5G NR Protocols: Layer 2

TP00005-V-1701 V0 - S02M02 Ed1

Learning objectives
Upon completion of this module, you should be able to:

- Describe NR Channels
- Explain NR Layer 2 Operation

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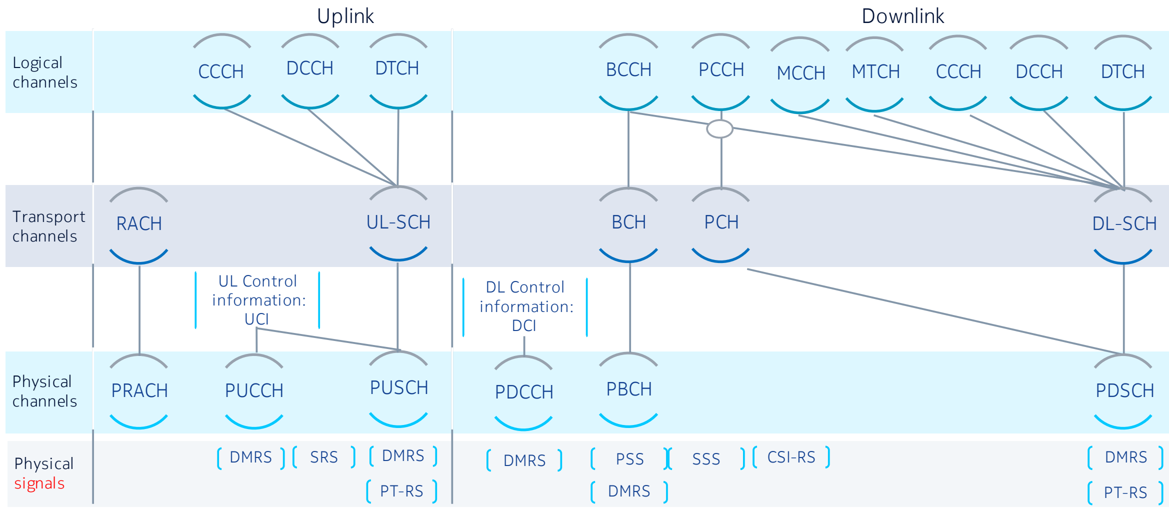
NR Channels

5G NR Radio channels



5G NR radio channels mapping

5G NR Radio Channels (Physical, Transport and Logical Channels) as well as the physical layer signals are displayed on this slide. The slide shows the mapping between logical channels and transport channels and the mapping between transport channels and physical channels.

A downlink physical channel corresponds to a set of resource elements carrying information originating from higher layers. The following downlink physical channels are defined:

-the Physical Downlink Shared Channel (PDSCH),

-the Physical Downlink Control Channel (PDCCH),

-the Physical Broadcast Channel (PBCH),

An uplink physical channel corresponds to a set of resource elements carrying information originating from higher layers. The following uplink physical channels are defined:

-the Physical Random Access Channel (PRACH),

-the Physical Uplink Shared Channel (PUSCH),

-and the Physical Uplink Control Channel (PUCCH).

In addition to the physical channels above, Physical layer signals are defined, which can be reference signals, primary and secondary synchronization signals.

- DMRS associated with NR-PDSCH,
- DMRS associated with NR-PDCCH,
- DMRS associated with NR-PBCH,
- CSI-RS (UE specific, as Cell specific CSI-RS is not considered by 3GPP)
- Phase Tracking RS (PT-RS)
- DM-RS associated with NR-PUCCH,
- DM-RS associated with NR-PUSCH,
- Phase Tracking RS (PT-RS),
- SRS

The following transport channels, and their mapping to PHY channels, are defined:

In Uplink:

Uplink Shared Channel (UL-SCH), mapped to PUSCH and Random Access Channel (RACH), mapped to PRACH

In Downlink:

Downlink Shared Channel (DL-SCH), mapped to PDSCH, Broadcast channel (BCH), mapped to PBCH. And Paging channel (PCH), mapped to PDSCH

Logical channels are classified into two groups: Control Channels and Traffic Channels.

Control channels:

Broadcast Control Channel (BCCH): a downlink channel for broadcasting system control information.

Paging Control Channel (PCCH): a downlink channel that transfers paging information and system information change notifications.

Common Control Channel (CCCH): channel for transmitting control information between UEs and network.

Dedicated Control Channel (DCCH): a point-to-point bi-directional channel that transmits dedicated control information between a UE and the network.

Traffic channels: Dedicated Traffic Channel (DTCH), which can exist in both UL and DL.

In Downlink, the following connections between logical channels and transport channels exist:

BCCH can be mapped to BCH, or DL-SCH;

PCCH can be mapped to PCH;

CCCH, DCCH, DTCH can be mapped to DL-SCH;

In Uplink, the following connections between logical channels and transport channels exist:

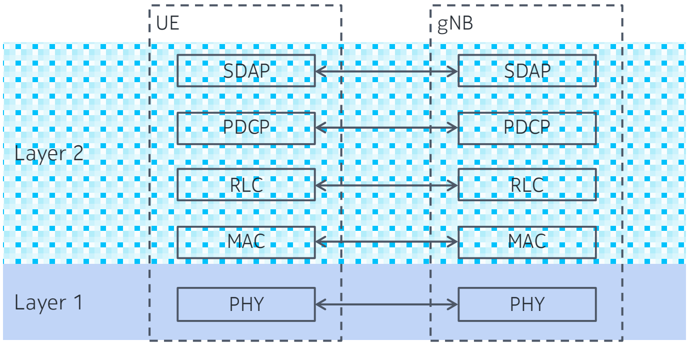
-CCCH,DCCH, DTCH can be mapped to UL-SCH.

NR Layer 2 Operation

NR Layer 2 Operation
Radio Interface Protocol Architecture

User Plane Protocol Stack

- 5G-NR User plane contains Physical, MAC, RLC, and PDCP, also it introduces a new layer named SDAP (Service Data Adaptation Protocol).
- New Service Data Adaptation Protocol supports per packet QoS
- Supports very low latency transmissions and efficient power saving techniques



User plane protocol stack

The concept of “plane” is used to differentiate data exchanged in the network; User plane transports user traffic, Control plane carries signaling, and Management plane is used for network administration purposes.

This diagram shows the protocol stack for the user plane, where Service Data Adaptation Protocol (SDAP) , Packet Data Convergence Protocol (PDCP) , Radio Link Control (RLC) , and Medium Access Control (MAC) sublayers (terminated in gNB on the network side) perform the functions described in coming slides.

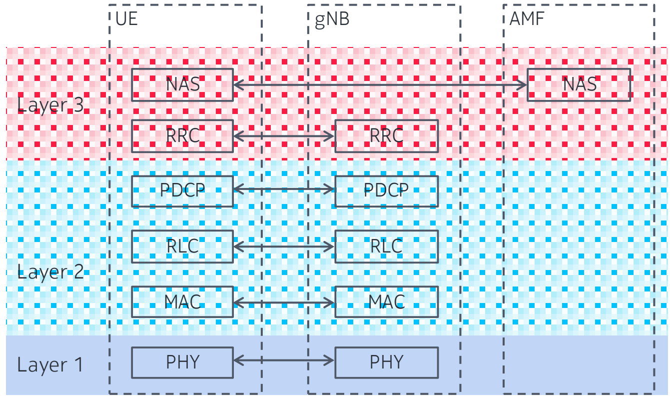
Please note that the SDAP is a new 5G sublayer, related to Quality of Service in 5G NR. It supports per packet QoS.

Layer 1 is the Physical Layer which performs the following functions: modulation, (de)coding, power control, error detection OFDM operations, FFT (Fast Fourier Transform) and iFFT (inverse Fast Fourier Transform).

NR Layer 2 Operation
Radio Interface Protocol Architecture

Control Plane Protocol Stack

As compared to User plane protocol stack, 3GPP defined 2 specific protocols to be used in control plane, they are:
- Radio Resource Control (RRC)- system information broadcast, connection and mobility control in RAN, measurement handling, configuration of ‚lower' protocol parameters
- Non-Access Stratum (NAS)- connection and mobility control between UE and Next Generation Core (NGC)



Control plane protocol stack

On the Control plane, the following protocols are defined:

-RRC, PDCP, RLC, MAC and PHY sublayers (terminated in UE and gNB);

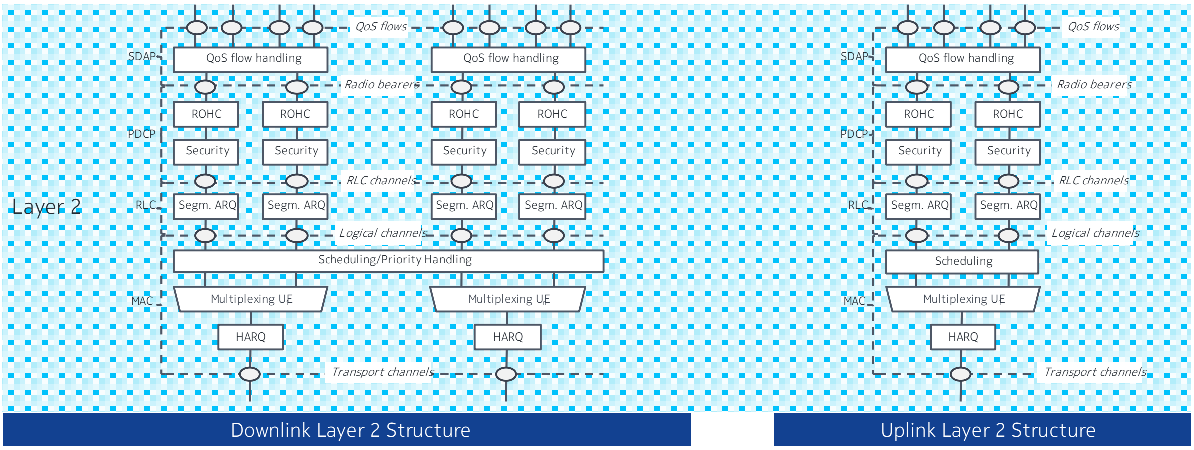
-NAS protocol (terminated in UE and AMF).

Two additional protocols used in control plane to be considered are:

- Radio Resource Control (RRC) – system information broadcast, connection and mobility control in RAN, measurement handling, configuration of ‚lower' protocol parameters
- Non-Access Stratum (NAS) – connection and mobility control between UE and Next Generation Core (NGC).

NR Layer 2 Operation

NR Layer 2 Overview



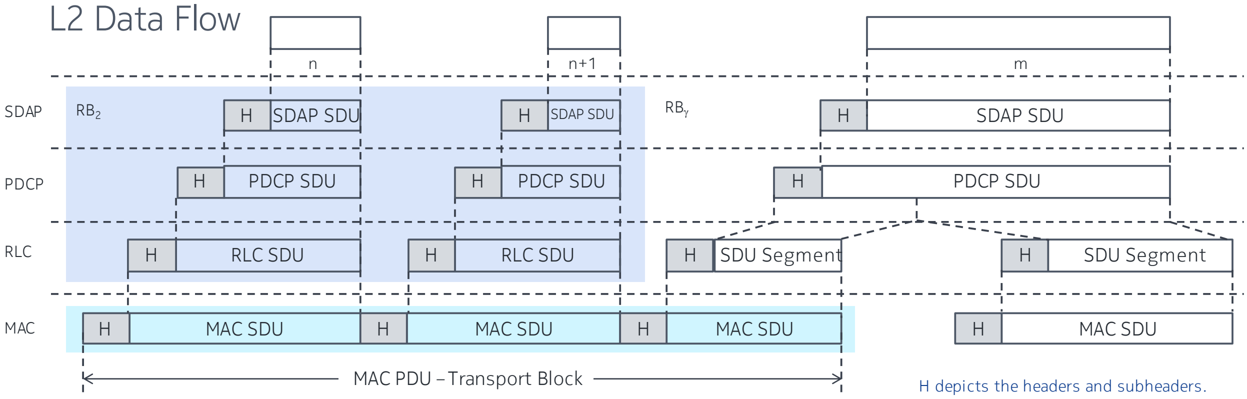
Comp. refers to header compression and segm. to segmentation

The layer 2 of NR is split into the following sublayers: MAC, RLC, PDCP and SDAP. These two diagrams depict the Layer 2 architecture for downlink and uplink, where:

- The physical layer offers to the MAC sublayer transport channels;
- The Medium Access Control (MAC) sublayer offers to the RLC sublayer logical channels. It performs fast retransmissions of packets with errors (Hybrid Automatic Repeat reQuest - HARQ), transmission format selection, scheduling, Quality-of-Service (QoS) handling
- The Radio Link Control (RLC) sublayer offers to the PDCP sublayer RLC channels. RLC functions are: segmentation and reassembly of e.g., IP payload, duplication detection, retransmissions (Automatic Repeat reQuest - ARQ)
- The Packet Data Convergence Protocol (PDCP) sublayer offers to the SDAP sublayer radio bearers. The PDCP performs cyphering, integrity protection, sequence numbering, header compression
- Finally, the Service Data Adaptation Protocol (SDAP) sublayer offers to 5GC QoS flows. It performs the mapping of core network data flows with certain QoS requirements to parametrized radio transmissions.

NR Layer 2 Operation

L2 Data Flow



PDU/SDU definitions:

General rules:

- PDU of a layer = SDU of this layer + this layer's header, e.g., PDCP PDU = PDCP SDU + header
- Upper layer's PDU becomes a lower layer's SDU, e.g., RLC PDU becomes MAC SDU

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Before going forward, let's recall PDU and SDU definitions and Layer 2 data flow:

- a PDU (Protocol Data Unit) is a unit of data that is transmitted among peer entities of a communications system
- SDU (Service Data Unit) is referring to a unit of data that has been passed down from an upper protocol layer to a lower layer.

Remember, Radio bearers are categorized into two groups: data radio bearers (DRB) for user plane data and signaling radio bearers (SRB) for control plane data. SRBs are associated with RRC layer while DRBs are associated with SDAP layer.

An example of the Layer 2 Data Flow is depicted on this Figure, where a transport block is generated by MAC by concatenating two RLC PDUs from RBx and one RLC PDU from RBy. The two RLC PDUs from RBx each corresponds to one IP packet (n and n+1) while the RLC PDU from RBy is a segment of an IP packet (m).

