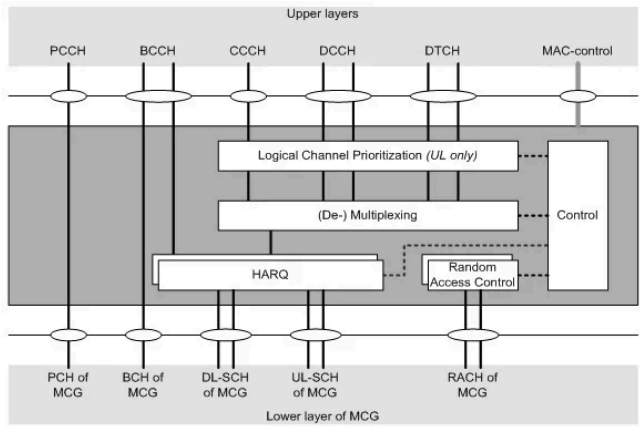
MAC Architecture

Monday, August 5, 2024 11:45 AM



The MAC sublayer of the 5G NR protocol stack interfaces to the RLC sublayer from above and the PHY layer from below.
It maps information between logical and transport channels. Logical channels are about the type of information carried whereas transport channels are about how such information is carried.
The physical layer offers transport channels to the MAC layer to support transport services for data transfer over the radio interface.
MAC layer offers transport channels to the RLC sublayer.
The logical channels exist between MAC and PHY whereas transport channels exist between PHY and the radio layer.
Hence MAC is the interface between logical channels and physical transport channels.

The MAC sublayer provides two main services to upper layers viz. data transfer and radio resource allocation. The other functions of 5G NR MAC are as follows.
• Mapping between logical and transport channels (Both Downlink and Uplink).
• Multiplexing of MAC SDUs onto TBs (Transport Blocks) (In Uplink), SDUs belong to logical channels and transport blocks belong to transport channels.

Demultiplexing of MAC SDUs from TBs (In Downlink)
• Scheduling information reporting (In Uplink)
• Error correction through HARQ (In Downlink and Uplink)
• Logical Channel Prioritisation (In Uplink)

Functions:

MAC function	Downlink	Uplink
Mapping between logical channels and transport channels	X	X
Multiplexing		X
Demultiplexing	X	
Scheduling information reporting		X
Error correction through HARQ	X	X
Logical Channel prioritisation		X

Uplink (UL) MAC Functions:

- Buffer Management:
- Manages the data buffers for Uplink Shared Channel (UL-SCH) transmissions from the UE.

- Multiplexing:
- Multiplexes Logical Channels onto one or more UL-SCH transport channels for transmission.

- PUSCH Transport Channel Processing:
- Handles the processing of the Physical Uplink Shared Channel (PUSCH), including encoding, modulation, and resource

allocation.

- Activation/Deactivation of SCells When the MAC entity is set up with one or more SCells, the network has the capability to enable or disable these configured SCells.

- Initially, upon configuring an SCell, it is in a deactivated state.

- PUCCH Transport Channel Processing:
- Manages the Physical Uplink Control Channel (PUCCH) transport channel for control signalling.

- Harq-ACK Processing:
- Handles the acknowledgment (ACK) or negative acknowledgment (NACK) signaling for uplink HARQ processes.

- Random Access Handling:
- Manages the Random-Access Channel (RACH) for initial access and contention resolution.

- UL Grant Reception:
- Receives UL grant information from the network for resource allocation.

- Scheduling Request Handling:
- Manages scheduling requests from the UE to request UL resources for uplink transmissions.

Downlink (DL) MAC Functions:

- Buffer Management:
- Manages the data buffers for Downlink Shared Channel (DL-SCH) receptions at the UE.

