rates (PERs), and/or maximum packet loss rates. QoS flows may also be subject to per-UE and per-session aggregate bit rates.

[0224] In order to work within the QoS model, UE **1701** may apply resource mapping rules **1718** to the QoS flows **1716**A-**1716**C. The air interface between UE **1701** and AN **802** may be associated with resources **1720**. In the present illustration, QoS flow **1716**A is mapped to resource **1720**A, whereas QoS flows **1716**B, **1716**C are mapped to resource **1720**B. The resource mapping rules **1718** may be provided by the RAN **1702**. In order to meet QoS requirements, the resource mapping rules **1718** may designate more resources for relatively high-priority QoS flows. With more resources, a high-priority QoS flow such as QoS flow **1716**A may be more likely to obtain the high flow bit rate, low packet delay budget, or other characteristic associated with QoS rules **1714**. The resources **1720** may comprise, for example, radio bearers. The radio bearers (e.g., data radio bearers) may be established between the UE **1701** and the RAN **1702**. The radio bearers in 5G, between the UE **1701** and the RAN **1702**, may be distinct from bearers in LTE, for example, Evolved Packet System (EPS) bearers between a UE and a packet data network gateway (PGW), S1 bearers between an eNB and a serving gateway (SGW), and/or an S5/S8 bearer between an SGW and a PGW.

[0225] Once a packet associated with a particular QoS flow is received at RAN **1702** via resource **1720**A or resource **1720**B, RAN **1702** may separate packets into respective QoS flows **1756**A-**1756**C based on QoS profiles **1728**. The QoS profiles **1728** may be received from an SMF. Each QoS profile may correspond to a QFI, for example, the QFI marked on the uplink packets **1712**A-**1712**E. Each QoS profile may include QoS parameters such as 5G QoS identifier (5QI) and an allocation and retention priority (ARP). The QoS profile for non-GBR QoS flows may further include additional QoS parameters such as a reflective QoS attribute (RQA). The QoS profile for GBR QoS flows may further include additional QoS parameters such as a guaranteed flow bit rate (GFBR), a maximum flow bit rate (MFBR), and/or a maximum packet loss rate. The 5QI may be a standardized 5QI which have one-to-one mapping to a standardized combination of 5G QoS characteristics per well-known services. The 5QI may be a dynamically assigned 5QI which the standardized 5QI values are not defined. The 5QI may represent 5G QoS characteristics. The 5QI may comprise a resource type, a default priority level, a packet delay budget (PDB), a packet error rate (PER), a maximum data burst volume, and/or an averaging window. The resource type may indicate a non-GBR QoS flow, a GBR QoS flow or a delay-critical GBR QoS flow. The averaging window may represent a duration over which the GFBR and/or MFBR is calculated. ARP may be a priority level comprising pre-emption capability and a pre-emption vulnerability. Based on the ARP, the RAN **1702** may apply admission control for the QoS flows in a case of resource limitations.

[0226] The RAN **1702** may select one or more N3 tunnels **1750** for transmission of the QoS flows **1756**A-**1756**C. After the packets are divided into QoS flows **1756**A-**1756**C, the packet may be sent to UPF **1705** (e.g., towards a DN) via the selected one or more N3 tunnels **1750**. The UPF **1705** may verify that the QFIs of the uplink packets **1712**A-**1712**E are aligned with the QoS rules **1714** provided to the UE **1701**. The UPF **1705** may measure and/or count packets and/or provide packet metrics to, for example, a PCF.

[0227] The figure also illustrates a process for downlink. In particular, one or more applications may generate downlink packets **1752**A-**1752**E. The UPF **1705** may receive downlink packets **1752**A-**1752**E from one or more DNs and/or one or more other UPFs. As per the QoS model, UPF **1705** may apply packet detection rules (PDRs) **1754** to downlink packets **1752**A-**1752**E. Based on PDRs **1754**, UPF **1705** may map packets **1752**A-**1752**E into QoS flows. In the present illustration, downlink packets **1752**A, **1752**B are mapped to QoS flow **1756**A, downlink packet **1752**C is mapped to QoS flow **1756**B, and the remaining packets are mapped to QoS flow **1756**C.

[0228] The QoS flows **1756**A-**1756**C may be sent to RAN **1702**. The RAN **1702** may apply resource mapping rules to the QoS flows **1756**A-**1756**C. In the present illustration, QoS flow **1756**A is mapped to resource **1720**A, whereas QoS flows **1756**B, **1756**C are mapped to resource **1720**B. In order to meet QoS requirements, the resource mapping rules may designate more resources to high-priority QoS flows.

[0229] One or more applications in this specification may comprise at least one of an advanced media service; a High Data Rate Low Latency (HDRLL) service; a virtual reality (VR) service; an augmented reality service; an extended reality (XR) service; a tactile/multi-modality communication services; a streaming service (e.g., video, audio); a multimedia telephony service for IMS (MTSI) service; a multimedia broadcast and multicast service (MBMS); a multicast broadcast service (MBS); and/or the like.

[0230] Extended Reality (XR) may refer to all real-and-virtual combined environments and human-machine interactions generated by computer technology and wearables. XR may be an umbrella term for different types of realities.

[0231] Virtual reality (VR) may be a rendered version of a delivered visual and audio scene. The rendering may be designed to mimic the visual and audio sensory stimuli of the real world as naturally as possible to an observer or user as they move within the limits defined by the application. Virtual reality usually, but not necessarily, may require a user to wear a head mounted display (HMD), to completely replace the user's field of view with a simulated visual component, and to wear headphones, to provide the user with the accompanying audio. Some form of head and motion tracking of the user in VR may be usually also necessary to allow the simulated visual and audio components to be updated in order to ensure that, from the user's perspective, items and sound sources remain consistent with the user's movements.

[0232] Augmented reality (AR) may be when a user is provided with additional information or artificially generated items or content overlaid upon their current environment. Such additional information or content may usually be visual and/or audible and their observation of their current environment may be direct, with no intermediate sensing, processing and rendering, or indirect, where their perception of their environment may be relayed via sensors and may be enhanced or processed.

[0233] Mixed reality (MR) may be an advanced form of AR where some virtual elements may be inserted into the physical scene with the intent to provide the illusion that these elements are part of the real scene.

[0234] Other terms used in the context of XR may be Immersion as the sense of being surrounded by the virtual environment as well as Presence providing the feeling of being physically and spatially located in the virtual environment. The sense of presence may provide significant minimum performance requirements for different technologies such as tracking, latency, persistency, resolution and optics.

[0235] Field of view may be the angle of visible field expressed in degrees measured from the focal point.

[0236] In an example, media and XR technologies may employ different types of media e.g., I, P, and B frames. An I-frame (Intra-coded picture) may be a complete image, like a JPG or BMP image file. A P-frame (Predicted picture) may hold changes in the image from the previous frame. For example, in a scene where a car moves across a stationary background, only the car's movements need to be encoded. The encoder does not need to store the unchanging background pixels in the P-frame, thus saving space. P-frames are also known as delta-frames. A B-frame (Bidirectional predicted picture) may employ techniques to save space by using differences between the current frame and both the preceding and following frames to specify its content.