SDAP

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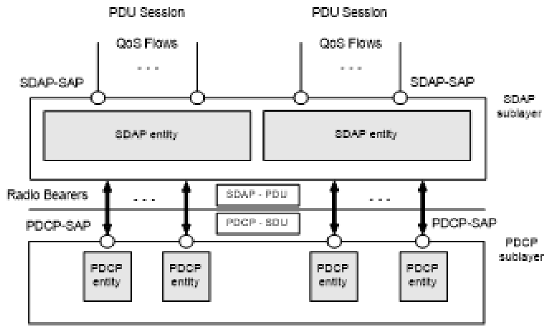
NR Layer 2 Operation
Service Data Adaptation Protocol

Function

- New layer to interface with 5GC
  - It works only with the 5G Core Network
- One SDAP entity is configured per PDU session (as seen from 5GC)
- Specified in 37.324

- It supports the following functions:
  - transfer of user plane data;
  - mapping between a QoS flow and a DRB for both DL and UL;
  - marking QoS flow ID in both DL and UL packets;
  - reflective QoS flow to DRB mapping for the UL SDAP data PDUs.



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Now, Let's a do a quick tour through the different radio protocols.

- SDAP (Service Data Adaptation Protocol) is a new sublayer, not defined for LTE systems.
- It works only with the 5G Core Network
- Its main purpose: mapping Quality of Service flows to Data Radio Bearers (DRBs, many-to-one relationship). And marking QoS flow ID (QFI) in both DL and UL packets.
  - Handles QoS flows and their mapping on data radio bearers as well as reflective QoS for which an SDAP header is added
  - RQI: Reflective QoS indicator, telling the UE to update the mapping rules
  - QFI: QoS flow indicator.

A single protocol entity of SDAP is configured for each individual PDU session.

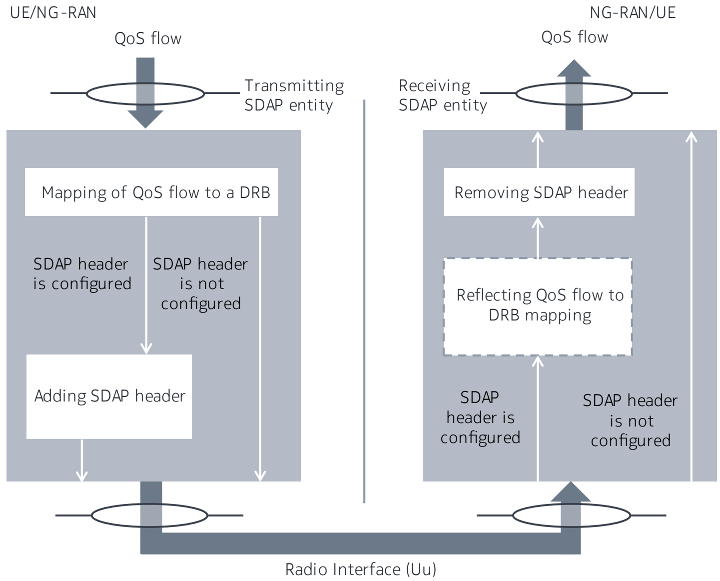
The service provided by SDAP to upper layers: transfer of user plane data.

NR Layer 2 Operation

Service Data Adaptation Protocol

Mapping of QoS flows

- Each QoS flow is identified by a QFI and each QFI is characterized by a QoS profile by 5GC.
- In uplink, mapping rules tell the UE which DRB to use for which QoS flow
- A default DRB carries all QFI for which no mapping rules are configured
- Mapping rules are explicitly configured via RRC or implicitly via user plane (Reflective QoS)



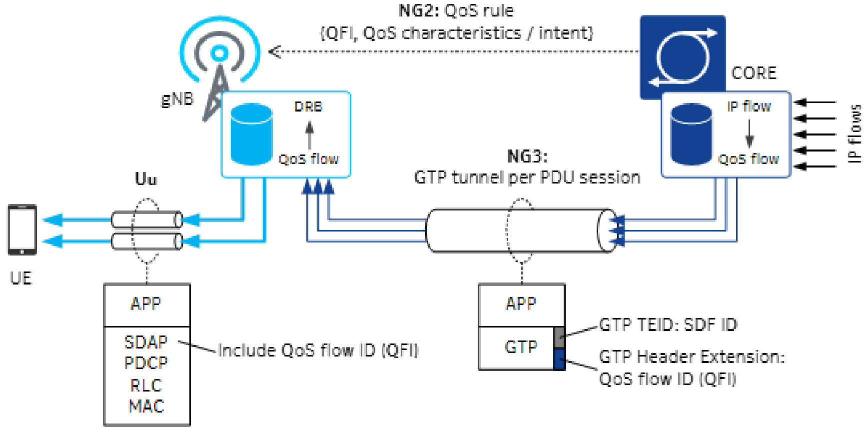
Each QoS flow is identified by a QFI and each QFI is characterized by a QoS profile by 5GC

- A QoS profile contains QoS parameters and characteristics (resource type, bit rate, delays…)
- All QFIs and their characteristics are known to the gNB at PDU session establishment
- With the QoS profile, the gNB knows how to treat packets over the radio and can map flows onto DRBs.

Reflective QoS flow to DRB mapping is performed at UE.

NR Layer 2 Operation
Service Data Adaptation Protocol

Mapping of QoS flows - DL



The NG-RAN and 5GC ensure quality of service (for example, reliability and target delay) by mapping packets to appropriate QoS Flows and DRBs. Hence, there is a 2-step mapping of IP-flows to QoS flows (Non Access Stratum) and from QoS flows to DRBs (Access Stratum).

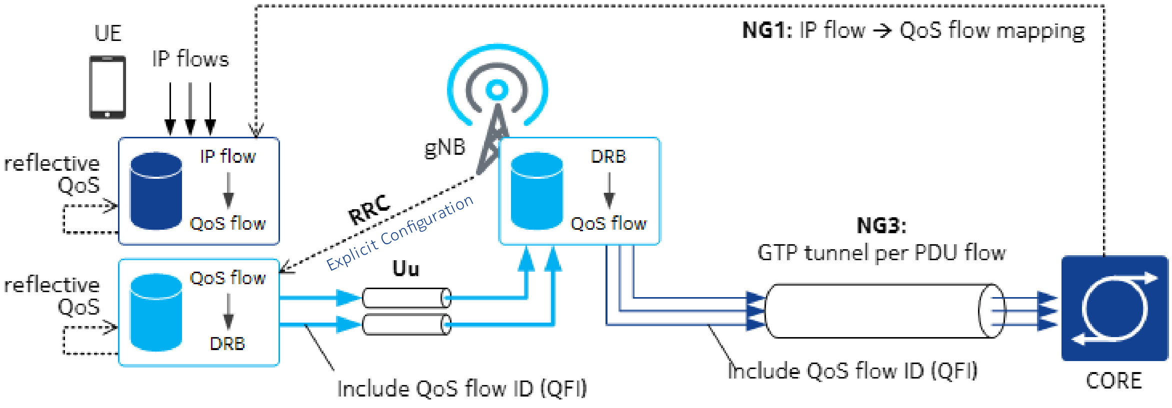
The SDAP sublayer is configured by RRC. The SDAP sublayer maps QoS flows to DRBs. One or more QoS flows may be mapped onto one DRB. One QoS flow is mapped onto only one DRB at a time in the UL.

A QoS flow is identified within a PDU session by a QoS Flow ID (QFI) carried in an encapsulation header over NG-U.

In the Downlink, the UPF uses policy from the PCF and the SMF to identify flows and adds a QFI tag to downlink packets. Then, the RAN uses the QFI tag and policy to map flows to Data Radio Bearers (DRBs).

NR Layer 2 Operation
Service Data Adaptation Protocol

Mapping of QoS flows - UL



In the uplink, the UE uses either a signaling or “reflective” learning approach to learn the policies QFI usage to map to DRBs.

The NG-RAN may control the mapping of QoS Flows to DRBs in two different ways:

- Reflective mapping: for each DRB, the UE monitors the QFI(s) of the downlink packets and applies the same mapping in the uplink; that is, for a DRB, the UE maps the uplink packets belonging to the QoS flows(s) corresponding to the QFI(s) and PDU Session observed in the downlink packets for that DRB. To enable this reflective mapping, the NG-RAN marks downlink packets over Uu with QFI.
- Explicit Configuration (shown on the slide): besides the reflective mapping, the NG-RAN may configure an uplink "QoS Flow to DRB mapping“ by RRC.

The UE shall always apply the latest update of the mapping rules regardless of whether it is performed via reflecting mapping or explicit configuration.

Note that the Reflective QoS enables the UE to map UL User Plane traffic to QoS Flows without the SMF provided QoS rules. This is achieved by creating UE derived QoS rules in the UE based on the received DL traffic. It shall be possible to apply Reflective QoS and non-Reflective QoS concurrently within the same PDU Session.

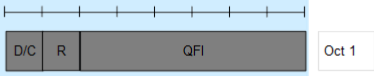
To learn more about 5GS QoS model, please refer to 5GS QoS Flow handling module.

NR Layer 2 Operation
Service Data Adaptation Protocol

PDU Format

- A "transparent mode" is allowed to minimize overhead
  - will typically be used when only one flow is mapped on one bearer e.g. for voice
- Downlink Format
  - QFI: indicates the ID of the QoS flow to which the SDAP PDU belongs
  - RDI: QoS flow to DRB mapping (AS) rules update
  - RQI: SDF to QoS flow mapping (NAS) rules update
- Uplink Format
  - D/C: to signal User Data or End Marker
  - QFI: indicates the ID of the QoS flow to which the SDAP PDU belongs
  - R: reserved bit

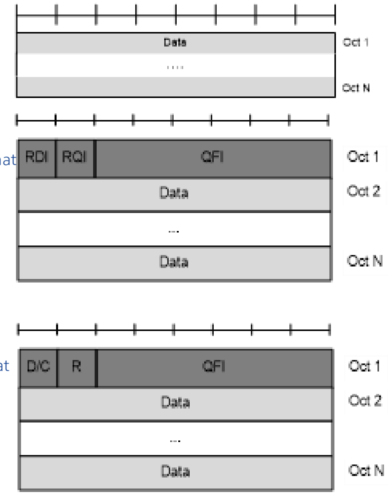
End-Marker Control PDU



SDAP Data PDU format without SDAP header

DL SDAP Data PDU format with SDAP header

UL SDAP Data PDU format with SDAP header



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The SDAP Data PDU is used to convey one or more of followings: SDAP header and user plane data.

End-Marker Control PDU is used by the SDAP entity at UE to indicate that it stops the mapping of the SDAP SDU of the QoS flow indicated by the QFI to the DRB on which the End-Marker PDU is transmitted.

The D/C bit indicates whether the SDAP PDU is an SDAP Data PDU or an SDAP Control PDU.

The QFI (QoS Flow ID) field indicates the ID of the QoS flow to which the SDAP PDU belongs.

The RQI (Reflective QoS Indication) bit indicates whether NAS should be informed of the updated of SDF to QoS flow mapping rules.

The RDI (Reflective QoS flow to DRB mapping Indication) bit indicates whether QoS flow to DRB mapping rule should be updated.

NR Layer 2 Operation
Quiz 1

1. Which of the following is a correct statement?
   a. SDAP works only with the 5G Core Network
   b. SDAP works only with the EPC Core Network
   c. SDAP works with both 5G and EPC Core Networks
2. Where user data packets are mapped to QoS flows?
   a. At the gNB (in the Uplink) and at the UPF (in the Downlink)
   b. At the UE (in the Uplink) and at the SMF (in the Downlink)
   c. At the UE (in the Uplink) and at the UPF (in the Downlink)
   d. At the UE (in the Uplink) and at the gNB (in the Downlink)

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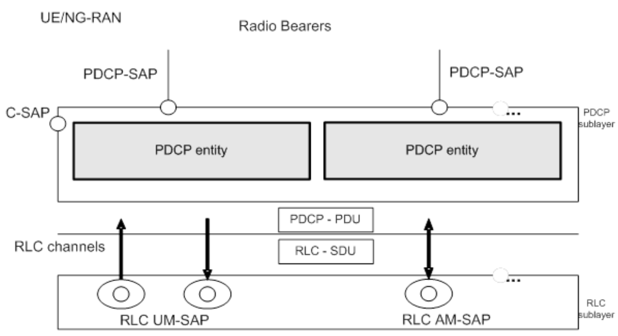
PDCP

NR Layer 2 Operation
Packet Data Convergence Protocol

Services

- The PDCP layer provides its services to the RRC or SDAP layers:
  - transfer of user plane data;
  - transfer of control plane data;
  - header compression;
  - ciphering;
  - integrity protection



The PDCP (specified in TS38.323) performs header compression, security operations (Ciphering and Integrity protection) and guarantees in-order delivery without duplicates. The PDCP functions are listed on the slide.

The PDCP sublayer is used for RBs mapped on DCCH and DTCH type of logical channels. The PDCP sublayer is not used for any other type of logical channels.

Each RB (except for SRB0) is associated with one PDCP entity. Each PDCP entity is associated with one, two, or four RLC entities depending on the RB characteristic (e.g. uni-directional/bi-directional or split/non-split) or RLC mode.

For non-split bearers, each PDCP entity is associated with one UM RLC entity, two UM RLC entities (one for each direction), or one AM RLC entity.

For split bearers, each PDCP entity is associated with two UM RLC entities (for same direction), four UM RLC entities (two for each direction), or two AM RLC entities (for same direction).

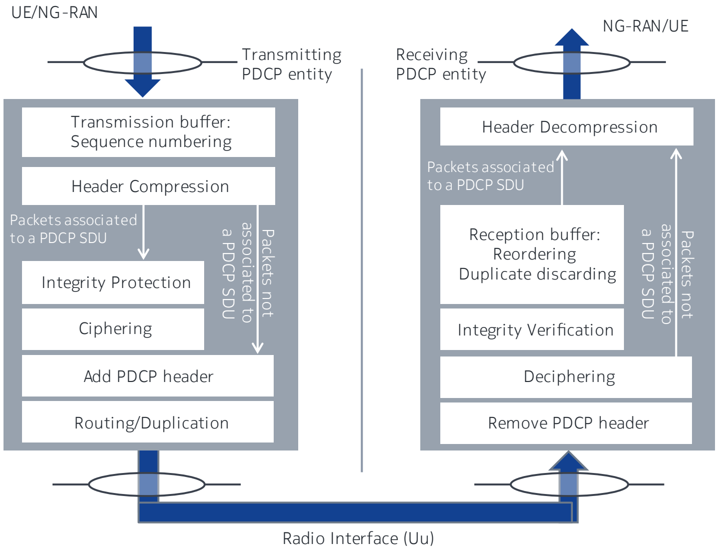
Main differences with LTE

- allows integrity protection to be configured for the data radio bearers as well
- always-on re-ordering window
- only 2 PDCP SN (12 and 18 bits)
- support for duplication over two RLC legs
- in-order delivery can be turned off.