- Power Headroom ReportingThe Power Headroom reporting procedure provides the serving gNB with information about three types of power headroom: Type 1 for UL-SCH transmission on the activated Serving Cell, Type 2 for UL-SCH and PUCCH transmission on the other MAC entity (in EN-DC case), and Type 3 for SRS transmission on the activated Serving Cell

- Logical Channel Demultiplexing:
- De-multiplexes incoming data streams from one or more DL-SCH transport channels onto corresponding logical channels.

- SUL operationThe Supplementary UL (SUL) carrier can be set up to enhance the normal UL (NUL) carrier. If, during an ongoing Random Access procedure, the MAC entity receives a UL grant that indicates a SUL switch, it is required to disregard the UL grant.

- Beam Failure Detection and Recovery procedure:
- RRC configuration can include a beam failure recovery procedure for the MAC entity, which signals the serving gNB about a new SSB or CSI-RS in the event of detected beam failure on the serving SSB(s)/CSI-RS(s). Detection of beam failure is accomplished by tallying instances of beam failure indications received by the MAC entity from the lower layers.

- DL Grant Reception:
- Receives DL grant information from the network for resource allocation.

- DL-SCH Harq Processing:
- Manages HARQ processes for DL-SCH retransmissions and acknowledgments.

Channel structure:

Transport channel name	Acronym	Downlink	Uplink
Broadcast Channel	BCH	X	
Downlink Shared Channel	DL-SCH	X	
Paging Channel	PCH	X	
Uplink Shared Channel	UL-SCH		X
Random Access Channel	RACH		X

Transport channels used by MAC

Logical Channel Name	Acronym	Control Channel	Traffic Channel
Broadcast Control Channel	BCCH	X	
Paging Control Channel	PCCH	X	
Common Control Channel	CCCH	X	
Dedicated Control Channel	DCCH	X	

Dedicated Control Channel	DCCH	X	
Dedicated Traffic Channel	DTCH		X

Logical channels provided by MAC

The figure depicts MAC logical channels and PHY layer transport channels used in 5G NR technology. They have specific functions in the downlink or uplink. PDSCH, PBCH and PDCCH are used in the downlink where as PUSCH, PUCCH and RACH are used in the uplink. The reference signals in the downlink are DMRS, PT-RS, CSI-RS, PSS and SSS. The reference signals in the uplink are DMRS, PTRS and SRS.

Transport channel / Logical channel	UL-SCH	RACH
CCCH	X	
DCCH	X	
DTCH	X	

Uplink Channel Mapping

Transport channel / Logical channel	BCH	PCH	DL-SCH
BCCH	X		X
PCCH		X	
CCCH			X
DCCH			X
DTCH			X

Downlink Channel Mapping

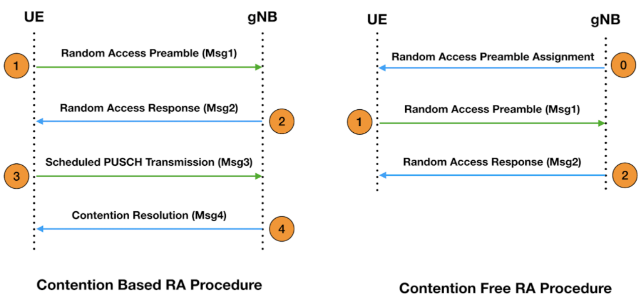
The figure depicts 5G NR channel mapping. It does mapping of logical channels to transport channels and vice versa.

mac procedure:

5G NR MAC Procedures	Description
Random Access Procedure	Get the initial uplink grant for UE and helps in performing synchronization with the gNB (i.e. network). It covers Random Access procedure initialization, Random Access Resource selection, Random Access Preamble transmission, Random Access Response reception, Contention Resolution and Completion of the Random Access procedure.
DL-SCH data transfer	It does everything needed to perform downlink data transfer.
UL-SCH data transfer	It does everything needed to perform uplink data transfer.
Scheduling request (SR)	It is used by UE to transmit request to gNB (i.e. network) to obtain UL grant.
PCH reception	It helps in monitoring paging message in special time period.
BCH reception	It carry basic information regarding the 5G NR cell (e.g. MIB, SFN etc.).
DRX (Discontinuous Reception)	It helps in monitoring PDCCH as per special pattern in discontinuous manner. Due to this discontinuous monitoring, energy consumption can be achieved.
Other procedures	The other 5G NR MAC procedures include transmission and reception without dynamic scheduling, activation/deactivation of SCells, activation/deactivation of PDCP duplication, BWP (Bandwidth Part) operation, handling of measurement gaps, handling of MAC CEs, beam failure detection and recovery operation etc.

Random access procedure:

the RA procedure can take two distinct forms: Contention-Based Random Access (CBRA) and Contention-Free Random Access (CFRA) procedures as shown below:



In CBRA, the UE randomly selects an RA preamble from a pool of preambles shared with other UEs in the cell. If multiple UEs

select/transmit same preamble (Msg1), all those UEs decode same Msg2 content and transmit Msg3 on the same UL time/frequency resources. In the next step (Msg4), the network resolves the contention. Complete details are discussed in the following sections.
In CFRA, the UE uses a dedicated preamble provided by the network specifically to this UE via RRC signaling or PDCCH order.
The RA procedure is initiated by a PDCCH order from the gNB, by the UE's MAC entity itself, or by RRC. The RA procedure is triggered by a number of events:

- Initial access from RRC_IDLE (CBRA)
- RRC Connection Re-establishment procedure (CBRA)
- DL data arrival during RRC_CONNECTED when UL synchronisation status is "non-synchronised" i.e., Out-of-Sync (CBRA or CFRA)
- UL data arrival during RRC_CONNECTED when UL synchronisation status is "non-synchronised" i.e., Out-of-Sync (CBRA)
- UL data arrival during RRC_CONNECTED when there are no PUCCH resources for SR available (CBRA)
- SR failure (CBRA)
- Request by RRC upon synchronous reconfiguration (e.g. handover) (CBRA or CFRA)
- Transition from RRC_INACTIVE (CBRA)
- To establish time alignment for a secondary TAG (CBRA or CFRA)
- Request for On-demand System Information (CBRA or CFRA)
- Beam failure recovery (CBRA or CFRA)

Uplink synchronization:

Uplink synchronization refers to the process in which a device (UE) figures out the exact timing when it should send uplink data (i.e., PUSCH/PUCCH) to the network (gNB). This process is necessary to ensure that the uplink signal from every UE is aligned with a common receiver timer of the network.

In cellular communication, including 5G/NR, there are two types of synchronization: Downlink Synchronization and Uplink Synchronization. Downlink Synchronization is the process in which the UE detects the radio boundary (i.e., the exact timing when a radio frame starts) and OFDM symbol boundary (i.e., the exact timing when an OFDM symbol starts). This process is done by detecting and analyzing the SS Block.

Uplink Synchronization, on the other hand, is a more complicated process that involves adjusting the UE's Tx timing (uplink timing) to align with the network's receiver timer. This process is also known as the RACH (Random Access Channel) process.

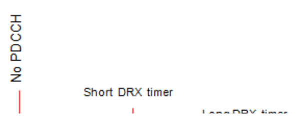
The overall procedure of synchronization and initial access involves several steps, including:

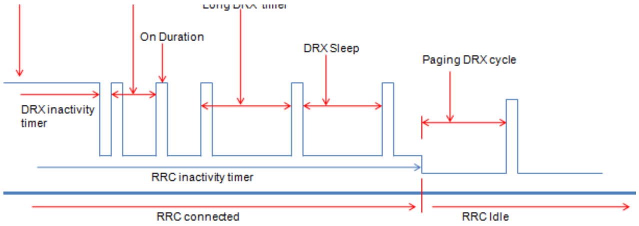
1. Downlink Synchronization: The UE detects the radio boundary and OFDM symbol boundary.
2. Uplink Synchronization: The UE adjusts its Tx timing to align with the network's receiver timer.
3. RACH Process: The UE sends a random access preamble to the network to establish a connection.