[0237] Some application (e.g., XR and Media (XRM) service) PDUs may have dependency with each other. The PDUs (e.g. I frame), on which are dependent by the other PDUs (e.g. P frame, B frame), may be expected to be more important and may be transmitted firstly. However, in some application (e.g., XR and Media (XRM) service), P frame and B frame may be also important as I frame to construct the fluent video, dropping of those P frame and B frame causes jitter to the QoE which is not better than giving up the whole service. In some other applications (e.g., XRM service), P frame and B frame may be used to enhance the high definition, e.g. from 720p to 1080p. dropping of those P frame and B frame makes sense to keep the service when the network resource cannot transmit all of the service data.

[0238] A PDU Set may comprise one or more PDUs carrying the payload of one unit of information generated at the application level (e.g. a frame or video for XR and media services). In some implementations all PDUs in a PDU Set may be needed by the application layer to use the corresponding unit of information. In other implementations, the application layer may still recover parts or all of the information unit, when some PDUs are missing. There may have several types (e.g, type A and type B) of PDU sets. Type A and type B may have different importance or priority. In an example, a type A PDU set may comprise one or more I frames with importance or priority, and a type B PDU set may comprise one or more P/B frames without importance or priority. In an example, a type A PDU set may comprise one or more I frames, and a type B PDU sets may comprise one or more P/B frames. The type A PDU set and the type B PDU set may have the same importance or priority.

[0239] In an example, multi-modal data may be employed to describe the input data from different kinds of devices/sensors or the output data to different kinds of destinations (e.g. one or more UEs) required for the same task or application. Multi-modal Data may consist of more than one Single-modal Data, and there may be strong dependency among each Single-modal Data. Single-modal Data can be seen as one type of data.

[0240] Data burst may be data produced by the application in a short period of time, comprising PDUs from one or more PDU Sets.

[0241] In both uplink and downlink, XR-Awareness contributes to optimizations of base station radio resource scheduling and may rely at least on the notions of PDU set and Data Burst. A Data Burst may comprise multiple PDUs belonging to one or multiple PDU Sets.

[0242] In order to handle PDUs efficiently in both UL and DL, the following information may be useful. Semi-static information provided by the core network comprise at least one of: the PDU-Set Delay Budget (PSDB); the PDU-Set Error Rate (PSER); Traffic parameters (e.g. periodicity); Jitter information (e.g. range); and/or the like. Dynamic information may comprise of the PDUs belonging to a PDU set (this includes the means to determine at least the PDU set boundaries) and the PDUs belonging to a Data Burst.

[0243] An example implementation as depicted FIG. **18** illustrates how an application data unit (ADU) is delivered from a sender to a receiver. The ADU may comprise, for example, a picture file, a video frame, text file and so on. For example, the ADU may comprise a data unit generated by one or more protocols (e.g., RTP, DASH, TCP, UDP, etc.). The ADU may, for example, be generated and/or created by a first instance of a particular application, for use and/or enjoyment by a second instance of the application, or for processing by an application server of the application. A middle layer may be responsible for packaging and/or formatting the ADU for the delivery from the sender to the receiver. For example, the middle layer may provide functionality of one or more protocols (e.g., IP, etc.). After formatting the ADU into one or more packets based on the one or more protocols, the middle layer may forward the one or more packets to a lower layer. The lower layer may provide functionality of forwarding the one or more packets, for example, over a particular interface, from one node/device to another. The second instance of the application may be located at the other node/device. The ADU may be described as PDU set. The ADU may be interchangeable with PDU set.

[0244] In an example as depicted in FIG. **18**, the upper layer (e.g., an application) in the UE may generate one or more application data units (ADUs). The one or more ADUs may comprise ADU 1 and/or ADU 2. The upper layer in the UE may deliver the ADU 1 and/or ADU 2 to the middle layer of the UE. For the delivered ADU 1 and/or ADU 2, the middle layer of the UE may process and may package/segment the one or more ADUs into one or more packets, based on the one or more protocols. For example, the one or more packets may comprise a packet 1 and/or a packet 2. For example, if IP protocol is used, the ADU 1 and/or ADU 2 may be processed into one or more IP packets. Each IP packet may comprise at least a portion of at least one of the one or more ADUs. For example, packet 1 may comprise at least a portion of the ADU 1. For example, packet 2 may comprise at least a portion of the ADU 2.

[0245] The middle layer may deliver the generated one or more packets to the lower layer. The lower layer may be

Access Stratum (AS), which is responsible for transferring data between a UE and a NG-RAN. For example, a SDAP entity of the AS may receive from the middle layer, the packet 1 as SDU 1. For example, the SDAP entity may receive from the middle layer, the packet 2 as SDU 2. The AS of the UE may process and send the SDU 1 and the SDU 2. For example, the AS of the UE may send the SDU 1 and the SDU 2 to a AS layer of a NG-RAN. For example, a RLC entity of the AS layer of the UE may generate one or more PDUs from the SDU 1 and SDU 2. For example, based on amount of radio resources allocated by the NG-RAN, the RLC layer of the AS may segment the SDU 1 into PDU 1 and PDU 2, the SDU 2 into PDU 3 and PDU 4. A MAC entity of the AS may receive the one or more PDUs from the RLC entity. The MAC entity may transmit the received one or more PDUs to the NG-RAN.

[0246] The various layers have different functions, such as those described above in, for example, FIG. **3**. The data that makes up the ADU 1 may be divided, subdivided, compressed, ciphered, reordered, multiplexed, encoded, etc. After the ADU 1 and/or the ADU 2 passes through these layers, the end result (e.g., the one or more PDUs) may be suitable for transmission. However, the PDUs may be indecipherable (literally) to the application associated with the ADU 1 and/or ADU 2. After transmission, described in greater detail below, the process may be reversed, and the ADU 1 and/or the ADU 2 may be reconstructed at the other side (e.g., the application server in FIG. **18**), so that the data becomes usable by the application.

[0247] In an example, as depicted in FIG. **18**, the MAC entity of the NG-RAN may receive the one or more PDUs sent by the UE. The received one or more PDUs may be reassembled into one or more SDUs. For example, with the received PDU 1 and PDU 2, the AS of the NG-RAN may reassemble the SDU 1. For example, with the received PDU 3 and PDU 4, the AS of the NG-RAN may reassemble the SDU 2. The packet 1 of the SDU 1 and the packet 2 of the SDU 2 may be delivered from the NG-RAN to a core network node (e.g., UPF). The core network node may send the packet 1 and the packet 2 toward the receiver (e.g., an application server associated with the ADU 1 and the ADU 2) via the internet. After receiving the packet 1 and packet 2, the middle layer of the application server may recover the ADU 1 and the ADU 2 and deliver the ADU 1 and the ADU 2 to the upper layer. The upper layer may perform application specific processing for the received ADU 1 and the ADU 2.