NR Layer 2 Operation
Packet Data Convergence Protocol

Functions

- The PDCP layer supports the following functions:
  - transfer of data (user plane or control plane);
  - maintenance of PDCP SNs;
  - header compression and decompression using the ROHC protocol;
  - ciphering and deciphering;
  - integrity protection and integrity verification;
  - timer based SDU discard;
  - for split bearers, routing;
  - duplication;
  - reordering and in-order delivery;
  - out-of-order delivery;
  - duplicate discarding.



When the user data IP packet from higher layer goes into PDCP layer it is stored in PDCP transmission buffer as PDCP SDU (PDCP Service Data Unit). The PDCP layer is processing these data by encrypting each PDCP SDU and adding PDCP Header. As result PDCP PDU (PDCP Packet Data Unit) is created and forwarded towards the lower layer RLC; in RLC layer this packet is known as RLC SDU.

Integrity protection ensures data consistency and data correctness. The data unit that is integrity protected is the PDU header and the data part of the PDU before ciphering.

Ciphering ensures encryption of data to avoid the information leakage. The ciphering algorithm and key to be used by the PDCP entity are configured by upper layers (specified in TS 38.331). When security is activated, the ciphering function shall be applied to all PDCP Data PDUs indicated by upper layers.

The PDCP allows integrity protection to be configured for the **Data Radio Bearers (DRBs),** as well. This was not the case in LTE. The main services and functions of the PDCP sublayer as well as the main differences with PDCP protocol in LTE are listed previously.

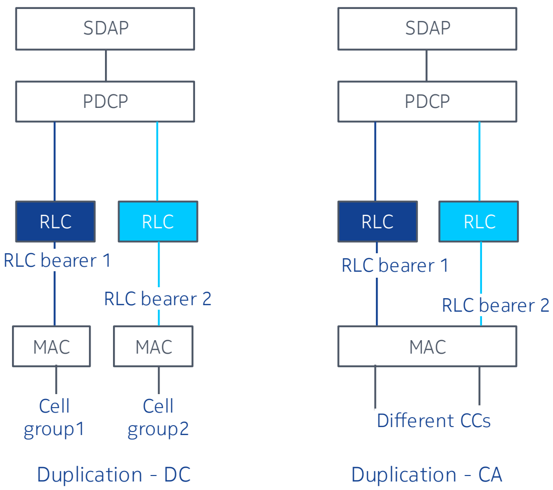
The header compression protocol is based on the Robust Header Compression (ROHC) framework defined in RFC 5795. There are multiple header compression algorithms, called profiles, defined for the ROHC framework. Each profile is specific to the particular network layer, transport layer or upper layer protocol combination e.g., TCP/IP and RTP/UDP/IP.

Duplication allows PDCP PDUs to be duplicated and sent over two different RLC legs. The RLC legs can either belong to the same CG (CA) or to different CGs (DC).

NR Layer 2 Operation
Packet Data Convergence Protocol

PDCP - Data duplication

PDCP PDUs can be duplicated for transmission over 2 RLC bearer:
- In case of carrier aggregation (CA): Restrictions configured in the MAC ensure that duplicated data is transmitted via different component carriers
- In case of dual connectivity (DC): RLC bearers are mapped to different cell groups (i.e., MCG and SCG)



PDCP PDUs can be duplicated for transmission over 2 RLC bearer.

Motivated to enable the reliability/delay requirements for URLLC applications.

In case of carrier aggregation (CA)

Restrictions configured in the MAC ensure that duplicated data is transmitted via different component carriers.

In case of dual connectivity (DC)

RLC bearers are mapped to different cell groups (i.e. MCG and SCG).

PDCP Duplication impact on MAC:

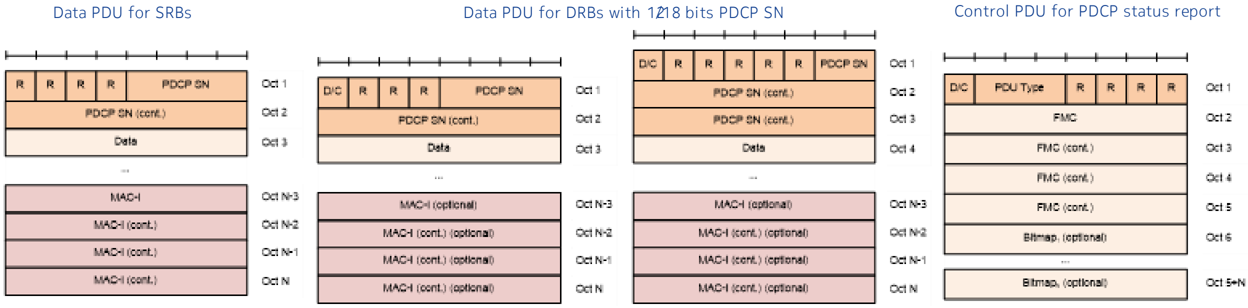
MAC CE with bitmap to control duplication activation/deactivation per DRB of the MAC entity, for both CA and DC duplication.

In case of CA duplication, carrier restrictions in LCP are used to ensure the duplicated PDUs are not multiplexed within the same carrier (NW ensures there are active SCells to multiplex data).

NR Layer 2 Operation
Packet Data Convergence Protocol

PDCP PDU formats:

- PDCP SN: 12 or 18 bits
- Data: This field includes one of the followings:
  - Uncompressed PDCP SDU (user plane data, or control plane data);
  - Compressed PDCP SDU (user plane data only).
- MAC-I: This field carries a message authentication code
- D/C: This field indicates whether the corresponding PDCP PDU is a PDCP Data PDU or a PDCP Control PDU.
- PDU Type: This field indicates the type of control information
- FMC: First Missing COUNT
- Bitmap: This field indicates which SDUs are missing and which SDUs are correctly received in the receiving PDCP entity.



The PDCP Data PDU is used to convey one or more of followings in addition to the PDU header:

- user plane data;
- control plane data;
- a MAC-I.

The PDCP Control PDU is used to convey one of followings in addition to the PDU header:

- a PDCP status report;
- an interspersed ROHC feedback;
- an EHC feedback.

PDCP SN length

12 bits: UM DRBs, AM DRBs, and SRBs

18 bits: UM DRBs, and AM DRBs

MAC-I

For SRBs, the MAC-I field is always present. If integrity protection is not configured, the MAC-I field is still present but should be padded with padding bits set to 0.

For DRBs, the MAC-I field is present only when the DRB is configured with integrity protection.

RLC

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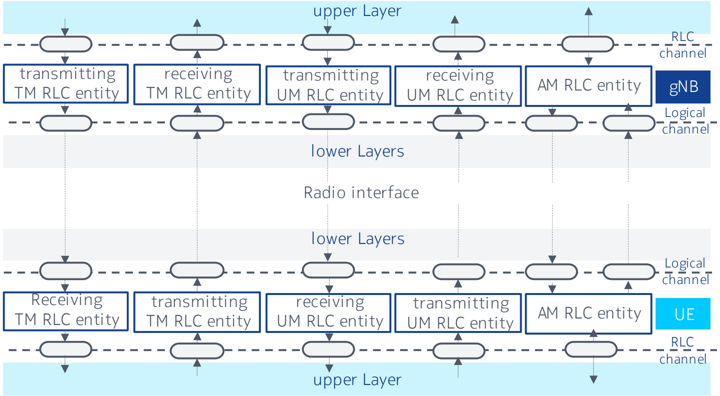
NR Layer 2 Operation
Radio Link Control

Functions:

The functions are supported by the RLC sub layer:
- transfer of upper layer PDUs;
- error correction through ARQ (only for AM data transfer);
- segmentation and reassembly of RLC SDUs (only for UM and AM data transfer);
- re-segmentation of RLC SDU segments(only for AM data transfer);
- duplicate detection(only for AM data transfer);
- RLC SDU discard (only for UM and AM data transfer);
- RLC re-establishment;
- Protocol error detection (only for AM data transfer).



The RLC sublayer supports 3 transmission modes:		
Transparent Mode (TM)	Unacknowledged Mode	Acknowledged Mode

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The main services and functions of the RLC sublayer (Specified in 38.322) depend on the transmission mode and include: Sequence numbering independent of the one in PDCP, Error Correction through ARQ (Automatic Repeat Request in Acknowledged Mode only); Segmentation and Reassembly and re-segmentation of RLC SDUs.

The RLC configuration is per logical channel with no dependency on numerologies and/or TTI durations, and ARQ can operate on any of the numerologies and/or TTI durations the logical channel is configured with.

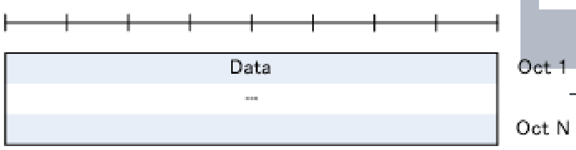
main differences with LTE
- no concatenation in TX, no re-ordering in RX, no SN for complete SDUs for RLC UM, offset-based segmentation always
- SN of 6 and 12 bits supported for UM, 12 and 18 bits for AM.

Reduced RLC functions motivated by pre-processing
- Removing concatenation allows RLC PDU pre-creation in the Tx side as the knowledge of available grant is not required – only segmentation needs to be performed in real time
- Removing reordering allows immediate submission to PDCP entity when full RLC PDU is received which allows deciphering before reordering (no bursts in deciphering in case RLC delivers bunch of RLC PDUs simultaneously):
    - Also, for UM, SN is only meaningful for segmentation and hence it is not indicated for full RLC SDUs. This allows overhead optimization as well as smaller SN space
- Segment Offset (SO) based segmentation always to avoid different PDU types as well as better pre-processing:
    - Segment Information (SI) can indicate ‘full SDU’, ‘first segment’, ‘middle segment’, or ‘last segment’
    - By means of the SI, the first segment does not come with SO (as it would be zero) which further improves pre-processing as for any new SDU the header size is known in advance regardless of possible segmentation.

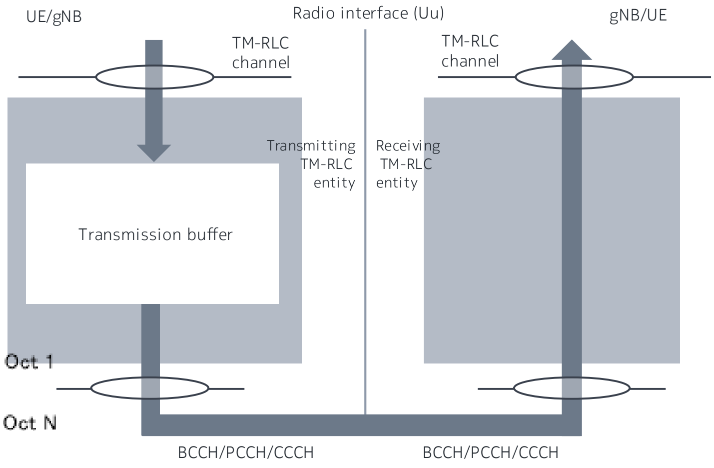
NR Layer 2 Operation
Radio Link Control

Transparent Mode (TM)

- Transparent Mode (TM), used for:
  - SRB0 (control information transfer before RRC connection is established)
  - Paging
  - broadcast system information



TM Data PDU structure



Model of Transparent Mode mode entity

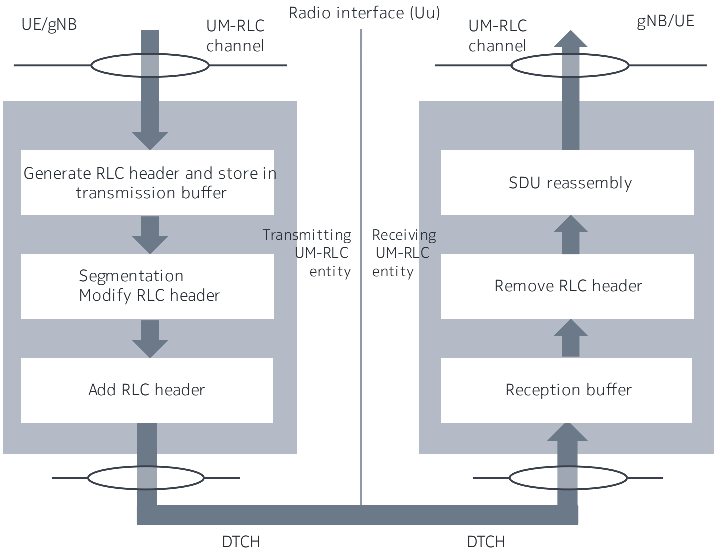
RLC Transparent Mode used for SRB0, Signaling Radio Bearer SRB0 is the control information transfer before RRC connection is established.

Transparent Mode is used also for Paging and broadcast system information.

NR Layer 2 Operation
Radio Link Control

Unacknowledged Mode (UM) :

- Unacknowledged Mode (UM) used for:
  DRBs (user data transfer), for which lossless transmission is not required/applicable, e.g., live TV broadcast, low latency data, voice, applications based on UDP



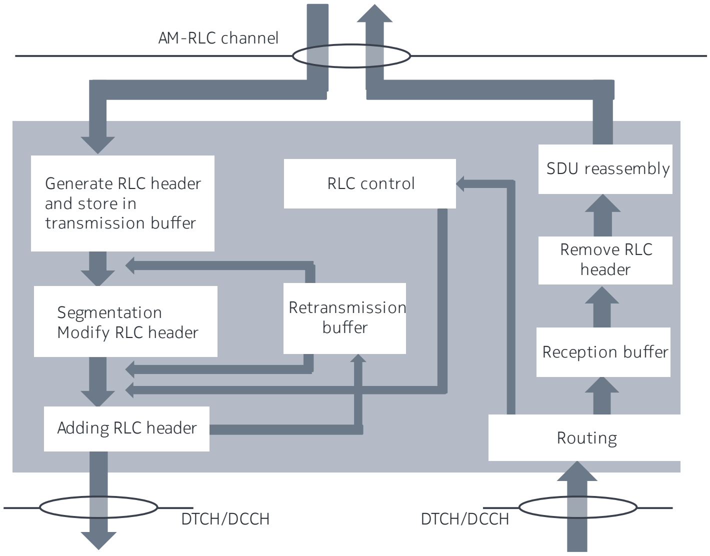
Model of an unacknowledged mode entity

RLC Unacknowledged Mode (UM) is used for DRBs (Data Radio Bearers carrying user data transfer), for which lossless transmission is not required or applicable, e.g. live TV broadcast, low latency data, voice, applications based on UDP.