Understanding the synchronization process is essential for designing and implementing wireless communication systems, including 5G/NR.

DRX:

Discontinuous Reception:
For this purpose, both LTE and 5G/NR power save protocols include Discontinuous Reception (DRX) and Discontinuous Transmission (DTX). Both involve reducing transceiver duty cycle while in active operation. DRX also applies to the RRC_Idle state with a longer cycle time than active mode.





When the UE is in RRC Connected state, it keeps monitoring PDCCH. During this period if any DL Grant or downlink data for that UE is received then that time DRX inactivity timer and the main RRC Inactivity timer are restarted

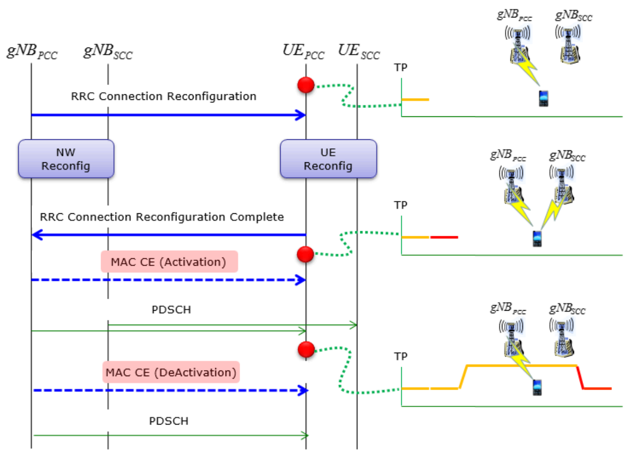
- If there is UL grant for UE with DL Grant that time both DRX and RRC inactivity timers are restarted and after 4 ms UE sends data in uplink.

- The DRX Inactivity timer gets expired when there are no further grants for uplink or downlink. Although UE was constantly monitoring PDCCH, UE now enters in the short DRX cycle. If operator has only configured long DRX then UE directly enters in Long DRX, but in the above example both are configured. The current consumption drops and battery is conserved.

- When the DRX short cycle timer expires, UE end up short DRX cycle and goes into the long DRX cycle

- When there is no activity in UL or DL for the duration of RRC Inactivity timer, the timer expires and the UE enters into RRC IDLE state. In this state, UE uses paging DRX cycle.

Activation and deactivation of scells:



The purpose and the mechanism of NR SCell Activation/Deactivation is same as [LTE SCell Activation/Deactivation](). It is used to activate or deactivate data transmission for SCell while it is in Carrier Aggregation as illustrated below. That is, setting up carrier aggregation is done by RRC process but once RRC job is done, the real swich on/off of data transmission is done by this MAC CE.

Activation and deactivation of SCG:

In 5G, a Secondary Cell Group (SCG) is a group of secondary cells that are configured to provide additional radio resources to a user equipment (UE) beyond the primary cell. The primary cell is the cell that provides the initial connection and control signaling, while the secondary cells provide additional data transmission resources.

SCG Activation

SCG activation is the process of adding one or more secondary cells to a UE's connection with the 5G network. When an SCG is activated, the UE can transmit uplink data on the secondary cells, in addition to the primary cell. The activation of an SCG is typically triggered by the network, and the UE receives a bearer reconfiguration message to activate the SCG.

The SCG activation process involves the following steps:

1. **Bearer reconfiguration message**: The network sends a bearer reconfiguration message to the UE, which includes the configuration parameters for the SCG, such as the cell ID, frequency, and bandwidth.
2. **SCG configuration**: The UE configures the SCG according to the received parameters, including setting up the necessary radio resources and adjusting the uplink timing.
3. **Uplink synchronization**: The UE adjusts its uplink timing to align with the network's receiver timer for the newly added secondary cells. This ensures that the uplink transmission from the UE is synchronized with the network's receiver timer.
4. **Data transmission**: The UE can now transmit uplink data on the secondary cells, in addition to the primary cell.