[0248] One or more protocol entities and/or one or more layers may be agnostic to differentiated characteristics of one or more types of ADU for an application. For example, an AS may not consider different characteristic of different applications. For example, the AS may not consider the difference and/or similarity and/or relationship among one or more ADUs of an application. For example, a data unit in lower layers (e.g., Packet 1, SDU 1, PDU 2 in FIG. **18**) may be associated with a portion of an ADU associated with a particular application (e.g., ADU 1 in FIG. **18**). But within the lower layers, the data unit may not be recognizable as being associated with a particular application data unit, or even a particular application. At lower layers, the data unit may simply be a series of ones and zeroes which are packaged for delivery. This application agnostic approach (e.g., ADU-agnostic approach) may contribute to supporting independent enhancement of one or more layers and/or one or more entities. For example, by not tying operation of the AS to a certain application characteristic, the AS may evolve without requiring change of behavior of one or more applications. Due to this application-agnostic approach, the AS may support introduction of new later-developed applications. However, as new advanced use cases emerge and QoS requirements of applications are tightened to provide users with enhanced experience, the application agnostic ADU processing by the AS may fail to support efficient use of radio resources and network resources, as will be discussed in greater detail below.

[0249] For example, FIG. **19** may illustrate one example of an advanced application. FIG. **19** may show how video (e.g., sequence of movements) input pictures are represented. For example, in FIG. **19**, the input pictures may show that a rectangular object does not move while a triangular object may move from the right of the screen to the left. Based on this sequence of movements, an encoder of the advanced application may generate one or more output data. The first output data (output data 1, Type A) may comprise information that describes details of a first input picture (input picture 1 at T=t1). The second output data (output data 2, Type B) may comprise information that describe difference of the first input picture and a second input picture (input picture 2 at T=t2). For example, the second output data may comprise information that the triangular object moves from the right to the left. Compared to sending the second input picture itself, sending information of changes in the pictures may reduce the amount of data that needs to be transmitted. Likewise, a third output data (output data 3, Type B) may comprise information of changes between the second input picture and a third input picture (input picture 3 at T=t3).

[0250] In an example, a sender of the video may transmit one or more output data to a receiver. For example, the one or more output data in FIG. **19** may be transmitted. The receiver may receive one or more data sent by the sender and/or the receiver may not receive one or more data sent by the sender. For example, the receiver may receive the second output data, the third output data and the fourth output data. For example, the receiver may not receive the first output data. Because the second output data includes information of changes between the first input picture and the second picture, for the recovery of the second picture from the second output data, the receiver may need the first input picture. If the first output data comprising the first input picture is not received, the receiver may not be able to recover the second input picture from the received second output data. Likewise, if the receiver does not have information of the second input picture, the receiver may not be able to recover the third input picture from the third output data. The usability of one or more output data (e.g., the second output data, the third output data, the fourth output data) may be dependent on the availability of one or more output data (e.g., the first output data).

[0251] FIG. **20** may illustrate an example of data delivery failure. Application A may generate a first ADU and a second ADU. One or more ADUs generated by the application A may comprise a service data flow. For operation of the application A, different ADUs may have different importance. For example, the first ADU may be of higher importance than the second ADU. For example, the first ADU may comprise the first output data in the example of FIG. **19**. For example, the second ADU may comprise the second output data or the third output data or the fourth output data in the example of FIG. **19**. The first ADU may be delivered to middle layer as a first packet. The first packet may be delivered to a lower layer as a SDU 1. The second ADU may be delivered to middle layer as a second packet. The second packet may be delivered to the lower layer as a SDU 2. The lower layer may generate PDU 1 and PDU 2 for the SDU 1. The lower layer may generate PDU 3 and PDU 4 for the SDU 2. The lower layer may send the PDU 1, PDU 2, PDU 3 and PDU 4. The PDU 1, the PDU 3 and the PDU 4 may be successfully delivered to a receiver. The PDU 2 may not be successfully delivered to a receiver. The ADU may be described as PDU set. The ADU may be interchangeable with PDU set.

[0252] Based on the PDU 3 and PDU 4, the receiver may reassemble SDU 2. The SDU 2 may be delivered to the middle layer as the second packet. The second packet may be delivered to the application server hosting the application A. The middle layer may deliver ADU 2 to the application A. For example, the ADU 2 may comprise the second output data of FIG. **19**. Due to reception failure of PDU 2, the receiver may not be able to reassemble SDU 1. Due to missing SDU 1, the packet 1 may not be recovered and may not be delivered to the application server. In turn, the application A may not receive the ADU 1. For example, the ADU 1 may comprise the first output data of FIG. **19**. As shown in the example of FIG. **19**, to process the ADU 2 (e.g., the second output data), the application A may need the ADU 1 (e.g., the first output data). Due to lack of the ADU 1, the application A may not be able to use the received ADU 2. Radio resource and/or network resources for the delivery of the ADU 2 may be unnecessarily wasted. The lower layer (e.g., AS layer of NR, AS layer of LTE) may not provide differentiated handling of ADUs based on the different characteristics of different ADUs of a service data flow. As such, more prioritized ADUs may not be delivered while less prioritized ADUs may be delivered. In above description and in the example of FIG. **20**, for simple illustration purpose, it is described that data is delivered from a UE to an application server. It may be also possible that data is delivered from the application server to the UE or that data is delivered from a first UE to a second UE directly.

[0253] An example depicted in FIG. **21** illustrates how data generated by an application is delivered from a sender to a receiver. The unit of data generated by the application may be an application data unit (ADU). The ADU may comprise, for example, a picture file, a video frame, text file and so on. The ADU may, for example, be generated and/or created by a first instance of a particular application, for use and/or enjoyment by a second instance of the application, or for processing by an application server of the application. To reliably deliver the ADU and/or to process the ADU efficiently, the ADU may be divided into one or more smaller units. For example, the one or more smaller units may be one or more protocol data units (PDUs). One or more first PDUs (e.g., PDU 1, PDU 2) for a first ADU may be of a first PDU set (e.g., PDU set 1). One or more second PDUs (e.g., PDU 3, PDU 4) for a second ADU may be of a second PDU set (e.g., PDU set 2).

[0254] In an example, the application may deliver the one or more first PDUs and/or the one or more second PDUs to an SDAP/PDCP entity (e.g., a SDAP entity, a PDCP entity, and/or both a SDAP entity and a PDCP entity). The first PDU (e.g., PDU 1) may be delivered from the application to the SDAP/PDCP entity. In the SDAP/PDCP entity, the first PDU may be a first SDAP SDU, a first SDAP PDU, a first PDCP SDU, and/or a first PDCP PDU. The second PDU (e.g., PDU 2) may be delivered from the application to the SDAP/PDCP entity. In the SDAP/PDCP entity, the second PDU may be a second SDAP SDU, a second SDAP PDU, a second PDCP SDU, and/or a second PDCP PDU. Similarly, the PDU 3 may be a third PDCP PDU (e.g., PDCP PDU 3) and/or the PDU 4 may be a fourth PDCP PDU (e.g., PDCP PDU 4).

[0255] In an example, one or more PDCP PDUs (e.g., PDCP PDU 1, 2, 3, 4) may be delivered from the SDAP/PDCP entity to a RLC entity. The RLC layer may provide functionality of forwarding the one or more packets, for example, over a particular interface, from one node to another, using a MAC entity and/or a PHY entity.