NR Layer 2 Operation
Radio Link Control

Acknowledged Mode (AM)

- Acknowledged Mode (AM) is used for:
  - SRBs other than SRB0 (control information transfer after RRC connection is established)
  - DRBs for which lossless data transmissions should be ensured (i.e., reliability more important than latency), e.g., TCP based applications (web browsing, FTP), most Internet applications



Model of an acknowledged mode entity

 Nokia Confidential

RLC Acknowledged Mode (AM) used for SRBs other than SRB0, DRBs for which lossless data transmissions should be ensured (i.e., reliability more important than latency), e.g., TCP based applications (web browsing, FTP), most Internet applications.

On transmitting side, PDCP PDUs are forwarded towards the RLC layer and are stored in the transmission buffer as RLC SDUs. RLC layer is responsible for further processing of the user data and the output is RLC PDU forwarded towards MAC layer.

The RLC operation depends on the information provided by MAC scheduler about TBS (Transport Block Size) – it tells which amount of user data, the RLC layer should prepare as RLC PDU, allowed for sending over air interface, assuming number of reserved PRBs as well as selected MCS by MAC layer.

For non-GBR DRB operating in RLC AM mode, RLC layer is sending the RLC PDU towards MAC layer, but also its copy is inserted into RLC retransmission buffer.

To adapt the RLC PDU data size to the requested TBS, RLC layer must be able to:

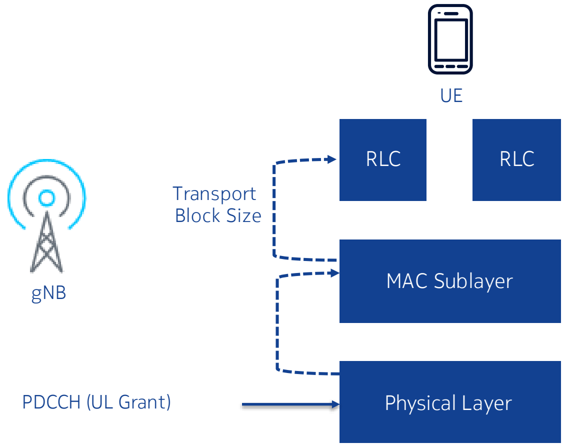
- segment RLC SDU which is bigger than the TBS requested by MAC layer
- no concatenation of multiple RLC SDUs into a single RLC PDU packet (as it was for in LTE).

NR Layer 2 Operation
Radio Link Control

The RLC operation depends on the information provided by MAC scheduler about TBS (Transport Block Size)

To adapt the RLC PDU data size to requested TBS, RLC layer has to :

- segment RLC SDU which is bigger than the TBS requested by MAC layer
- no concatenation of multiple RLC SDUs into a single RLC PDU packet (as it was for in LTE).



The following services are expected by RLC from lower layer (i.e., MAC): data transfer and notification of a transmission opportunity, together with the total size of the RLC PDU(s) to be transmitted in the transmission opportunity.

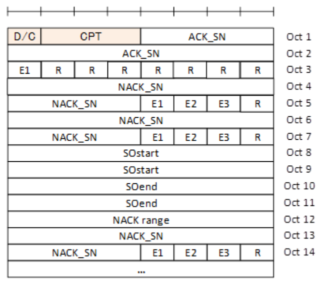
The RLC operation depends on the information provided by MAC scheduler about TBS (Transport Block Size).

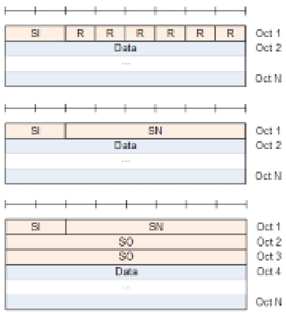
It tells which amount of user data, the RLC layer should prepare as RLC PDU, allowed for sending over air interface, assuming number of reserved PRBs as well as selected MCS by MAC layer.

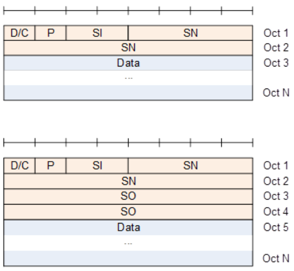
NR Layer 2 Operation
Radio Link Control

RLC PDU formats:

- For UM, 3 different PDU formats: full SDU, first segment, and middle/last segment
- For AM, 2 different PDU formats: full SDU/first segment and middle/last segment
- Control PDU can indicate range of consecutive NACK_SNs motivated by concatenation removal





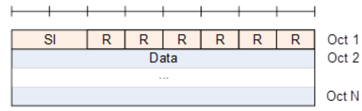


NR Layer 2 Operation
Radio Link Control

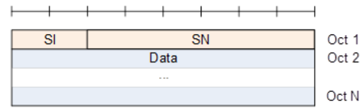
RLC Data PDU for UM:

3 different PDU formats: full SDU, first segment, and middle/last segment

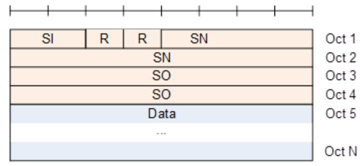
SI	• segmentation info
SN	• sequence number exists only for segments
SO	• segment offset exists only for non-first segment
R	• reserved. Shall be set to 0



UMD PDU containing a complete RLC SDU(no SN)



UMD PDU segment (6 bits SN, no SO)



UMD PDU segment (12 bits SN, with SO)

UMD PDU consists of a Data field and an UMD PDU header.

3 different PDU formats: full SDU, first segment, and middle/last segment.

- UMD PDU header only contains the SI and R fields, when the UMD PDU contains a complete RLC SDU.
- An UMD PDU header contains the SN field only when the corresponding RLC SDU is segmented.
- Segment offset, SO exist only for non-first segment: An UMD PDU carrying the first segment of an RLC SDU does not carry the SO field in its header. The length of the SO field is 16 bits.

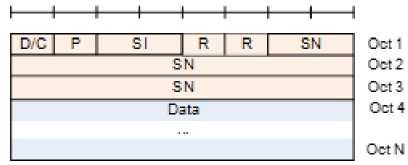
Note that an UM RLC entity is configured by RRC to use either a 6-bit SN or a 12-bit SN.

NR Layer 2 Operation
Radio Link Control

RLC Data PDU for AM:

If the RLC PDU can be composed from exactly one RLC SDU, the transmitting RLC entity is creating the RLC PDUs using following structure:

D/C = 1	• indicates that this RLC PDU is RLC Data PDU
P	• is a Polling bit
SI field	• is set to 00 which means that the whole RLC SDU is included in the Data and its location is started from 4th octet
R	• are padding bits set to 0 and ignored by receiving RLC entity
SN	• is the Sequence Number of RLC PDU



RLC PDU with SN size 18bits

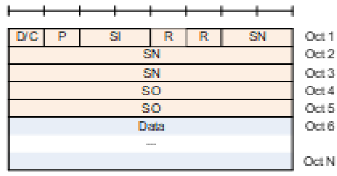
- Sequence Number (SN): It indicates the sequence number of the corresponding RLC SDU. For RLC AM, the sequence number is incremented by one for every RLC SDU. For RLC UM, the sequence number is incremented by one for every segmented RLC SDU.
- Segmentation Info (SI) : The SI field indicates whether an RLC PDU contains a complete RLC SDU or the first, middle, last segment of an RLC SDU:
  - 00: Data field contains all bytes of an RLC SDU
  - 01: Data field contains the first segment of an RLC SDU
  - 10: Data field contains the last segment of an RLC SDU
  - 11: Data field contains neither the first nor last segment of an RLC SDU.

NR Layer 2 Operation
Radio Link Control

RLC Data PDU for AM:

If the size of the RLC SDU is bigger than allowed RLC PDU as indicated by TBS from the MAC layer, then such RLC SDU must be divided into segments and the transmitting RLC entity is creating the RLC Data PDUs using following structure:

D/C	• is set to 1 what indicates that this is RLC PDU for Data
P	• is a Polling bit
SI field	• is set to 01, 11, 10 depending on which segment of the original RLC SDU is inserted into RLC PDU; it also means that in 4th and 5th octet SO fields are expected and the Data field begins in 6th octet
R	• are padding bits set to 0 and ignored by receiving side
SN	• is the Sequence Number of RLC PDU
SO	• is a Segment Offset indicates the position of the RLC SDU segment in bytes within the original RLC SDU (not the first segment)



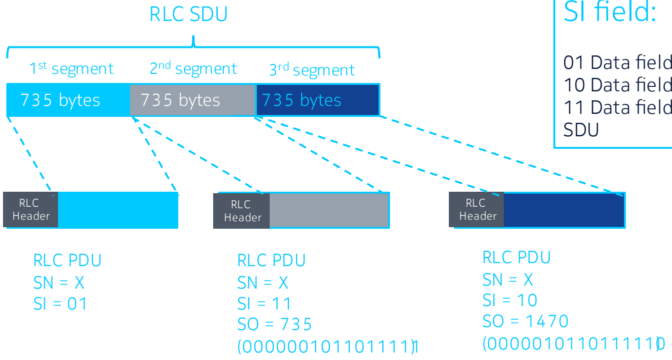
RLC PDU segment with SN size 18bits

Segment Offset (SO): It indicates the position of the RLC SDU segment in bytes within the original RLC SDU. Specifically, the SO field indicates the position within the original RLC SDU to which the first byte of the RLC SDU segment in the Data field corresponds. An AMD PDU header contains the SO field only when the Data field consists of an RLC SDU segment which is not the first segment, in which case a 16 bit SO is present.

NR Layer 2 Operation
Radio Link Control

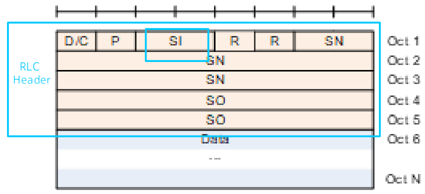
RLC Data PDU segment for AM:

The SI field indicates whether an RLC PDU contains a complete RLC SDU or the first, middle, last segment of an RLC SDU:



SI field:

01 Data field contains the first segment of an RLC SDU
10 Data field contains the last segment of an RLC SDU
11 Data field contains neither the first nor last segment of an RLC SDU



All RLC PDUs have the same SN, while SI and SO indicate the position of the segment within the RLC SDU

Segmentation only occurs in RLC when needed (e.g. for the last RLC SDU included into MAC PDU).

In consequence, the content of RLC PDU can be:

1 complete SDU; or

1 segment of SDU.

For RLC AM, SN is assigned to each PDU for ARQ purposes.

NR Layer 2 Operation
Radio Link Control

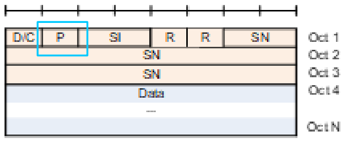
Polling:

An AM RLC entity can poll its peer AM RLC entity in order to trigger STATUS reporting at the peer AM RLC entity

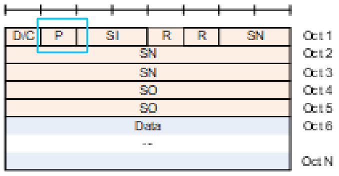
RLC PDUs ACK/NACK are not provided for each received RLC PDU separately; rather group of ACKs/NACKs for multiple RLC PDUs are provided periodically by message STATUS PDU which is of type RLC Control PDU

RLC transmitting side is requesting the receiving side to provide STATUS PDU, by Polling Bit included in RLC data PDU

- P = 0 there is no need to provide STATUS PDU
- P = 1 indicates the request for providing STATUS PDU



RLC PDU with SN size 18bits



RLC PDU segment with SN size 18bits

In AM mode, transmitting RLC entity has to get feedback from the RLC receiver about transmitted RLC PDUs.

The P field indicates whether or not the transmitting side of an AM RLC entity requests a STATUS report from its peer AM RLC entity.

NR Layer 2 Operation
Radio Link Control

RLC Control PDU

The RLC Control PDU which carries STATUS PDU message starts with the header of the length 4 bits:

- D/C bit = 0 indicates that the RLC PDU is RLC Control PDU
- CPT = 000 indicates that this is STATUS PDU message

The STATUS PDU payload consists of one ACK_SN and one E1, zero or more sets of a NACK_SN, an E1, E2, E3 and possibly a pair of a SOstart and a SOend or a NACK range field for each NACK_SN

D/C | CPT | ACK_SN	Oct 1
ACK_SN	Oct 2
ACK_SN | E1 | R	Oct 3
NACK_SN	Oct 4
NACK_SN	Oct 5
NACK_SN | E1 | E2 | E3 | R | R | R	Oct 6
NACK_SN	Oct 7
NACK_SN	Oct 8
NACK_SN | E1 | E2 | E3 | R | R | R	Oct 9
SOstart	Oct 10
SOstart	Oct 11
SOend	Oct 12
SOend	Oct 13
NACK range	Oct 14
NACK_SN	Oct 15
NACK_SN	Oct 16
NACK_SN | E1 | E2 | E3 | R | R | R	Oct 17
...	Oct 18

RLC Control PDU SN size 18bits

The CPT field indicates the type of the RLC control PDU:

- 000: STATUS PDU
- 001: Reserved (PDUs with this coding will be discarded by the receiving entity for this release of the protocol).

ACK_SN indicates that STATUS REPORT provides feedback about RLC PDUs identified by RLC Sequence Number up to value set by ACK_SN – 1.

When the transmitting side of an AM RLC entity receives a STATUS PDU, it interprets that all RLC SDUs up to but not including the RLC SDU with SN = ACK_SN have been received by its peer AM RLC entity, excluding:

- Those RLC SDUs indicated in the STATUS PDU with NACK_SN,
- portions of RLC SDUs indicated in the STATUS PDU with NACK_SN, SOstart and SOend,
- RLC SDUs indicated in the STATUS PDU with NACK_SN and NACK range,
- and portions of RLC SDUs indicated in the STATUS PDU with NACK_SN, NACK range, SOstart and SOend.

0: A set of NACK_SN, E1, E2 and E3 does not follow (indicates no more missing RLC PDU)

1: A set of NACK_SN, E1, E2 and E3 follows. (indicates that next three octets carry the information about another missing RLC PDU and so on).

Extension bit 2 (E2): The E2 field indicates whether or not a set of SOstart and SOend follows

Extension bit 3 (E3) field: The E3 field indicates whether or not information about a continuous sequence of RLC SDUs that have not been received follows.