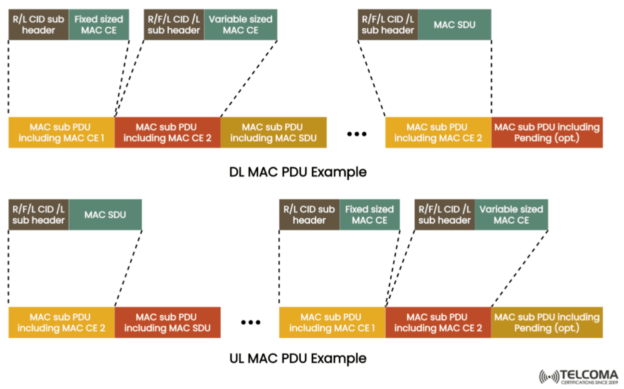
SCG Deactivation

SCG deactivation is the process of removing one or more secondary cells from a UE's connection with the 5G network. When an SCG is deactivated, the UE stops transmitting uplink data on the secondary cells. The deactivation of an SCG is typically triggered by the network, and the UE receives a bearer reconfiguration message to deactivate the SCG.

The SCG deactivation process involves the following steps:

1. **Bearer reconfiguration message**: The network sends a bearer reconfiguration message to the UE, which includes the configuration parameters for the SCG deactivation.
2. **SCG deactivation**: The UE deactivates the SCG, which includes releasing the radio resources and stopping uplink transmission on the secondary cells.
3. **Uplink synchronization**: The UE adjusts its uplink timing to maintain synchronization with the network's receiver timer for the remaining cells.
4. **Data transmission**: The UE continues to transmit uplink data on the primary cell and any remaining secondary cells.

Mac pdu and function:



A MAC PDU is a data unit that is transmitted over the air interface between the UE (User Equipment) and the gNB (5G NodeB). It is a formatted block of data that contains user data, control information, and error detection/correction codes.

MAC PDU Structure

A MAC PDU consists of the following components:

1. **MAC Header**: Contains control information, such as the MAC PDU format, sequence number, and priority.
2. **MAC SDU (Service Data Unit)**: Contains the user data, which is the actual payload being transmitted.
3. **MAC Footer**: Contains error detection and correction codes, such as CRC (Cyclic Redundancy Check) and padding bits.

MAC PDU Functions

The MAC PDU performs the following functions:

1. **Data Transmission**: The MAC PDU is responsible for transmitting user data over the air interface.
2. **Error Detection and Correction**: The MAC PDU contains error detection and correction codes, which enable the receiver to detect and correct errors that occur during transmission.
3. **Flow Control**: The MAC PDU header contains flow control information, which enables the receiver to control the amount of data transmitted by the sender.

4. **Priority Handling**: The MAC PDU header contains priority information, which enables the receiver to prioritize the transmission of MAC PDUs based on their priority level.
5. **Sequence Numbering**: The MAC PDU header contains a sequence number, which enables the receiver to detect and correct errors that occur during transmission.
6. **Segmentation and Reassembly**: The MAC PDU can be segmented into smaller fragments, which are transmitted separately and reassembled at the receiver.
7. **Padding**: The MAC PDU footer contains padding bits, which ensure that the MAC PDU is aligned with the transmission block size.

MAC PDU Types

There are several types of MAC PDUs, including:

1. **Data MAC PDU**: Contains user data and is used for data transmission.
2. **Control MAC PDU**: Contains control information and is used for control signaling.
3. **Random Access MAC PDU**: Used for random access procedures, such as initial access and handover.
4. **Scheduling Request MAC PDU**: Used for scheduling requests, which enable the UE to request resources from the gNB.