[0256] As depicted in FIG. **21**, for example, the application in the sender may generate one or more PDU sets. For example, the one or more PDU sets comprise the first PDU set and/or the second PDU set. The application in the sender may deliver the one or more PDU sets to the SDAP/PDCP entity of the sender. The SDAP/PDCP entity may classify the one or more PDUs of the one or more PDU sets, may apply header compression to the one or more PDUs to reduce size of headers of the one or more PDUs, may apply ciphering to the one or more PDUs to provide security, and/or may generate one or more PDCP PDUs.

[0257] In an example, the SDAP/PDCP entity of the sender delivers the generated one or more PDCP PDUs to the RLC entity. The RLC entity may be responsible for transferring data between a UE and a NG-RAN, using the MAC entity and/or the PHY entity. For example, the RLC entity of the sender may process and generate one or more RLC PDUs for the one or more PDCP PDUs (e.g., RLC SDUs) delivered from the PDCP/SDAP entity. For example, the RLC entity may generate a first RLC PDU from the first PDCP PDU (e.g., the first RLC SDU) and/or the RLC entity may generate a second RLC PDU from the second PDCP PDU (e.g., the second RLC SDU).

[0258] In an example, the one or more RLC PDUs generated by the RLC entity of the sender may be delivered to the MAC entity of the sender. The MAC entity of the sender may send the one or more RLC PDUs to a MAC entity of the receiver. The MAC entity of the receiver may deliver the one or more RLC PDUs to a RLC entity of the receiver. For example, the RLC entity of the receiver may receive the one or more RLC PDUs (e.g., RLC PDU 1, 2, 3, 4). The RLC entity of the receiver may recover the one or more RLC SDUs (e.g., PDCP PDUs) using the one or more RLC PDUs. The RLC entity may deliver the one or more recovered PDCP PDUs to a PDCP entity of the receiver. The PDCP entity of the receiver may process the one or more received PDCP PDUs, and/or may recover one or more PDUs from the one or more PDCP PDUs. To recover a PDCP SDU (or RLC SDU) from a PDCP PDU (or a RLC PDU) may be that the PDCP PDU is extracted from the PDCP PDU, that the PDCP PDU is re-assembled from the PDCP SDU.

[0259] As depicted in FIG. **22**, for example, there may have several types (e.g, type A and type B as described in FIG. **19**) of PDU sets. Type A and type B may have different importance or priority. Depending on how the mapping of PDU sets onto QoS flows is done in the NAS and how QoS flows are mapped onto DRBs in the AS, there may be four alternatives. FIG. **22**A illustrates one-to-one mapping between types (e.g., type A and type B) of PDU sets and QoS flows in the NAS and one-to-one mapping between QoS flows and DRBs in the AS. From a Layer 2 structure viewpoint, this alternative may require as many DRBs as types of PDU sets. FIG. **22**B illustrates one-to-one mapping between types (e.g., type A and type B) of PDU sets and QoS flows in the NAS and possible multiplexing of QoS flows in one DRB in the AS. From a Layer 2 structure viewpoint, this alternative may give each QoS flows multiplexed in a DRB the same QoS.

[0260] FIG. **22**C illustrates possible multiplexing of types (e.g., type A and type B) of PDU sets in one QoS flow in the NAS and one-to-one mapping between QoS flows and DRBs in the AS. From a Layer 2 structure viewpoint, this alternative may give each QoS flow/DRB one QoS. FIG. **22**D illustrates possible multiplexing of types of PDU sets in one QoS flow in the NAS and demultiplexing of types of PDU sets from one QoS flow on multiple DRBs in the AS. From a Layer 2 structure viewpoint, demultiplexing of types of PDU sets from one QoS flow onto multiple DRBs may be necessary.

[0261] FIG. **23** illustrates the split architecture of base station. A base station (BS) may be split into a base station central unit (BS-CU) and one or more base station distributed units (BS-DUs). The BS-CU may be split into a base station central unit-control plane (BS-CU-CP) and one or more base station central unit-user planes (BS-CU-UPs), which may be connected by a E1 interface. F1-C interface may connect BS-DU and BS-CU-CP. F1-U interface may connect BS-DU and BS-CU-UP. Wireless devices may be served by the split architecture.

[0262] FIG. **24** illustrates an example of layer 3 based handover. A wireless device may transmit a measurement report to a source base station (BS), based on which the source BS may determine to handover the wireless device to a target BS. The BS may initiate handover and issue a HANDOVER REQUEST over the Xn interface. The BS may perform admission control and provide the new RRC configuration as part of the HANDOVER REQUEST ACKNOWLEDGE. The source BS may provide the RRC configuration to the wireless device by forwarding the RRC reconfiguration message received in the HANDOVER REQUEST ACKNOWLEDGE. The RRC Reconfiguration message may include at least cell ID and all information required to access the target cell so that the wireless device can access the target cell without reading system information. For some cases, the information required for contention-based and contention-free random access can be included in the RRC Reconfiguration message. The access information to the target cell may include beam specific information, if any. The wireless device may switch the RRC connection to the target BS and may reply with the RRC Reconfiguration Complete message to the target BS.

[0263] FIG. **25** illustrates an example wherein a service of Application A (e.g., video, audio, XR, VR, AR) is provided to a wireless device via a base station (BS1). Application A may comprise PDU set 1 and PDU set 2. PDU Set 1 may be a type A (e.g., I frame). PDU Set 2 may be a type B (e.g., B/P frame). Usability of PDU Set 2 (type B, e.g., B/P frame) is dependent on the availability of PDU Set1 (type A). PDU set 1 may be mapping to DRB 1. PDU set 2 may be mapping to DRB 2. BS1 may initiate handover or dual connectivity for the wireless device to base station 2 (BS2). In the existing technology, the SDAP layer of BS1 may determine a first QoS flows to DRBs mapping for the wireless device before handover/dual connectivity. The SDAP layer of BS2 may determine a second QoS flows to DRBs mapping for the wireless device after handover/dual connectivity. The first QoS flows to DRBs mapping may be different from the second QoS flows to DRBs mapping. Thus, during the handover/setting dual connectivity for the wireless device, some PDUs of either PDU set 1 or PDU set 2 may be lost. If it happened to PDU set1 with high priority, the loss may be more serious. As a result, user experience of Application A may be degraded for the wireless device after handover or dual connectivity.

[0264] Example embodiments improve system performance by enhancement of signaling between two base stations and implementation of data forwarding.

[0265] Example embodiments of the present disclosure improve user experience of Application A for the wireless device after handover/dual connectivity by enhancing the data forwarding between BS1 and BS2 based on PDU sets (i.e., Application A) to DRB mapping. In an example as shown in FIG. **26** and FIG. **27**, the target base station (e.g., BS2) may receive the mapping information of PDU set 1 to DRB1 and PDU set 2 to DRB 2 and set up the data forwarding tunnels based on the mapping information. Thus, the loss of PDUs in the PDU sets may be reduced as much as possible. The embodiments above may improve user experience of Application A (PDU set 1 and PDU set 2) for the wireless device after handover or dual connectivity.