SO-start (SOstart) field and SO-end (SOend) field:

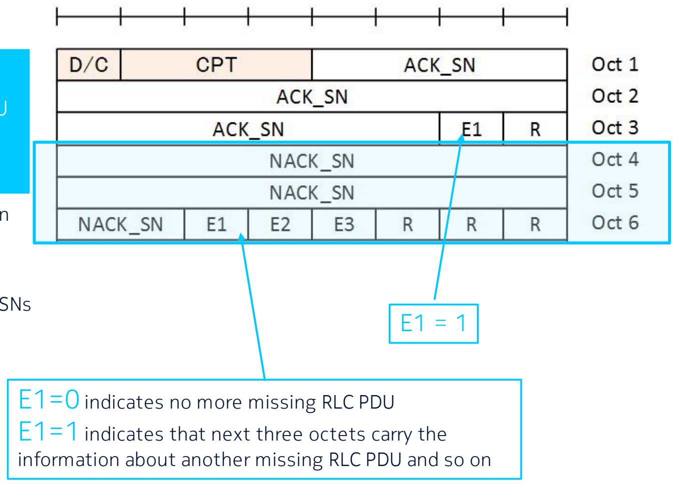
The SOstart field (together with the SOend field) indicates the portion of the RLC SDU with SN = NACK_SN (the NACK_SN for which the SOstart is related to) that has been detected as lost at the receiving side of the AM RLC entity.

NACK range field: This NACK range field is the number of consecutively lost RLC SDUs starting from and including NACK_SN.

Example:

All RLC PDUs acknowledged except one RLC PDU missing:

- E1 = 1 indicating that STATUS PDU covers information about missing RLC PDU identified by RLC Sequence Number reflected in the message as NACK_SN
- If multiple RLC PDUs are missing with separable RLC SNs then three octets covering NACK_SN, E1, E2,E3,R are repeated
- For the last missing RLC PDU the E1 0



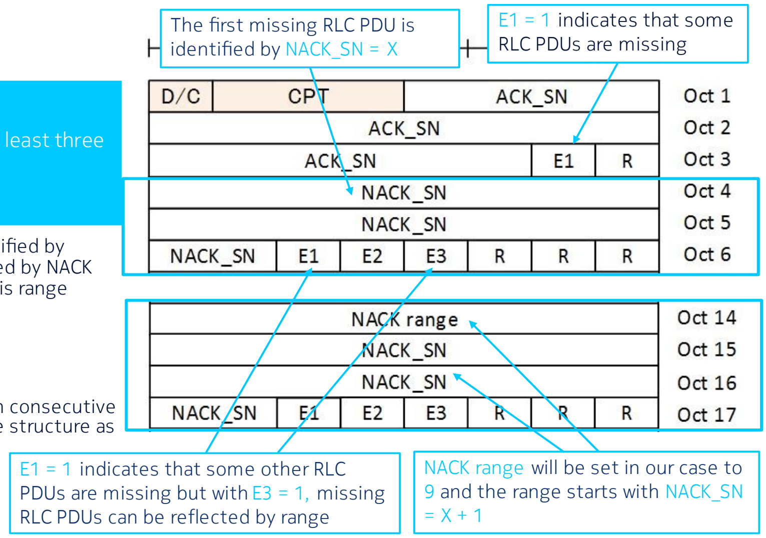
NR Layer 2 Operation

Radio Link Control

Example:

All RLC PDUs acknowledged except at least three RLC PDUs missing:

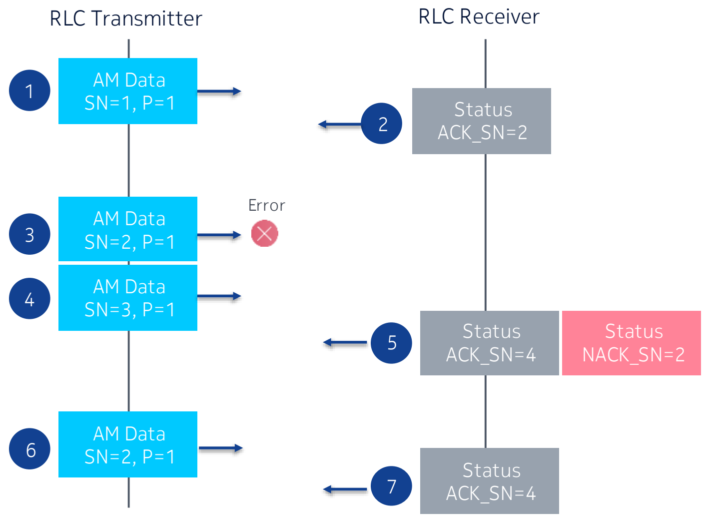
- If two or more missing RLC PDUs are identified by consecutive RLC SNs, they can be collected by NACK range and starting missing RLC PDU for this range identified by NACK_SN
- For this purposes E3=1 bit is used
- For instance, for 10 missing RLC PDUs with consecutive SNs and starting SN = X we can expect the structure as on the figure



NR Layer 2 Operation
Radio Link Control

ARQ Procedure :

- ARQ – Automatic Repeat Request :
  - Provides error correction functionality based on retransmissions of the same packet following NACK and ACK indications
  - In NR ARQ is executed on RLC layer and is slower than HARQ



An AM RLC entity sends STATUS PDUs to its peer AM RLC entity in order to provide positive and/or negative acknowledgements of RLC SDUs (or portions of them).

The Automatic Repeat Request (ARQ) within the RLC sublayer has the following characteristics:

- ARQ retransmits RLC SDUs or RLC SDU segments based on RLC status reports;
- Polling for RLC status report is used when needed by RLC;
- RLC receiver can also trigger RLC status report after detecting a missing RLC SDU or RLC SDU segment.

Remember, the ARQ is used at RLC is different from the Hybrid ARQ used at Physical layer (or Layer 1).

The HARQ functionality ensures delivery between peer entities at Physical Layer. In NR, HARQ provides fast retransmissions on Physical layer and is controlled by MAC. Whereas ARQ is executed on RLC layer and is slower than HARQ.

NR Layer 2 Operation
Quiz 2

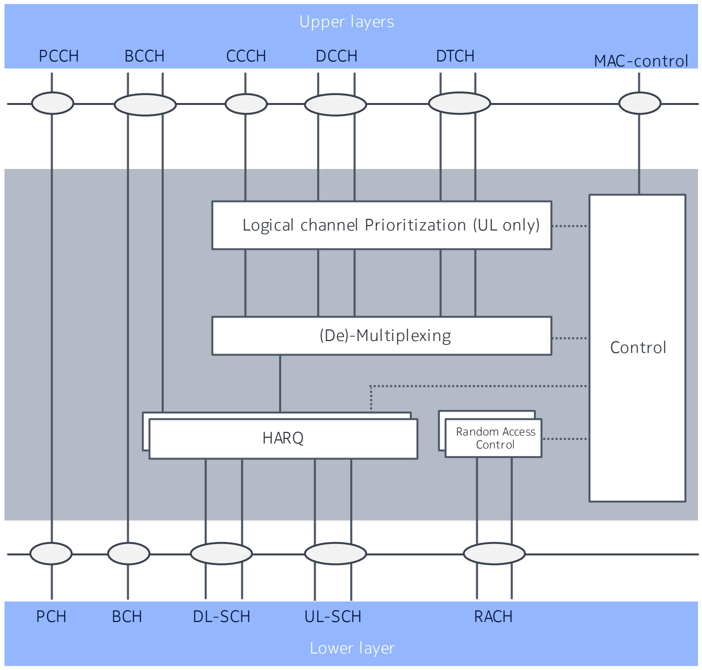
1. Select which are the logical channels that can be used by a Transparent Mode (TM) RLC entity?
   a. BCCH, DL/UL CCCH, and PCCH
   b. DL/UL DTCH
   c. DL/UL DCCH or DL/UL DTCH
2. Which are the logical channels that can be used by a Acknowledged Mode (AM) RLC entity?
   a. BCCH, DL/UL CCCH, and PCCH
   b. DL/UL DTCH
   c. DL/UL DCCH or DL/UL DTCH
3. Mark the correct option for the logical channels that can be used by an Unacknowledged Mode (UM) RLC entity?
   a. BCCH, DL/UL CCCH, and PCCH
   b. DL/UL DTCH
   c. DL/UL DCCH or DL/UL DTCH

MAC

NR Layer 2 Operation
Medium Access Control

MAC main functions

- Mapping between logical channels and transport channels
- Multiplexing/Demultiplexing of MAC SDUs from one or different logical channels onto transport blocks (TB)
- Error correction through HARQ
- Scheduling



The main services and functions of the MAC sublayer (Specified in 38.321) are illustrated here.

The MAC sublayer supports the following functions:

- mapping between logical channels and transport channels;
- multiplexing of MAC SDUs from one or different logical channels onto transport blocks (TB) to be delivered to the physical layer on transport channels;
- demultiplexing of MAC SDUs to one or different logical channels from transport blocks (TB) delivered from the physical layer on transport channels;
- scheduling information reporting;
- error correction through HARQ;
- logical channel prioritization

Services provided to upper layers/

The MAC sublayer provides the following services to upper layers:

- data transfer;
- radio resource allocation.

Services expected from physical layer

The MAC sublayer expects the following services from the physical layer:

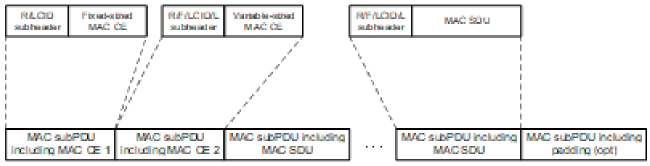
- data transfer services;
- signaling of HARQ feedback;
- signaling of Scheduling Request;
- measurements (e.g., Channel Quality Indication (CQI)).

In 5G NR, MAC supports multiple numerologies and Multiple MAC SDUs from the same logical channel without concatenation in RLC. A single MAC entity can support multiple numerologies, transmission timings and cells. Mapping restrictions in logical channel prioritization control which numerology(ies), cell(s), and transmission timing(s) a logical channel can use.

NR Layer 2 Operation
Medium Access Control

MAC PDU structure

- MAC PDU consists of MAC sub -PDUs:
  - SDUs (RLC PDUs).
  - MAC control elements.
- MAC sub -header structure:
  - MAC sub-header interlaced with corresponding
    MAC SDU or MAC CE to allow pipeline processing in the transmitter and receiver efficiently
  - Combination of MAC sub-header and MAC SDU/CE is called "MAC subPDU"
  - MAC CE multiplexing
    DL: multiplexed in front of the PDU to allow UE to process the control as soon as possible
    UL: multiplexed in the end of the PDU to allow UE to process the control if possible



Example of a DL MAC PDU

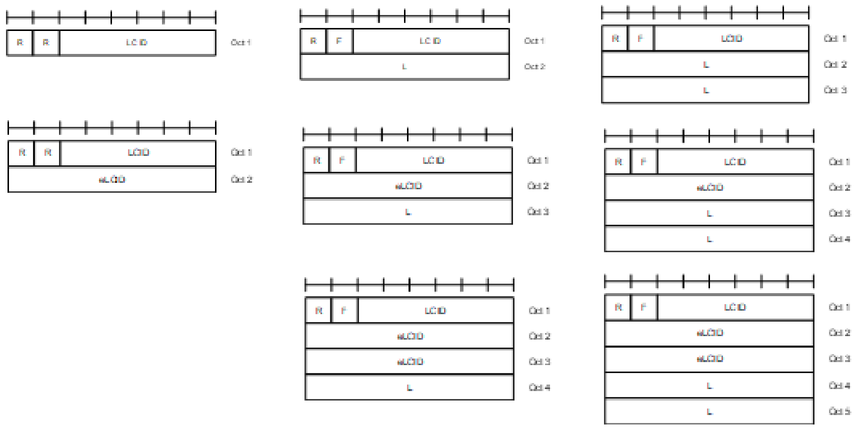
MAC PDU structure (UL/DL-SCH) is motivated by processing efficiency

Existence of a subsequent SDU/CE is not explicitly indicated as in LTE with E bit.

NR Layer 2 Operation
Medium Access Control

MAC subheader for DL-SCH and UL-SCH

R	• Reserved bit, set to 0
F	• format field. Value 0 indicates 8 bits L field. Value 1 indicates 16 bits L field.
L	• length (in bytes) of MAC SDU or variablesized MAC CE.
LCID	• Logical Channel ID. Indicates either logical channel instance or MAC CE type.
eLCID	• extended Logical Channel ID. Indicates either logical channel instance or MAC CE type.



MAC subheader without L field | MAC subheader 8 bits L field | MAC subheader 16 bits L field

MAC PDU structure (UL/DL-SCH) is motivated by processing efficiency

Existence of a subsequent SDU/CE is not explicitly indicated as in LTE with E bit.

NR Layer 2 Operation
Medium Access Control

MAC PDU example:

43 05 78 ... [1400 bytes] ... 03 c8 ... [200 bytes] ... 3f .. [rest of PD

Offset	Hex	Bin							
0	43	0	1	0	0	0	0	1	1
1	05	0	0	0	0	0	1	0	1
2	78	0	1	1	1	0	0	0	0
3-1402	...	-	-	-	-	-	-	-	-
1403	03	0	0	0	0	0	0	1	1
1404	c8	1	1	0	0	1	0	0	0
1405-1604	...	-	-	-	-	-	-	-	-
1605	3f	0	0	1	1	1	1	1	1
1606-END	...	-	-	-	-	-	-	-	-

16 bits length

LCID: 00 $0011_B = 3_D$ → DRB data

SDU length: 0000 0101 0111 $0000_B = 1400_D$

MAC SDU

8 bits length

LCID: 00 $0011_B = 3_D$ → DRB data

SDU length: 1100 $1000_B = 200_D$

MAC SDU

LCID: 11 $1111_B = 63_D$ → padding

Padding

NR Layer 2 Operation
Medium Access Control

Index	LCID
0	CCCH
1-32	Identity of the logical channel of DCCH,DTCH and multicast MTCH
33	Extended logical channel ID field (two-octet eLCID field)
34	Extended logical channel ID field (one-octet eLCID field)
35-46	Reserved
47	Recommended bit rate
48	SP ZP CSI-RS Resource Set Activation/Deactivation
49	PUCCH spatial relation Activation/Deactivation
50	SP SRS Activation/Deactivation
51	SP CSI reporting on PUCCH Activation/Deactivation
52	TCI State Indication for UE-specific PDCCH

Index	LCID
53	TCI States Activation/Deactivation for UE specific PDSCH
54	Aperiodic CSI Trigger State Subselection
55	SP CSI-RS/CSI-IM Resource Set Activation/Deactivation
56	Duplication Activation/Deactivation
57	SCell Activation/Deactivation (4 octet)
58	SCell Activation/Deactivation (1 octet)
59	Long DRX Command
60	DRX Command
61	Timing Advance Command
62	UE Contention Resolution Identity
63	Padding

LCIDs for DL -SCH

MAC Control Element:

- The Buffer Status reporting (BSR) is sent by the UE to provide the serving gNB with information about UL data volume in the MAC entity
- C-RNTI Sent by UE to identify the sending UE and traffic flow
- DRX Command Sent by gNB to trigger discontinuous reception in the UE
- UE Contention Resolution ID Sent by gNB to resolve UE contention on the PRACH
- Timing Advance (TA) Sent by gNB to adjust UE timing
- Power Headroom Report Sent by UE to indicate the difference (headroom) between its current power output and its maximum power output
- Activation /Deactivation Sent to UE to indicate which Scells have been activated.