Mac control CE, BSR:

LCG_7	LCG_6	LCG_5	LCG_4	LCG_3	LCG_2	LCG_1	LCG_0	Oct 1
Buffer Size 1								Oct 2
Buffer Size 2								Oct 3
...								
Buffer Size m								Oct m+1

Short BSR is a format for a Short Buffer Status Report (BSR). These reports are used to inform the network about the status of data buffers in the User Equipment (UE). The following diagram outlines the structure of these reports, which include fields for the Logical Channel Group ID (LCG ID) and Buffer Size.

The LCG ID is used to identify which group of logical channels the report pertains to, and the Buffer Size field indicates the amount of data waiting to be transmitted.

MAC CE BSR is a control element used by the UE (User Equipment) to report its buffer status to the gNB (5G NodeB). The buffer status report provides information about the amount of data available in the UE's buffer for transmission.

MAC CE BSR Structure

The MAC CE BSR consists of the following fields:

1. **BSR Type**: Indicates the type of BSR being reported. There are two types of BSR:
   - **Short BSR**: Reports the buffer status for a single logical channel group (LCG).
   - **Long BSR**: Reports the buffer status for multiple LCGs.
2. **LCG ID**: Identifies the logical channel group for which the buffer status is being reported.
3. **Buffer Size**: Indicates the amount of data available in the UE's buffer for transmission.
4. **Priority**: Indicates the priority of the data in the buffer.

MAC CE BSR Types

There are two types of MAC CE BSR:

1. **Regular BSR**: Reports the buffer status periodically, based on a timer.
2. **Padding BSR**: Reports the buffer status when the UE has no data to transmit, but needs to maintain the connection with the gNB.

MAC CE BSR Procedure

The MAC CE BSR procedure involves the following steps:

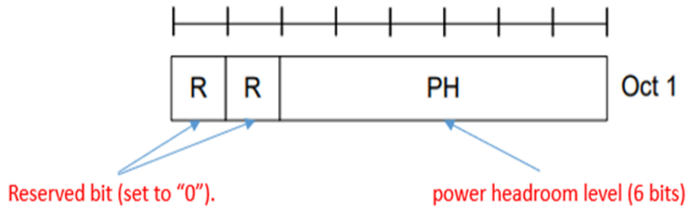
1. **Triggering**: The UE triggers the BSR procedure when the buffer status changes or when a timer expires.
2. **BSR Generation**: The UE generates a MAC CE BSR, which includes the buffer status information.
3. **Transmission**: The UE transmits the MAC CE BSR to the gNB.
4. **Receipt**: The gNB receives the MAC CE BSR and updates its scheduling information.
5. **Scheduling**: The gNB schedules the UE for transmission, based on the buffer status information.

MAC CE BSR Functions

The MAC CE BSR performs the following functions:

1. **Buffer Status Reporting**: Reports the buffer status of the UE to the gNB.
2. **Scheduling**: Enables the gNB to schedule the UE for transmission, based on the buffer status information.
3. **Resource Allocation**: Enables the gNB to allocate resources to the UE, based on the buffer status information.
4. **Flow Control**: Enables the gNB to control the amount of data transmitted by the UE, based on the buffer status information.

PHR(power headroom report):



PHR stands for **Power Headroom Reporting**. It is a mechanism used by User Equipment (UE) to report its available transmit power to the base station (eNodeB) in the LTE network.

The purpose of PHR is to allow the eNodeB to effectively manage the resources and allocate appropriate power levels to UEs. By knowing the power headroom of each UE, the eNodeB can make informed decisions regarding resource allocation and power control, ensuring efficient and reliable communication.

- Power Headroom: Power headroom refers to the difference between the maximum transmit power of the UE and the actual power level it is currently using. It represents the UE's capability to increase its transmit power without exceeding the limits.