[0266] In the specification, a term AF (application function) may be interpreted as a AS (application server), which may host and/or run one or more applications. A wireless device (e.g., UE) may receive the service of the one or more applications. The one or more applications may comprise at least one of an advanced media service; a High Data Rate Low Latency (HDRLL) service; a virtual reality (VR) service; an augmented reality service; an extended reality (XR) service; a tactile/multi-modality communication services; a streaming service (e.g., video, audio); a multimedia telephony service for IMS (MTSI) service; a multimedia broadcast and multicast service (MBMS); a multicast broadcast service (MBS); and/or the like.

[0267] In the specification, a term base station, which may comprise at least one of a NG-RAN, a gNB, an eNB, a ng-eNB, a NodeB, a master base station, a secondary base station, access node, an access point, an N3IWF, a relay node, and/or the like.

[0268] In the specification, a term core network node may be interpreted as a core network device, which may comprise at least one of an AMF, a SMF, a NSSF, a UPF, a NRF a UDM, a PCF, a SoR-AF, an AF, an DDNMF, an MB-SMF, an MB-UPF and/or the like.

[0269] In the specification, a term PDU set may be interpreted as one or more PDUs carrying a payload of one unit of information generated at an application layer level (e.g. a frame or video for XR and media services). In some implementations all PDUs in a PDU Set may be needed by the application layer to use the corresponding unit of information. In other implementations, the application layer may be able to recover parts of the unit of information unit, when some PDUs are missing. There may have several types (e.g, type A and type B as described in FIG. **19**, FIG. **22**, and the descriptions above) of PDU sets. Type A and type B may have different importance or priority. In an example, a type A PDU set may comprise one or more I frames with importance or priority, and a type B PDU set may comprise one or more P/B frames without importance or priority. In an example, a type A PDU set may comprise one or more I frames, and a type B PDU sets may comprise one or more P/B frames. The type A PDU set and the type B PDU set may have the same importance or priority.

[0270] In the specification, a term ADU may be interpreted as one unit of information. The unit of information may be exchanged among one or more hosts serving an application. In an example, an application (e.g., an internet browser, an instant messaging application, a video-player application, etc.) may be running on a first host (e.g., a smartphone, computer, application server, etc.) and the same application may be running on a second host (e.g., another smartphone, computer, application server, etc.). The application on a first host may generate one or more units (e.g., a picture file, a text message, etc.) of information. Each of the one or more units of information may comprises one or more PDUs, and/or the one or more PDUs for a unit of information may be a PDU set.

[0271] In the specification, the terms PDU set, sub-QoS flow, QoS flow and ADU may be interchangeable. That is, PDU set may be interpreted as sub-QoS flow, QoS flow or ADU.

[0272] In the specification, parameters for PDU set/sub-QoS flow/QoS flow or ADU may comprise at least one of: QoS flow/sub-QoS flow/PDU Set Delay Budget, QoS flow/sub-QoS flow/PDU set arrival period and start time, QoS flow/sub-QoS flow/PDU set arrival jitter, QoS flow/sub-QoS flow/PDU set discarding allowed indication, QoS flow/sub-QoS flow/Maximum tolerable delay difference for group of associated flows/bearer, QoS flow/sub-QoS flow/PDU Set identifier, number of PDUs in a QoS flow/sub-QoS flow/PDU set, last QoS flow/sub-QoS flow/PDU indication in a QoS flow/sub-QoS flow/PDU set, QoS flow/sub-QoS flow/PDU Set bit Size, QoS flow/sub-QoS flow/PDU Set delay information, QoS flow/sub-QoS flow/PDU set importance, QoS flow/sub-QoS flow/PDU set common identifier/correlation information (e.g., common identifier, group identifier, correlation identifier, group of picture (GOP) identifier).

[0273] In an example, the common identifier/correlation information, e.g., (e.g., common identifier, group identifier, correlation identifier, group of picture (GOP) identifier), may indicate the relation of the QoS flows/sub-QoS flows/PDU sets of some Application (e.g., XR and Media (XRM) service). A QoS flow/sub-QoS flow/PDU set (e.g. I frame) of an Application (e.g., XR and Media (XRM) may have dependency with another QoS flow/sub-QoS flow/PDU set (e.g. P frame, B frame) of the Application (e.g., XR and Media (XRM) service). In some applications, I frame may be expected to be more important than P frame and B frame. In other applications, P frame and B frame may be also important as I frame. In some other applications, P frame and B frame may be used to enhance the high definition, e.g. from 720p to 1080p.

[0274] In an example, the common identifier/correlation information, e.g., (e.g., common identifier, group identifier, correlation identifier, group of picture (GOP) identifier), may also apply to multi-modal data, which may be to describe the input data from different kinds of devices/sensors or the output data to different kinds of destinations (e.g. one or more UEs) required for the same task or application. Multi-modal Data may consist of more than one single-modal data, and there may be strong dependency among each single-modal data. Single-modal data can be seen as one type of data, which may be transmitted by a QoS flow/sub-QoS flow/PDU set. The common identifier/correlation information, e.g., (e.g., common identifier, group identifier, correlation identifier, group of picture (GOP) identifier) may indicate the relation of one or more single-modal data.

[0275] FIG. **26** and FIG. **27** depict example embodiments of the present disclosure. FIG. **26** or FIG. **27** illustrate a source base station 1 (BS1), a target base station 2 (BS2) and a wireless device (UE in FIG. **26** or FIG. **27**). FIG. **27** also illustrates a source AMF (AMF1), a target AMF (AMF2). This may improve user experience of an Application for the wireless device after handover/setting dual connectivity.

[0276] In an example, as shown in FIG. **26** or in FIG. **27**, the source base station 1 (BS1) may provide one or more services to the wireless device. For example, the service may be Application A, as shown in FIG. **25**, comprising PDU sets, i.e, PDU set 1 and PDU set 2. The four alternatives on PDU set to QoS flow to DRB mapping as described in FIG. **22** may apply to PDU set 1 and PDU set 2's mapping to DRBs. In an example, BS1 may receive one or more radio measurement reports from the wireless device. The one or more radio measurement reports received from the wireless device may comprise RSRPs, RSRQs, and/or SINRs of one or more cells of the master base station (BS1). The radio measurement report received from the wireless device may comprise RSRPs, RSRQs, and/or SINRs of one or more cells of the target base station (BS2).

[0277] Based on the radio measurement report received from the wireless device, BS1 may determine to handover the wireless device to BS2 or trigger/set up dual connectivity to BS2 for the wireless device. In case of dual connectivity, an example, both BS1 and BS 2 may provide services to the wireless device, wherein the service of Application A may be offloaded/handed over to BS2 and other service may be still in BS1.

[0278] Based on the determination, as shown in FIG. **26** or in FIG. **27**, BS2 may receive from BS1 one or more messages. In FIG. **26**, BS2 may receive the one or more messages directly from BS1. In FIG. **27**, BS2 may receive the one or more messages from BS1 via the source AMF 1 and the target AMF 2.

[0279] In an example, the one or more messages may be a request message requesting a handover of the wireless device or requesting to set up dual connectivity of the wireless device. The request message may indicate establishing PDU sets (e.g., PDU set 1 and PDU set 2 as shown in FIG. **25**) in BS2 for the wireless device. The request message may comprise at least one of: a Xn/X2 interface message; a handover request message, a secondary node (SN) modification request message; a SN addition request message; an N2/NG interface message; a S1 interface message; a NG/S1 handover request message; a handover required message; and/or the like. The request message may be, for example, a single message. It may be understood that the message may have any suitable name.