To learn more about CE, refer to TS38.321 “NR; Medium Access Control (MAC) protocol specification”.

Ref: 3GPP 38.321 –V17.1.0

Index	LCID values
0	CCCH
1–32	Identity of the logical channel of DCCH and DTCH
33	Extended logical channel ID field (two-octet eLCID field)
34	Extended logical channel ID field (one-octet eLCID field)
35	CCCH of size 48 bits for a RedCap UE
36	CCCH of size 64 bits for a RedCap UE
37-42	Reserved
43	Truncated Enhanced BFR
44	Timing Advance Report
45	Truncated Sidelink BSR
46	Sidelink BSR
47	Reserved

Index	LCID values
48	LBT failure (four octets)
49	LBT failure (one octet)
50	BFR
51	Truncated BFR
52	CCCH of size 48 bits, except for a RedCap UE
53	Recommended bit rate query
54	Multiple Entry PHR
55	Configured Grant Confirmation
56	Multiple Entry PHR
57	Single Entry PHR
58	C-RNTI
59	Short Truncated BSR
60	Long Truncated BSR
61	Short BSR
62	Long BSR
63	Padding

LCIDs for UL -SCH

BFR	Beam Failure Recovery
BSR	Buffer Status Report
PHR	Power Headroom Report

MAC Control Element:

- The Buffer Status reporting (BSR) is sent by the UE to provide the serving gNB with information about UL data volume in the MAC entity
- C-RNTI Sent by UE to identify the sending UE and traffic flow
- DRX Command Sent by gNB to trigger discontinuous reception in the UE
- UE Contention Resolution ID Sent by gNB to resolve UE contention on the PRACH
- Timing Advance (TA) Sent by gNB to adjust UE timing
- Power Headroom Report Sent by UE to indicate the difference (headroom) between its current power output and its maximum power output
- Activation /Deactivation Sent to UE to indicate which Scells have been activated.

To learn more about CE, refer to TS38.321 “NR; Medium Access Control (MAC) protocol specification”.

Ref: 3GPP 38.321 –V17.1.0

NR Layer 2 Operation
Medium Access Control

Random Access

The main purpose of RACH procedure is to:

- Obtain the resources for Msg3
- Assign a unique identifier to communicate with the UE over the air interface (C-RNTI)
- Initial L1 synchronization (Timing and power)

Random access procedure is needed in the following cases:

- Initial access
- Loss of UL synchronization
- Handover
- Request for Other System Information

Random Access types in NR

Contention based	Non-contention base
• UEs randomly select preamble • More than 1 UE may select same preamble (collision)	• gNB dedicates preamble to UE • No collision possible • Used during handovers

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Initial Access means a sequence of process between UE and gNB for UE to achieve Uplink Synchronization and obtain the resource for RRC Connection Request message.

Initial channel access is typically accomplished via the “random-access procedure” (assuming no dedicated/scheduled resources are allocated).

The random-access procedure can be contention based (e.g., at initial connection from idle mode) or non-contention based (e.g., during Handover to a new cell). Random access resources and parameters are configured by the network and signaled to the UE (via broadcast or dedicated signaling).

Contention based random access procedure encompasses the transmission of a random-access preamble by the UE (subject to possible contention with other UEs), followed by a random-access response (RAR) in DL (including allocating specific radio resources for the uplink transmission). Afterwards, the UE transmits the initial UL message (e.g., RRC connection Request) using the allocated resources, and wait for a contention resolution message in DL (to confirming access to that UE). The UE could perform multiple attempts until it is successful in accessing the channel or until a timer (supervising the procedure) elapses.

Non-contention based random access procedure foresees the assignment of a dedicated random-access resource/preamble to a UE (e.g. part of an HO command). This avoids the contention resolution phase, i.e. only the random-access preamble and random-access response messages are needed to get channel access.

From a L1 perspective, a random-access preamble is transmitted (UL) in a PRACH, random access response (DL) in a PDSCH, UL transmission in a PUSCH, and contention resolution message (DL) in a PDSCH.

The random-access procedure is triggered by a number of events, for instance:

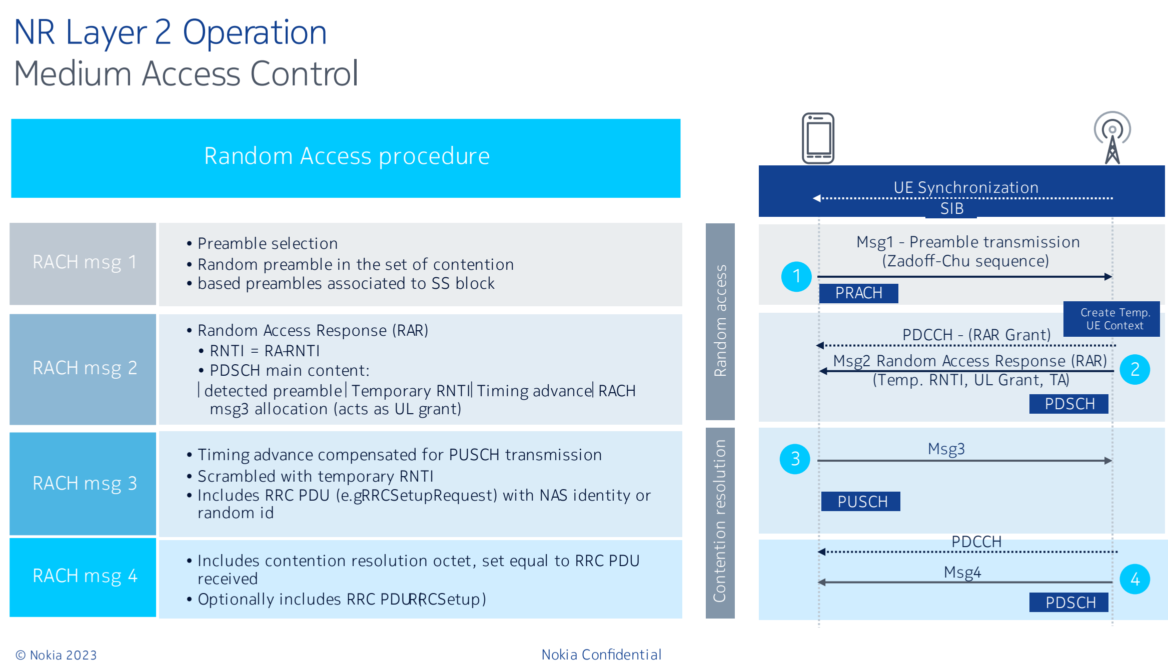
- Initial access from RRC_IDLE;
- RRC Connection Re-establishment procedure;
- Handover;

DL or UL data arrival during RRC_CONNECTED when UL synchronization status is "non-synchronized";

- Transition from RRC_INACTIVE;
- Request for Other SI
- Beam failure recovery.

Furthermore, the random-access procedure takes two distinct forms: contention-based and contention-free as shown on here. Normal DL/UL transmission can take place after the random-access procedure.

For initial access in a cell configured with SUL, the UE selects the SUL carrier if and only if the measured quality of the DL is lower than a broadcast threshold. Once started, all uplink transmissions of the random-access procedure remain on the selected carrier.



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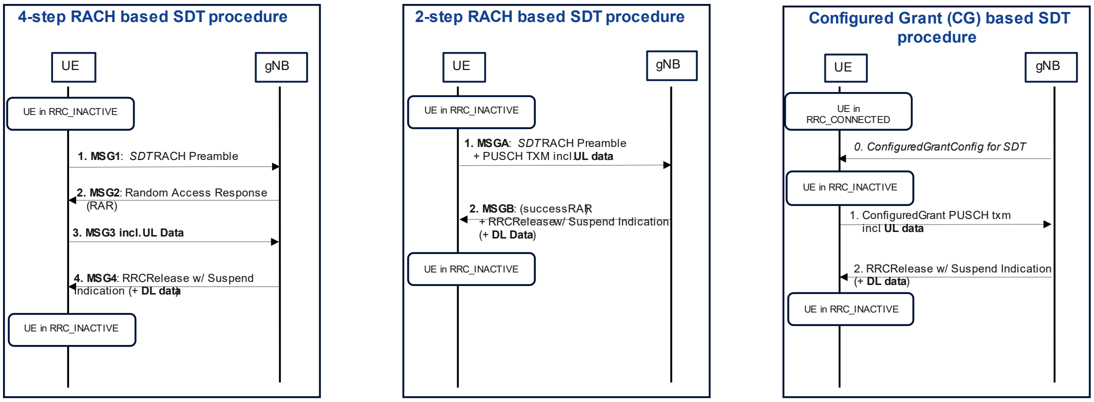
From a L1 perspective, a random-access preamble is transmitted (UL) in a PRACH, random access response (DL) in a PDSCH, UL transmission in a PUSCH, and contention resolution message (DL) in a PDSCH.

NR Layer 2 Operation
Medium Access Control

Small Data Transmission (SDT) is a procedure allowing data and/or signalling transmission while remaining in RRC_INACTIVE state (i.e. without transitioning to RRC_CONNECTED state).



Until Rel-16, an RRC_INACTIVE UE has to resume the connection for performing any data transfer. Thus, small and infrequent data transfers from RRC_INACTIVE state entail that a connection resume and a subsequent connection suspend to RRC_INACTIVE state may occur for each and every data transmission. This results in unnecessary UE power consumption and signalling overhead as well as increased packet latency.

Rel-15 RRC_INACTIVE and Rel-17 small data transmission (SDT) have a large potential in UE power efficiency, latency & signalling overhead reduction.

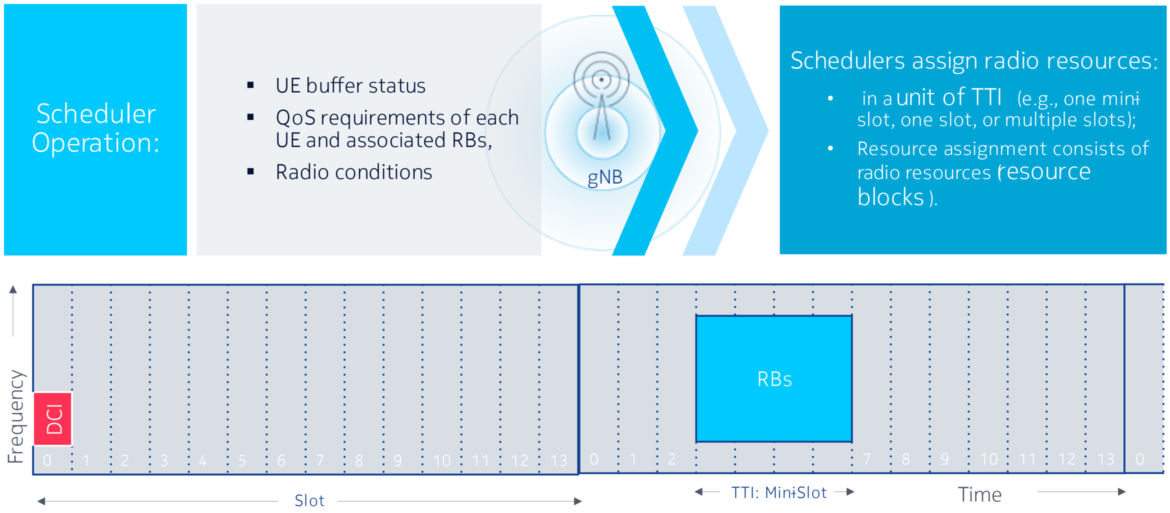
SDT procedure is initiated with either a transmission over RACH (configured via system information) or over Type 1 CG resources (configured via dedicated signalling in *RRCRelease*).

For RACH, the network can configure 2-step and/or 4-step RA resources for SDT.

SDT procedure over CG resources can only be initiated with valid UL timing alignment.

NR Layer 2 Operation

Medium Access Control



In 5G NR physical control and shared channels can be separately and dynamically scheduled for both uplink and downlink. A scheduling unit for downlink shared channel may span from 2-14 symbols and for uplink shared channel from 1-14 symbols. Furthermore, sub-carrier spacing for different physical channels may be dynamically changed by switching bandwidth-parts (BWP).

Scheduling in NR is typically based on the instantaneous radio-link quality as seen by the different users (based on CQI reports from the User Equipments (downlink) or measurements of sounding signals from the terminals (uplink)), and the traffic demand and quality-of-service requirements of individual users and in the cell as a whole. Based on this the base station may apply for example a proportional fair scheduling algorithm. The QoS assessment is supported by means of receiving QoS information from the “higher layers”.

For the downlink and the uplink, intercell-interference coordination can be realized by the scheduler that is transparent to the physical layer.

Before describing the basic NR Scheduler operation, it is worth noting that although 3GPP have standardized many scheduler related details, scheduler algorithms are left completely open for implementation. How to e.g. implement multi-service QoS-aware MAC algorithms is a vendor differentiation factor.

NR scheduler assigns resources between UEs, taking into account the UE buffer status and the QoS requirements of each UE and associated radio bearers (RBs). Scheduler may assign resources taking into account the radio conditions at the UE identified through measurements made at the gNB and/or reported by the UE.

Scheduler assigns radio resources in a unit of TTI (e.g. one mini-slot, one slot, or multiple slots); Resource assignment consists of radio resources (resource blocks). Data transmissions can be scheduled on a slot basis, as well as on a partial slot basis, where the partial slot transmissions that occur several times within one slot. The supported partial slot allocations and scheduling intervals are 2, 4 and 7 symbols for DL and 1-14 symbols for UL for normal cyclic prefix, and 2, 4 and 6 symbols for DL and 1-12 symbols for UL for extended cyclic prefix.

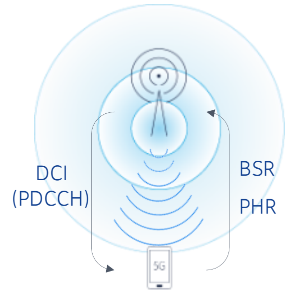
The DCI means « Downlink Control Information ». It is described in 38.212. It is transported from gNB to UE, in downlink direction, over the PDCCH physical channel. In general, the gNB « decides » almost everything about UL and DL traffic transmissions, and the UE has to « obey » to the gNB commands.

The two main purposes of DCI are :

- To trigger uplink traffic to some UEs
- To indicate to some UEs that downlink traffic will happen.