Power Headroom = UE Max Transmission Power – PUSCH Power = Pmax – P_pusch

Power Headroom is Positive in Value (+) = means still have some bandwidth and can transmit more data if allowed.

power Headroom is negative in value (-) = Already transmitting more power than allowed.

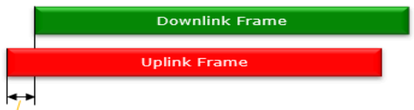
- **Power Headroom Reporting (PHR):** UEs periodically measure their available power headroom and report it to the eNodeB. This reporting is initiated by the eNodeB through specific signalling messages.
- **PHR Configuration:** The eNodeB configures the PHR parameters for each UE, including the reporting periodicity and the measurement rules. The reporting periodicity determines how often the UE needs to send the PHR report, while the measurement rules define how the UE calculates its power headroom.
- **PHR Calculation**: The UE calculates its power headroom by considering factors such as the maximum transmit power defined by the network, the current transmit power, and any power limitations due to neighbouring cells or interference. The calculation ensures that the UE reports an accurate representation of its available power.
- **PHR Report:** The UE sends the PHR report to the eNodeB over the uplink channel. The report includes the power headroom value and any additional information specified by the PHR configuration.
- **Resource Allocation:** Upon receiving the PHR reports from UEs, the eNodeB utilizes the information to make decisions on resource allocation and power control. It can adjust the assigned resources and power levels

for each UE to maintain optimal system performance and avoid interference issues.

Timing Advance

The concept and functionality of NR Timing Advance is same as the LTE Timing Advance. So I suggest you to read LTE Timing Advance as well if you are not familiar with the concept.

Simply put, Timing Advance is a special command (notification) from eNB to UE that enable UE to adjust its uplink transmission as shown below. This kind of UL adjustment applies to PUSCH, PUCCH and SRS.



$$(N_{TA} + N_{TAoffset})T_c$$

Timing Advance from MAC-CE or RAR

$T_c = 0.509\ ns$

< 38.133 v15.6 - Table 7.1.2-2 >

Frequency range and band of cell used for uplink transmission	$N_{\mathrm{TA\ offset}}$ (Unit: Tc)
FR1 FDD band without LTE-NR coexistence case or FR1 TDD band without LTE-NR coexistence case	25600 (Note 1)
FR1 FDD band with LTE-NR coexistence case	0 (Note 1)
FR1 TDD band with LTE-NR coexistence case	39936 (Note 1)
FR2	13792

Note 1: The UE identifies $N_{\mathrm{TA\ offset}}$ based on the information n-TimingAdvanceOffset according to [2]. If UE is not provided with the information n-TimingAdvanceOffset, the default value of $N_{\mathrm{TA\ offset}}$ is set as 25600 for FR1 band. In case of multiple UL carriers in the same TAG, UE expects that the same value of n-TimingAdvanceOffset is provided for all the UL carriers according to clause 4.2 in TS 38.213 [3] and the value 39936 of $N_{\mathrm{TA\ offset}}$ can also be provided for a FDD serving cell.

Note 2: Void

$$N_{TA}\_new = N_{TA}\_old + (T_A - 31)\cdot 16\cdot 64 / 2^{\mu}$$: MAC CE TA, 38.213-4.2

$T_A = 0,1,2,\ldots,63$

$$N_{TA} = T_A \cdot 16\cdot 64 / 2^{\mu}$$

$T_A = 0,1,2,\ldots,3846$: RAR TA, 38.213-4.2

Case 1 : Through RAR

the timing advance value from two different MAC layer command depending on situation. For the first Uplink message after PRACH, UE applies the Timing Advance value that it extracts from RAR (RACH Response). After the initial RACH process, UE would apply the timing Advance value that it extract from Timing Advance MAC CE if it received it.