[0280] The request message may comprise at least one of: an identifier (e.g., MME UE S1AP ID) of the wireless device within mobility management entity (MME); an identifier (e.g., AMF UE NGAP ID) of the wireless device within AMF; an identifier (e.g., eNB UE S1AP ID) of the wireless device within eNB; an identifier (e.g., RAN UE NGAP ID) of the wireless device within NG radio access network

(NG-RAN); an identifier (e.g., MeNB UE X2AP ID, SgNB UE X2AP ID) of the wireless device within eNB or gNB; an identifier (e.g., M-NG-RAN node UE XnAP ID, S-NG-RAN node UE XnAP ID) of the wireless device within master NG-RAN node or secondary NG-RAN node; an identifier (e.g., source NG-RAN node UE XnAP ID, target NG-RAN node UE XnAP ID) of the wireless device within source NG-RAN node or target NG-RAN node and/or the like.

[0281] In an example, the request message may indicate that BS1 may propose to perform data forwarding. The request message may comprise data forwarding and/or off-loading information of BS1. The request message may indicate the DRB to PDU set mapping list of BS1. In an example, the request message may indicate/comprise at least one of: a first DRB is associated with a first PDU set (e.g., PDU set 1); a second DRB is associated with a second PDU set (e.g., PDU set 2); and/or the like.

[0282] In an example, the first DRB is associated with the first PDU set may indicate that the first PDU set is mapped to the first DRB. The second DRB is associated with the second PDU set may indicate that the second PDU set is mapped to the second DRB. In an example, the second DRB may be the same as the first DRB, wherein the first PDU set and the second PDU set are mapping to this DRB.

[0283] In an example, the four alternatives on PDU set to QoS flow to DRB mapping as described in FIG. **22** may apply to: the second PDU set mapping to the second DRB, the first PDU set mapping to the first DRB, the first PDU set and the second PDU set mapping to the same DRB.

[0284] In an example, FIG. **22**A illustrates one-to-one mapping between types (e.g., type A and type B) of PDU sets and QoS flows in the NAS and one-to-one mapping between QoS flows and DRBs in the AS. FIG. **22**B illustrates one-to-one mapping between types (e.g., type A and type B) of PDU sets and QoS flows in the NAS and possible multiplexing of QoS flows in one DRB in the AS. FIG. **22**C illustrates possible multiplexing of types (e.g., type A and type B) of PDU sets in one QoS flow in the NAS and one-to-one mapping between QoS flows and DRBs in the AS. FIG. **22**D illustrates possible multiplexing of types of PDU sets in one QoS flow in the NAS and demultiplexing of types of PDU sets from one QoS flow on multiple DRBs in the AS.

[0285] In an example, the first DRB may comprise an identifier of the first DRB. the second DRB may comprise an identifier of the second DRB. The first PDU set may comprise an identifier of the first PDU set. The second PDU set may comprise an identifier of the second PDU set.

[0286] In an example, the first PDU set may comprise at least one of: a QoS flow; a sub-QoS flow; a PDU set, a ADU; and/or the like. The second PDU set may comprise at least one of: a QoS flow; a sub-QoS flow; a PDU set, a ADU; and/or the like.

[0287] The first PDU set and the second PDU set may be for the same application (e.g. Application A) of the wireless device. The application may comprise at least one of: an advanced media service; a High Data Rate Low Latency (HDRLL) service; a virtual reality (VR) service; an augmented reality service; an extended reality (XR) service; a tactile/multi-modality communication services; a streaming service (e.g., video, audio); a multimedia telephony service for IMS (MTSI) service; a multimedia broadcast and multicast service (MBMS); a multicast broadcast service (MBS); and/or the like.

[0288] In an example, the first PDU set and/or the second PDU set may further comprise parameters at least one of: QoS flow/sub-QoS flow/PDU Set Delay Budget, QoS flow/sub-QoS flow/PDU set arrival period and start time, Qos flow/sub-QoS flow/PDU set arrival jitter, QoS flow/sub-QoS flow/PDU set discarding allowed indication, QoS flow/sub-QoS flow/Maximum tolerable delay difference for group of associated flows/bearer, QoS flow/sub-QoS flow/PDU Set identifier, number of PDUs in a QoS flow/sub-QoS flow/PDU set, last QoS flow/sub-QoS flow/PDU indication in a QoS flow/sub-QoS flow/PDU set, QoS flow/sub-QoS flow/PDU Set bit Size, QoS flow/sub-QoS flow/PDU Set delay information, QoS flow/sub-QoS flow/PDU set importance or priority, QoS flow/sub-QoS flow/PDU set common identifier/correlation information (e.g., common identifier, group identifier, correlation identifier, group of picture (GOP) identifier), and/or the like. In an example, the QoS flow/sub-QoS flow/PDU set importance or priority may comprise type A, type B as described above.

[0289] In an example, the common identifier may comprise at least one of: a common identifier; a group identifier; a correlation identifier; GOP identifier; and/or the like. The common identifier the first PDU set and the common identifier of the second PDU set may indicate the relation/correlation of the first PDU set and the second PDU set. BS2 may understand that the first PDU set and the second PDU set are for the same application (e.g., Application A).

[0290] In an example, as shown in FIG. **26** or in FIG. **27**, BS2 may determine whether to accept the proposal of performing data forwarding from BS1. BS2 may determine to use the same DRB configuration and to map the same PDU sets to DRBs as BS1. The determination may be based on the received information from the BS1, as described above.

[0291] In an example, BS2 may further determine to accept or reject the first PDU set and/or the second PDU set. In an example, BS2 may further determine, based on the PDU sets importance/priority/type A/type B information, radio resources allocation handling for the first PDU set and/or the PDU set.

[0292] Based on the determination, as shown in FIG. **26** or in FIG. **27**, BS2 may send to BS1 a response message. In FIG. **26**, BS2 may send the response messages directly to BS1. In FIG. **27**, BS2 may send the response message to BS1 via the target AMF 2 and the source AMF 1.

[0293] In an example, the response message may comprise at least one of: first data forwarding information for the first DRB associated with the first PDU set; second data forwarding information for the second DRB associated with the second PDU set.

[0294] In an example, the first data forwarding information for the first DRB associated with the first PDU set may comprise at least one of: the identifier of the first DRB, the first identifier of the first PDU set, a first downlink forwarding user plane transport and network layer information comprising a first transport layer address and a first general packet radio service (GPRS) tunnelling protocol (GTP) tunnel endpoint identifier, a first uplink forwarding user plane transport and network layer information comprising a second transport layer address and a second general packet radio service (GPRS) tunnelling protocol (GTP) tunnel endpoint identifier.

[0295] In an example, the second data forwarding information for the second DRB associated with the second PDU set may comprise at least one of: the identifier of the second DRB, the second identifier of the second PDU set, a second downlink forwarding user plane transport and network layer information comprising a third transport layer address and a third general packet radio service (GPRS) tunnelling protocol (GTP) tunnel endpoint identifier, a second uplink forwarding user plane transport and network layer information comprising a fourth transport layer address and a fourth general packet radio service (GPRS) tunnelling protocol (GTP) tunnel endpoint identifier.