NR Layer 2 Operation
Medium Access Control

Signaling of Scheduler Decisions:	• UEs identify the resources by receiving a scheduling (resource assignment) channel. • In the downlink, the gNB can dynamically allocate resources to UEs via the C-RNTI on PDCCH(s). • In the uplink, the gNB can dynamically allocate resources to UEs via the C-RNTI on PDCCH(s).
Measurements to Support Scheduler Operation:	• Uplink buffer status (BSR) reports are used to provide support for QoS-aware packet scheduling. • Power headroom (PHR) reports are used to provide support for power aware packet scheduling.



UEs identify the allocated resources by receiving a scheduling (resource assignment) channel. In the downlink, the gNB can dynamically allocate resources to UEs via the C-RNTI on PDCCH(s). In the uplink, the gNB can dynamically allocate resources to UEs via the C-RNTI on PDCCH(s).

When CA is configured, the same C-RNTI applies to all serving cells.

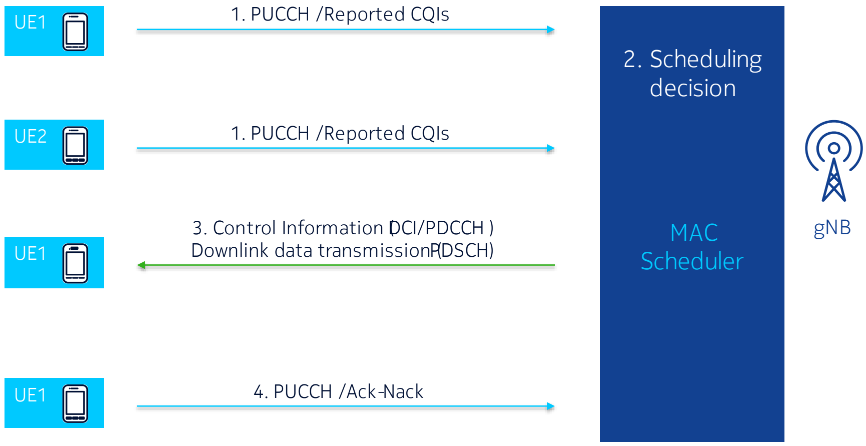
Some Measurements are used to support Scheduler Operation:

Uplink buffer status reports (measuring the data that is buffered in the logical channel queues in the UE) are used to provide support for QoS-aware packet scheduling. Uplink buffer status reports are transmitted using MAC signaling.

Power headroom reports (measuring the difference between the nominal UE maximum transmit power and the estimated power for uplink transmission) are used to provide support for power aware packet scheduling. In NR, three types of reporting are supported: one for PUSCH transmission, one for PUSCH and PUCCH transmission and a third one for SRS transmission. Power headroom reports are transmitted using MAC signaling.

NR Layer 2 Operation
Medium Access Control

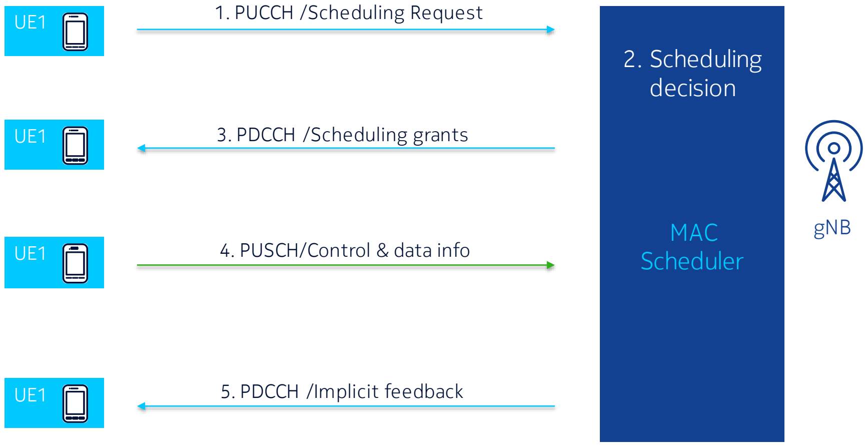
DL data transmission



Downlink assignments received on the PDCCH both indicate that there is a transmission on a DL-SCH for a particular MAC entity and provide the relevant HARQ information.

NR Layer 2 Operation
Medium Access Control

UL data transmission



The Scheduling Request (SR) is used for requesting UL-SCH resources for new transmission.

The MAC entity may be configured with zero, one, or more SR configurations. An SR configuration consists of a set of PUCCH resources for SR across different BWPs and cells. For a logical channel, at most one PUCCH resource for SR is configured per BWP.

Uplink grant is either received dynamically on the PDCCH, in a Random Access Response, or configured semi-persistently by RRC. The MAC entity shall have an uplink grant to transmit on the UL-SCH. To perform the requested transmissions, the MAC layer receives HARQ information from lower layers.

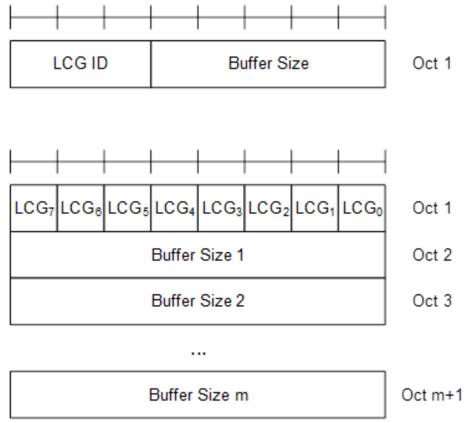
NR Layer 2 Operation
Medium Access Control

BSR (Buffer Status Report)

- BSR signaled how much user data is buffered in groups of logical channels, the LCGs
- 8 LCGs can be configured and reported at most (was 4 in LTE)
- BSR Formats are similar to LTE: short + long BSR + Truncated

LCG ID	• logical channel group id for which buffer status is being reported.
Buffer Size	• index indicating how many bytes are waiting for transmission at the moment of BSR creation.

Index	BS value	Index	BS value	Index	BS value	Index	BS value
0	0	8	≤ 102	16	≤ 1446	24	≤ 20516
1	≤ 10	9	≤ 142	17	≤ 2014	25	≤ 28581
2	≤ 14	10	≤ 198	18	≤ 2806	26	≤ 39818
3	≤ 20	11	≤ 276	19	≤ 3909	27	≤ 55474
4	≤ 28	12	≤ 384	20	≤ 5446	28	≤ 77284
5	≤ 38	13	≤ 535	21	≤ 7587	29	≤ 107669
6	≤ 53	14	≤ 745	22	≤ 10570	30	≤ 150000
7	≤ 74	15	≤ 1038	23	≤ 14726	31	> 150000



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BSR signaled how much user data is buffered in groups of logical channels, the LCGs

8 LCGs can be configured and reported at most (was 4 in LTE)

- Twice more bearers + duplication justified the increase to 8

BSR Formats are like LTE: short + long BSR + Truncated

- Short BSR motivated by low bit rate services, still one byte long but offers only 5 bits for the buffer size (BS)
- Long BSR has 1-byte bitmap + 8 bits BS for LCGs reported

  Bitmap for Long BSR indicates LCG with BS reported (value can be zero as the size determined before LCP)

  Bitmap for Long Truncated indicates LCGs with data (To provide more information to gNB about which LCG has data even if the BS value itself cannot be reported).

- Truncated BSR – as in LTE – signals that more LCGs than being reported have buffered data (for padding BSR).

NR Layer 2 Operation
Medium Access Control

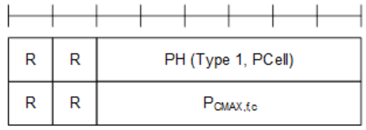
PHR (Power Headroom Report)

- Single and Multiple Entry PHR formats specified, i.e.., no separate formats for dual connectivity
- For Multiple Entry PHR format, 1 octet and 4 octet formats specified similarly to LTE even though NR supports maximum of 16 carriers for a cell group. In case of DC, the 16 carriers limit may be exceeded

Power Headroom (PH)	• This field indicates the power headroom level
$P_{CMAX,f,c}$	• $P_{CMAX,f,c}$: This field indicates the $P_{CMAX,f,c}$

PH	Power Headroom Level
0	POWER_HEADROOM_0
1	POWER_HEADROOM_1
2	POWER_HEADROOM_2
3	POWER_HEADROOM_3
…	…
60	POWER_HEADROOM_60
61	POWER_HEADROOM_61
62	POWER_HEADROOM_62
63	POWER_HEADROOM_63

$P_{CMAX,f,c}$	Nominal UE transmit power level
0	PCMAX_C_00
1	PCMAX_C_01
2	PCMAX_C_02
…	…
61	PCMAX_C_61
62	PCMAX_C_62
63	PCMAX_C_63



Single Entry PHR MAC CE

- PCMAX,c,f) : UE configured maximum output power
- Power Headroom = UE Max Transmission Power- PUSCH Power

Single and Multiple specified, i.e.., no separate formats for dual connectivity

- For Multiple Entry PHR format, 1 octet and 4 octet formats specified similarly to LTE even though NR supports maximum of 16 carriers for a cell group. In case of DC, the 16 carriers limit may be exceeded

In case of EN-DC, NR cells are reported to LTE and vice versa

- In LTE, the 4-octet bitmap is always used for the PHR format given the eNB does not need to comprehend NR configuration and hence does not know which indices of serving cells come with configured UL
- In NR, separate LCIDs are used to indicate either 1 octet or 4 octet bitmap which allows the overhead optimization of not using always the 4-octet format

Type 2 PH is not supported by L1 but is supported by MAC specification

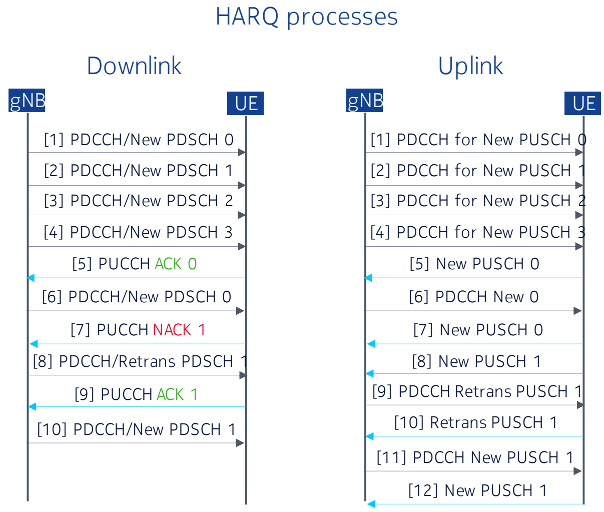
- NW shall ensure by configuration, the UE is not required to report Type 2 PH for NR initial Release 15

- Power Headroom (PH): This field indicates the power headroom level. The length of the field is 6 bits. The reported PH and the corresponding power headroom levels are shown on the slide (the corresponding measured values in dB are specified in TS 38.133);
- PCMAX,f,c: This field indicates the PCMAX,f,c (as specified in TS 38.213) used for calculation of the preceding PH field. The reported PCMAX,f,c and the corresponding nominal UE transmit power levels are shown on the slide (the corresponding measured values in dBm are specified in TS 38.133).

NR Layer 2 Operation
Medium Access Control

HARQ – Automatic Repeat Request :

- Combines ARQ with Forward Error Correction (FEC) functions, re-sent packet does not necessarily have to be exactly the same
- In NR HARQ provides fast retransmissions on PHY layer and is controlled by MAC



HARQ stands for Hybrid Automatic Repeat Request. It is referred to as Hybrid ARQ because it is a combination of high-rate forward error-correcting coding and ARQ error-control.

Hybrid ARQ with soft-combining between transmissions is supported on the MAC layer. Different redundancy versions can be used for different transmissions. The modulation and coding scheme may be changed for retransmissions. In order to minimize delay and feedback, a set of parallel stop-and-wait protocols are used. To correct possible residual errors, the MAC ARQ is complemented by a robust selective-repeat ARQ protocol on the RLC layer.

One HARQ entity in the UE and the gNB

Number of HARQ processes:
- PDSCH: configured by RRC with value from the set {2,4,6,8,10,12,16}
- PUSCH: fixed to 16
- In Rel-17, for both downlink and uplink the support of 32 HARQ processes is defined

Each process handles STOP and WAIT HARQ protocol

Each process is responsible for generating ACK or NACK indicating delivery status of PDSCH/PUSCH

Each process runs in parallel with the others

Anticipating window = 1 i.e. each process is blocked until the ACK/NACK is received

Multiple processes permit to compensate for the round trip time

The HARQ functionality ensures delivery between peer entities at Layer 1. A single HARQ process supports one Transport Block (TB) when the physical layer is not configured for downlink/uplink spatial multiplexing, and when the physical layer is configured for downlink/uplink spatial multiplexing, a single HARQ process supports one or multiple TBs.

[38.214] For downlink, a maximum of 16 HARQ processes per cell is supported by the UE. The number of processes the UE may assume will at most be used for the downlink is configured to the UE for each cell separately by higher layer parameter *nrofHARQ-processesForPDSCH*, and when no configuration is provided the UE may assume a default number of 8 processes.

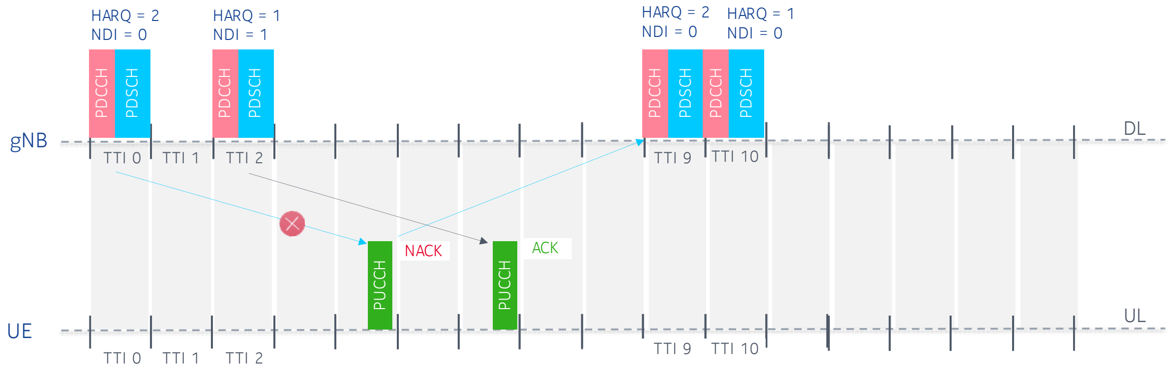
A UE shall upon detection of a PDCCH with a configured DCI format 1_0 or 1_1 decode the corresponding PDSCHs as indicated by that DCI. The UE is not expected to receive another PDSCH for a given HARQ process until after the end of the expected transmission of HARQ-ACK for that HARQ process, where the timing is given by next slide.