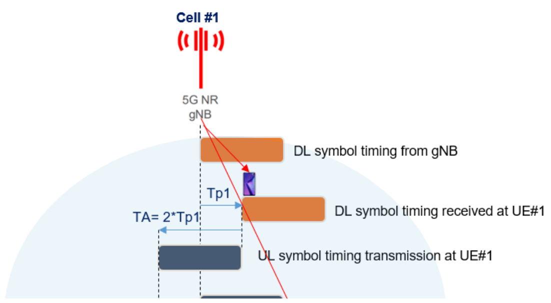
Case 2 : Through MAC CE

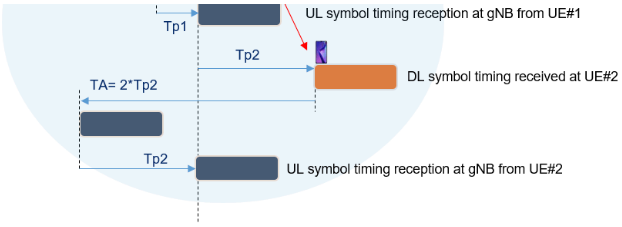
UE adjust UL transmission timing based on RAR during the initial attach. Once the initial attach is complete, UE adjust UL transmission based on the MAC CE-Timing Advance.

Timing Advanced Report MAC CE:

Timing Advance:

Timing Advance (TA) is a command sent by Base Station (BS) to UE to adjust its uplink transmission means that the UE sends UL symbols in advance according to command for i.e. PUSCH, PUCCH and SRS transmission. Timing Advance Command (TAC) informs the UE the amount of time that it needs to advance the UL transmissions.





Timing Advanced Report MAC CE is a control element used by the UE (User Equipment) to report its timing advance (TA) to the gNB (5G NodeB). The TA is the time difference between the UE's transmit timing and the gNB's receive timing.

Timing Advanced Report MAC CE Structure

The Timing Advanced Report MAC CE consists of the following fields:

1. **TA Value**: Indicates the timing advance value, which is the time difference between the UE's transmit timing and the gNB's receive timing.
2. **TA Validity**: Indicates the validity of the TA value, which can be either valid or invalid.
3. **TA Type**: Indicates the type of TA being reported, which can be either Type 1 or Type 2.

Timing Advanced Report MAC CE Types

There are two types of Timing Advanced Report MAC CE:

1. **Type 1**: Reports the TA value based on the UE's transmit timing and the gNB's receive timing.
2. **Type 2**: Reports the TA value based on the UE's receive timing and the gNB's transmit timing.

Timing Advanced Report MAC CE Procedure

The Timing Advanced Report MAC CE procedure involves the following steps:

1. **Triggering**: The UE triggers the Timing Advanced Report MAC CE procedure when the TA value changes or when a timer expires.
2. **TA Calculation**: The UE calculates the TA value based on its transmit timing and the gNB's receive timing.
3. **MAC CE Generation**: The UE generates a Timing Advanced Report MAC CE, which includes the TA value and validity.
4. **Transmission**: The UE transmits the Timing Advanced Report MAC CE to the gNB.
5. **Receipt**: The gNB receives the Timing Advanced Report MAC CE and updates its timing information.

Timing Advanced Report MAC CE Functions

The Timing Advanced Report MAC CE performs the following functions:

1. **Timing Advance Reporting**: Reports the TA value to the gNB, which enables the gNB to adjust its timing.
2. **Timing Alignment**: Enables the gNB to align its timing with the UE's timing, which improves the overall system performance.
3. **Handover**: Enables the gNB to perform handover procedures, which involve switching the UE from one cell to another.

Timing Advanced Report MAC CE Benefits

The Timing Advanced Report MAC CE provides several benefits, including:

1. **Improved Timing Alignment**: Enables the gNB to align its timing with the UE's timing, which improves the overall system performance.
2. **Increased Handover Efficiency**: Enables the gNB to perform handover procedures more efficiently, which reduces the handover latency.
3. **Reduced Interference**: Enables the gNB to reduce interference between cells, which improves the overall system performance.