[0296] In an example, the response message may indicate that BS2 accept the proposed data forwarding for the first DRB and the second DRB from BS1.

[0297] In an example, the response message may comprise one or more identifiers of the first PDU set or the second PDU set, wherein one or both of the first PDU set or the second PDU set are admitted or failed to be admitted. Upon failure of one or more of the first PDU set or the second PDU set, the response message may further comprise a cause value.

[0298] In an example, the cause value may comprise at least one of: radio resources not available, radio resources not available to accept both the PDU set 1 and 2, resources not available for the slice of the PDU set 1 and/or the PDU set 2, unknown or invalid QoS flow/sub-QoS flow/PDU set/DRB identifier, and/or the like.

[0299] The response message may comprise at least one of: a Xn/X2 interface message; a handover request acknowledge message, a secondary node (SN) modification request acknowledge message; a SN addition request acknowledge message; an N2/NG interface message; a S1 interface message; a NG/S1 handover request acknowledge message; a handover command message; and/or the like. The response message may be, for example, a single message. It may be understood that the message may have any suitable name.

[0300] The response message may comprise at least one of: an identifier (e.g., MME UE S1AP ID) of the wireless device within mobility management entity (MME); an identifier (e.g., AMF UE NGAP ID) of the wireless device within AMF; an identifier (e.g., eNB UE S1AP ID) of the wireless device within eNB; an identifier (e.g., RAN UE NGAP ID) of the wireless device within NG radio access network (NG-RAN); an identifier (e.g., MeNB UE X2AP ID, SgNB UE X2AP ID) of the wireless device within eNB or gNB; an identifier (e.g., M-NG-RAN node UE XnAP ID, S-NG-RAN node UE XnAP ID) of the wireless device within master NG-RAN node or secondary NG-RAN node; an identifier (e.g., source NG-RAN node UE XnAP ID, target NG-RAN node UE XnAP ID) of the wireless device within source NG-RAN node or target NG-RAN node and/or the like.

[0301] In an example, the response message may comprise at least one of: the common identifier of the first PDU set and the second PDU set, wherein the first PDU set and the second PDU set are both successfully established; the common identifier of the first PDU set and the second PDU set, wherein the first PDU set and the second PDU set both failed to be established; the common identifier of either the first PDU set or the second PDU set, wherein the first PDU set or the second flow failed to be established; the common identifier of either the first PDU set or the second PDU set, wherein the first PDU set or the second PDU set is successfully established; and/or the like.

[0302] In an example, as shown in FIG. **26** or in FIG. **27**, BS1 may perform, based on the response message, data forwarding for the wireless device.

[0303] In an example embodiment, as shown in FIG. **28**, a target base station (BS2) may receive, from a source base station (BS1), request message requesting a handover of a wireless device, wherein the first request message indicates: a first data radio bearer (DRB) is associated with a first PDU set; a second DRB is associated with a second PDU set. The target base station may determine whether to accept the proposal of performing data forwarding from BS1 for the wireless device. The target base station may send, to the source base station, a response message comprising at least a response message comprising at least one of: first data forwarding information for the first DRB associated with the first PDU set; second data forwarding information for the second DRB associated with the second PDU set.

[0304] In an example embodiment, as shown in FIG. **29**, a source base station (BS1) may send, to a target base station (BS2), request message requesting a handover of a wireless device, wherein the first request message indicates: a first data radio bearer (DRB) is associated with a first PDU set; a second DRB is associated with a second PDU set. The source base station may receive, from the target base station, a response message comprising at least a response message comprising at least one of: first data forwarding information for the first DRB associated with the first PDU set; second data forwarding information for the second DRB associated with the second PDU set. The source base station may perform data forwarding based on the received information above.

[0305] In an example, a second base station may receive from a first base station, a request message requesting to requesting a handover of a wireless device, wherein the first request message indicates: a first data radio bearer (DRB) is associated with a first PDU set; a second DRB is associated with a second PDU set; and/or the like.

[0306] In an example, the second base station may send to the first base station a response message comprising at least first data forwarding information for the first DRB associated with the first PDU set; second data forwarding information for the second DRB associated with the second PDU set.

[0307] In an example, the first DRB is associated with the first PDU set may indicate that the first PDU set is mapped to the first DRB. The second DRB is associated with the second PDU set may indicate that the second PDU set is mapped to the second DRB. In an example, the second DRB may be the same as the first DRB, wherein the first PDU set and the second PDU set are mapping to this DRB.

[0308] In an example, the first DRB may comprise an identifier of the first DRB. the second DRB may comprise an identifier of the second DRB. The first PDU set may comprise an identifier of the first PDU set. The second PDU set may comprise an identifier of the second PDU set.

[0309] In an example, the first PDU set may comprise at least one of: a QoS flow; a sub-QoS flow; a PDU set, a ADU; and/or the like. The second PDU set may comprise at least one of: a QoS flow; a sub-QoS flow; a PDU set, a ADU; and/or the like.

[0310] The first PDU set and the second PDU set may be for the same application (e.g. Application A) of the wireless device. The application may comprise at least one of: an advanced media service; a High Data Rate Low Latency

(HDRLL) service; a virtual reality (VR) service; an augmented reality service; an extended reality (XR) service; a tactile/multi-modality communication services; a streaming service (e.g., video, audio); a multimedia telephony service for IMS (MTSI) service; a multimedia broadcast and multicast service (MBMS); a multicast broadcast service (MBS); and/or the like.

[0311] In an example, the first PDU set and/or the second PDU set may further comprise parameters at least one of: QoS flow/sub-QoS flow/PDU Set Delay Budget, QoS flow/sub-QoS flow/PDU set arrival period and start time, Qos flow/sub-QoS flow/PDU set arrival jitter, QoS flow/sub-QoS flow/PDU set discarding allowed indication, QoS flow/sub-QoS flow/Maximum tolerable delay difference for group of associated flows/bearer, QoS flow/sub-QoS flow/PDU Set identifier, number of PDUs in a QoS flow/sub-QoS flow/PDU set, last QoS flow/sub-QoS flow/PDU indication in a QoS flow/sub-QoS flow/PDU set, QoS flow/sub-QoS flow/PDU Set bit Size, QoS flow/sub-QoS flow/PDU Set delay information, QoS flow/sub-QoS flow/PDU set importance or priority, QoS flow/sub-QoS flow/PDU set common identifier/correlation information (e.g., common identifier, group identifier, correlation identifier, group of picture (GOP) identifier), and/or the like. In an example, the QoS flow/sub-QoS flow/PDU set importance or priority may comprise type A, type B as described above.

[0312] In an example, the common identifier may comprise at least one of: a common identifier; a group identifier; a correlation identifier; GOP identifier; and/or the like. The common identifier the first PDU set and the common identifier of the second PDU set may indicate the relation/correlation of the first PDU set and the second PDU set. BS2 may understand that the first PDU set and the second PDU set are for the same application (e.g., Application A).

[0313] In an example, as shown in FIG. **26** or in FIG. **27**, the second base station may determine whether to accept the proposal of performing data forwarding from the first base station, the second base station may determine to use the same DRB configuration and to map the same PDU sets to DRBs as BS1.