For uplink, a maximum of 16 HARQ processes per cell is supported by the UE.

From Release 17, subject to UE capability, a maximum of 32 HARQ processes per cell can be supported.

NR Layer 2 Operation
Medium Access Control

Downlink asynchronous HARQ



HARQ process is signaled in PDCCH

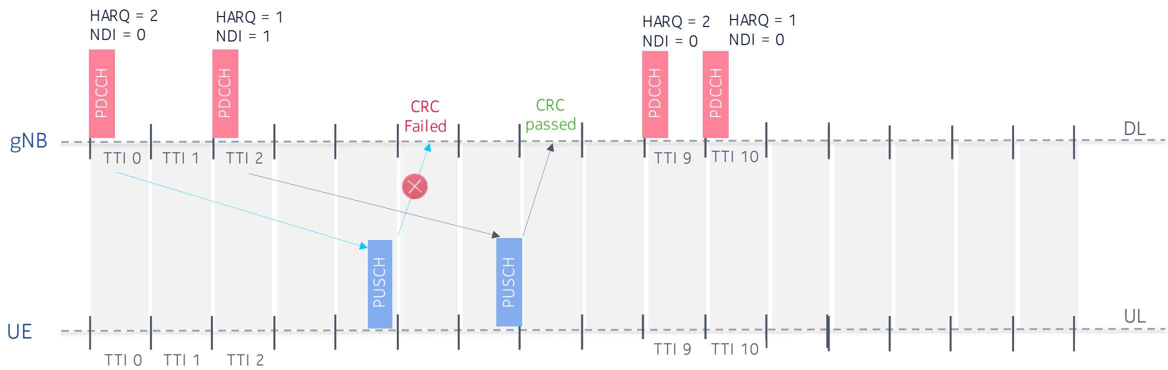
NDI toggled for fresh transmission (per HARQ process)

Asynchronous and adaptive DL HARQ is supported at least for eMBB and URLLC. From UE perspective, HARQ ACK/NACK feedback for multiple DL transmissions in time can be transmitted in one UL data/control region. Timing between DL data reception and corresponding acknowledgement is indicated by a field in the DCI from a set of values and the set of values is configured by higher layer. The timing(s) is (are) defined at least for the case where the timing(s) is (are) unknown to the UE.

New Data Indicator (NDI). If the value is the same as the previously transmitted one, UL retransmission is expected. In turn, toggled value indicates new transmission request.

NR Layer 2 Operation
Medium Access Control

Uplink asynchronous HARQ



HARQ process is signaled in PDCCH

Explicit retransmission (no pHICH HARQ feedback channel)

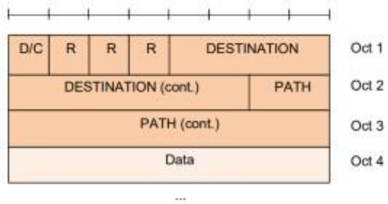
Asynchronous and adaptive UL HARQ is supported

BAP

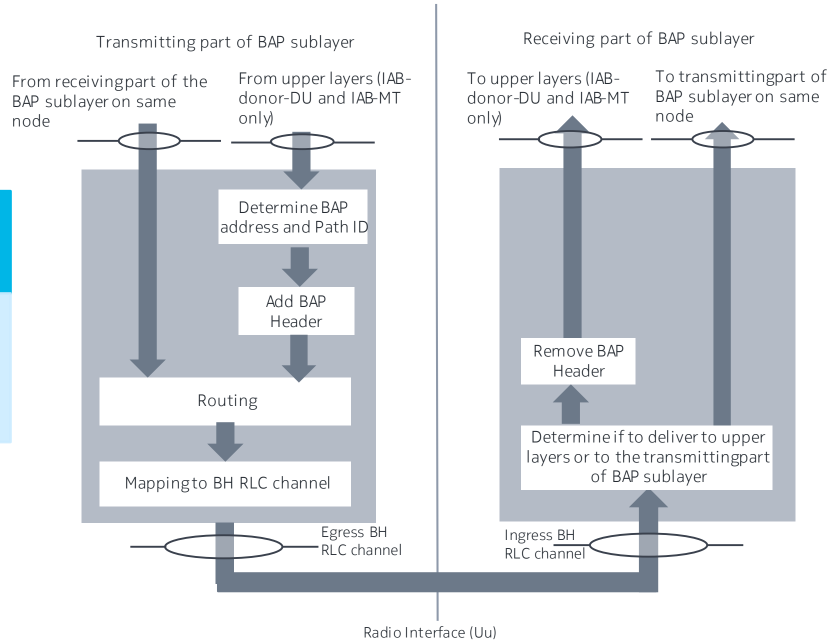
NR Layer 2 Operation
Backhaul Adaptation Protocol (BAP)

MAC main functions

1. Accepts services from RLC layer in both AM and UM modes
2. Determines BAP destination and path for packets from upper layers
3. Routes packets to next hop



Example Data PDU



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The main services and functions of the MAC sublayer (Specified in 38.321) are illustrated here.

The MAC sublayer supports the following functions:

- mapping between logical channels and transport channels;
- multiplexing of MAC SDUs from one or different logical channels onto transport blocks (TB) to be delivered to the physical layer on transport channels;
- demultiplexing of MAC SDUs to one or different logical channels from transport blocks (TB) delivered from the physical layer on transport channels;
- scheduling information reporting;
- error correction through HARQ;
- logical channel prioritization

Services provided to upper layers/

The MAC sublayer provides the following services to upper layers:

- data transfer;
- radio resource allocation.

Services expected from physical layer

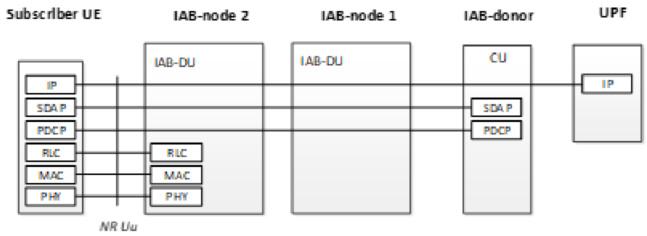
The MAC sublayer expects the following services from the physical layer:

- data transfer services;
- signaling of HARQ feedback;
- signaling of Scheduling Request;
- measurements (e.g., Channel Quality Indication (CQI)).

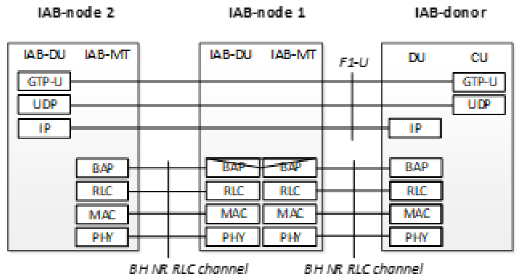
In 5G NR, MAC supports multiple numerologies and Multiple MAC SDUs from the same logical channel without concatenation in RLC. A single MAC entity can support multiple numerologies, transmission timings and cells. Mapping restrictions in logical channel prioritization control which numerology(ies), cell(s), and transmission timing(s) a logical channel can use.

IAB protocol stack - User plane

- IAB is transparent for subscriber Ues
- Inside IAB network, modified protocol stack is used on Uu interface:
  - Backhaul Adaptation Protocol (BAP) is added
  - BAP PDUs are carried by Backhaul (BH) RLC channels
- BAP enables routing over multiple hops
- BH RLC channels are single hop, i.e., hop by hop RLC ARQ
- From RAN network interfaces perspective:
  - Full F1-U stack (GTP-U/UDP/IP) is carried on top of BAP on wireless backhaul
  - F1-U is carried over IP
  - UE bearers are not visible in Donor DU (only IP flows are visible)



User Plane stack – subscriber UE perspective



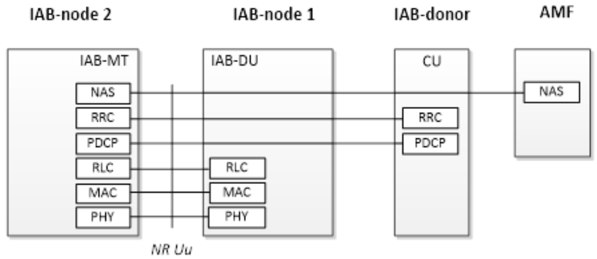
User Plane stack – backhaul network perspective

UE connects normally to DU, F1-U terminated in the IAB-node DU, IP transported on top of adaptation layer

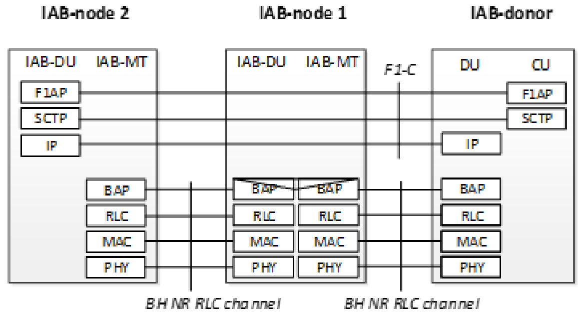
- IAB is transparent for subscriber UEs (same protocol stack is used and no modification to the UE is required to utilize IAB)
- For its own traffic (e.g. OAM), IAB MT connects to the network in the same way as a subscriber UE
- Inside IAB network, modified protocol stack is used on Uu interface:
  - Backhaul Adaptation Protocol (BAP) is added above RLC
  - BAP PDUs are carried by Backhaul (BH) RLC channels (there are no radio bearers associated with BH RLC channels)
  - MAC is modified with an extension of the number of supported Logical Channels
- BAP enables routing over multiple hops
- Multiple BH RLC channels can be configured for each BH link to allow traffic prioritization and QoS enforcement
- BH RLC channels are single hop, i.e., hop by hop RLC ARQ
- From RAN network interfaces perspective:
  - Full F1-U stack (GTP-U/UDP/IP) is carried on top of BAP on wireless backhaul
  - F1-U is carried over IP between IAB-DU and IAB-donor CU and IP layer is terminated at Access IAB node
  - UE bearers are not visible in Donor DU (only IP flows are visible)

IAB protocol stack – Control plane

- IAB is transparent for subscriber UEs and both IAB-MT and subscriber UE maintain normal NAS/RRC connections
- On the wireless backhaul links, UE's and MT's RRC/PDCP is encapsulated into F1AP carried over SCTP/IP
- The IAB-DU's F1AP is carried over SCTP/IP (full F1-C)
- The extended IP-plane allows native F1-C to be used between IAB-node DU and IAB-donor CU-CP
- IAB-donor DU encapsulates F1AP into BAP based on IP header and configuration from Donor CU
- All IAB-nodes hold IP-addresses, which are routable from the IAB-donor CU-CP
- The IP addresses are provided to IAB nodes by the CU-CP via RRC



Control Plane stack – IAB-MT (and subscriber UE) perspective



Control Plane stack – backhaul network perspective

- Similarly as in the case of user plane, IAB is transparent for subscriber UEs and both IAB-MT and subscriber UE maintain normal NAS/RRC connections
- On the wireless backhaul links, UE's and MT's RRC/PDCP is encapsulated into F1AP carried over SCTP/IP
- The IAB-DU's F1AP is carried over SCTP/IP (full F1-C) terminated in the IAB node
- The extended IP-plane allows native F1-C to be used between IAB-node DU and IAB-donor CU-CP
- F1AP is protected via Network Domain Security (NDS), i.e., DTLS or IPsec
- IAB-donor DU encapsulates F1AP into BAP based on IP header and configuration from Donor CU
- All IAB-nodes hold IP-addresses, which are routable from the IAB-donor CU-CP (and the OAM server)
- The IP addresses are provided to IAB nodes by the CU-CP via RRC

BAP Routing

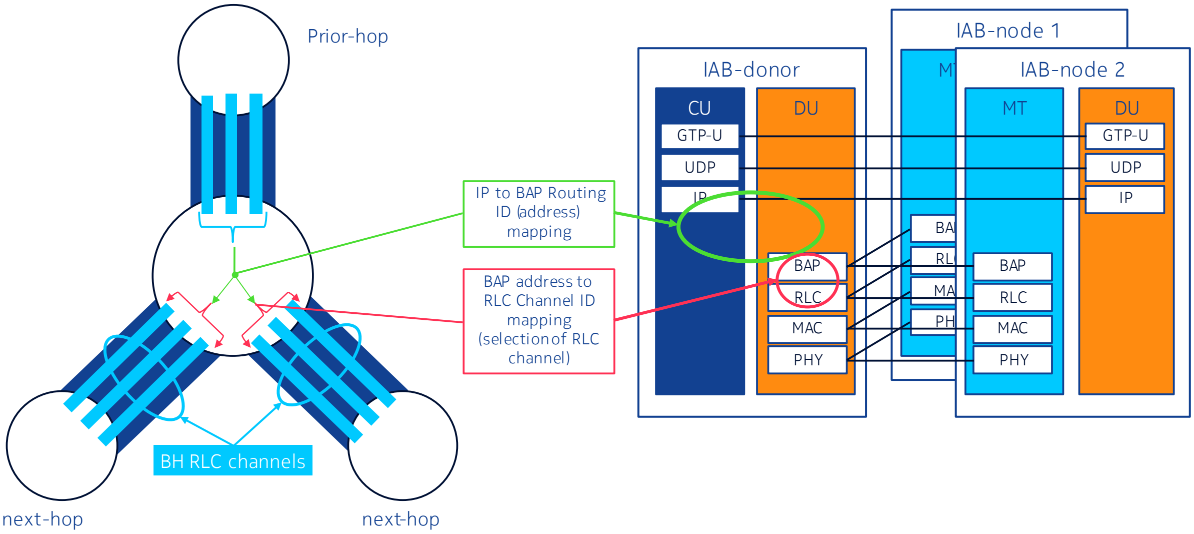
- In downlink, IAB-donor DU maps the IP header (IP address/DSCP/Flow Label) to BAP routing ID
- In uplink, access IAB node maps GTP FTEID or non-UP traffic type to BAP routing ID

BAP Routing ID – 20 bits

DESTINATION – 10 bits PATH – 10 bits

- BAP to RLC channel mapping is performed to send the data to the proper IAB node.

RLC channel mapping



NR Layer 2 Operation

Quiz 3

1. Which of the following are functions supported by the MAC sub layer?
   a. Mapping between logical channels and transport channels
   b. Multiplexing/Demultiplexing of MAC SDUs from one or different logical channels onto transport blocks
   c. Error correction through HARQ
   d. Error correction through ARQ (only for AM data transfer)

Wrap-up
In this module we have covered the following items

- Describe NR Channels
- Explain NR Layer 2 Operation