[0314] In an example, the second base station may further determine to accept or reject the first PDU set and/or the second PDU set. In an example, the second base station may further determine, based on the PDU sets importance/priority/type A/type B information, radio resources allocation handling for the first PDU set and/or the PDU set.

[0315] In an example, the first data forwarding information for the first DRB associated with the first PDU set may comprise at least one of: the identifier of the first DRB, the first identifier of the first PDU set, a first downlink forwarding user plane transport and network layer information comprising a first transport layer address and a first general packet radio service (GPRS) tunnelling protocol (GTP) tunnel endpoint identifier, a first uplink forwarding user plane transport and network layer information comprising a second transport layer address and a second general packet radio service (GPRS) tunnelling protocol (GTP) tunnel endpoint identifier.

[0316] In an example, the second data forwarding information for the second DRB associated with the second PDU set may comprise at least one of: the identifier of the second DRB, the second identifier of the second PDU set, a second downlink forwarding user plane transport and network layer information comprising a third transport layer address and a third general packet radio service (GPRS) tunnelling protocol (GTP) tunnel endpoint identifier, a second uplink forwarding user plane transport and network layer information comprising a fourth transport layer address and a fourth general packet radio service (GPRS) tunnelling protocol (GTP) tunnel endpoint identifier.

[0317] In an example, the response message may indicate that the second base station accept the proposed data forwarding for the first DRB and the second DRB from the first base station.

[0318] In an example, the response message may comprise one or more identifiers of the first PDU set or the second PDU set, wherein one or both of the first PDU set or the second PDU set are admitted or failed to be admitted. Upon failure of one or more of the first PDU set or the second PDU set, the response message may further comprise a cause value.

[0319] In an example, the cause value may comprise at least one of: radio resources not available, radio resources not available to accept both the PDU set 1 and 2, resources not available for the slice of the PDU set 1 and/or the PDU set 2, unknown or invalid QoS flow/sub-QoS flow/PDU set/DRB identifier, and/or the like.

[0320] The response message may comprise at least one of: a Xn/X2 interface message; a handover request acknowledge message, a secondary node (SN) modification request acknowledge message; a SN addition request acknowledge message; an N2/NG interface message; a S1 interface message; a NG/S1 handover request acknowledge message; a handover command message; and/or the like. The response message may be, for example, a single message. It may be understood that the message may have any suitable name.

[0321] The response message may comprise at least one of: an identifier (e.g., MME UE S1AP ID) of the wireless device within mobility management entity (MME); an identifier (e.g., AMF UE NGAP ID) of the wireless device within AMF; an identifier (e.g., eNB UE S1AP ID) of the wireless device within eNB; an identifier (e.g., RAN UE NGAP ID) of the wireless device within NG radio access network (NG-RAN); an identifier (e.g., MeNB UE X2AP ID, SgNB UE X2AP ID) of the wireless device within eNB or gNB; an identifier (e.g., M-NG-RAN node UE XnAP ID, S-NG-RAN node UE XnAP ID) of the wireless device within master NG-RAN node or secondary NG-RAN node; an identifier (e.g., source NG-RAN node UE XnAP ID, target NG-RAN node UE XnAP ID) of the wireless device within source NG-RAN node or target NG-RAN node and/or the like.

[0322] In an example, the response message may comprise at least one of: the common identifier of the first PDU set and the second PDU set, wherein the first PDU set and the second PDU set are both successfully established; the common identifier of the first PDU set and the second PDU set, wherein the first PDU set and the second PDU set both failed to be established; the common identifier of either the first PDU set or the second PDU set, wherein the first PDU set or the second flow failed to be established; the common identifier of either the first PDU set or the second PDU set, wherein the first PDU set or the second PDU set is successfully established; and/or the like.

1. A method comprising:

receiving, by a first base station from a second base station, a message requesting a configuration of a data radio bearer (DRB) for a wireless device, wherein the message indicates that the DRB is associated with a protocol data unit (PDU) set of an application.

2. The method of claim **1**, wherein the request message requests a handover of the wireless device.

3. The method of claim **1**, wherein the message indicates that:

a first DRB is associated with a first PDU set of the application; and

a second DRB is associated with a second PDU set of the application.

4. The method of claim **3**, wherein:

the first DRB being associated with the first PDU set indicates that the first PDU set is mapped to the first DRB; and

the second DRB being associated with the second PDU set indicates that the second PDU set is mapped to the second DRB.

5. The method of claim **3**, wherein the second DRB is the same as the first DRB.

6. The method of claim **1**, further comprising sending, by the first base station to the second base station, a response message comprising at least one of:

first data forwarding information for the first DRB associated with the first PDU set; or

second data forwarding information for the second DRB associated with the second PDU set.

7. The method of claim **1**, wherein the DRB comprises an identifier of the DRB.

8. A first base station comprising one or more processors and memory storing instructions that, when executed by the one or more processors, cause the first base station to:

receive, from a second base station, a message requesting a configuration of a data radio bearer (DRB) for a wireless device, wherein the message indicates that the DRB is associated with a protocol data unit (PDU) set of an application.

9. The first base station of claim **8**, wherein the request message requests a handover of the wireless device.

10. The first base station of claim **8**, wherein the message indicates that:

a first DRB is associated with a first PDU set of the application; and

a second DRB is associated with a second PDU set of the application.

11. The first base station of claim **10**, wherein:

the first DRB being associated with the first PDU set indicates that the first PDU set is mapped to the first DRB; and

the second DRB being associated with the second PDU set indicates that the second PDU set is mapped to the second DRB.

12. The first base station of claim **10**, wherein the second DRB is the same as the first DRB.

13. The first base station of claim **8**, wherein the instructions further cause the first base station to send, to the second base station, a response message comprising at least one of:

first data forwarding information for the first DRB associated with the first PDU set; or

second data forwarding information for the second DRB associated with the second PDU set.

14. The first base station of claim **8**, wherein the DRB comprises an identifier of the DRB.

15. A non-transitory computer-readable medium comprising instructions that, when executed by one or more processors of a first base station, cause the first base station to:

receive, from a second base station, a message requesting a configuration of a data radio bearer (DRB) for a wireless device, wherein the message indicates that the DRB is associated with a protocol data unit (PDU) set of an application.

16. The non-transitory computer-readable medium of claim **15**, wherein the request message requests a handover of the wireless device.

17. The non-transitory computer-readable medium of claim **15**, wherein the message indicates that:

a first DRB is associated with a first PDU set of the application; and

a second DRB is associated with a second PDU set of the application.

18. The non-transitory computer-readable medium of claim **17**, wherein:

the first DRB being associated with the first PDU set indicates that the first PDU set is mapped to the first DRB; and

the second DRB being associated with the second PDU set indicates that the second PDU set is mapped to the second DRB.

19. The non-transitory computer-readable medium of claim **17**, wherein the second DRB is the same as the first DRB.

20. The non-transitory computer-readable medium of claim **15**, wherein the instructions further cause the first base station to send, to the second base station, a response message comprising at least one of:

first data forwarding information for the first DRB associated with the first PDU set; or

second data forwarding information for the second DRB associated with the second PDU set.

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