COURSE 2
5G NETWORKS

Ș.L. DR. ING. ZSUZSANNA ȘUTA

COMMUNICATIONS DEPARTMENT

CONTENT

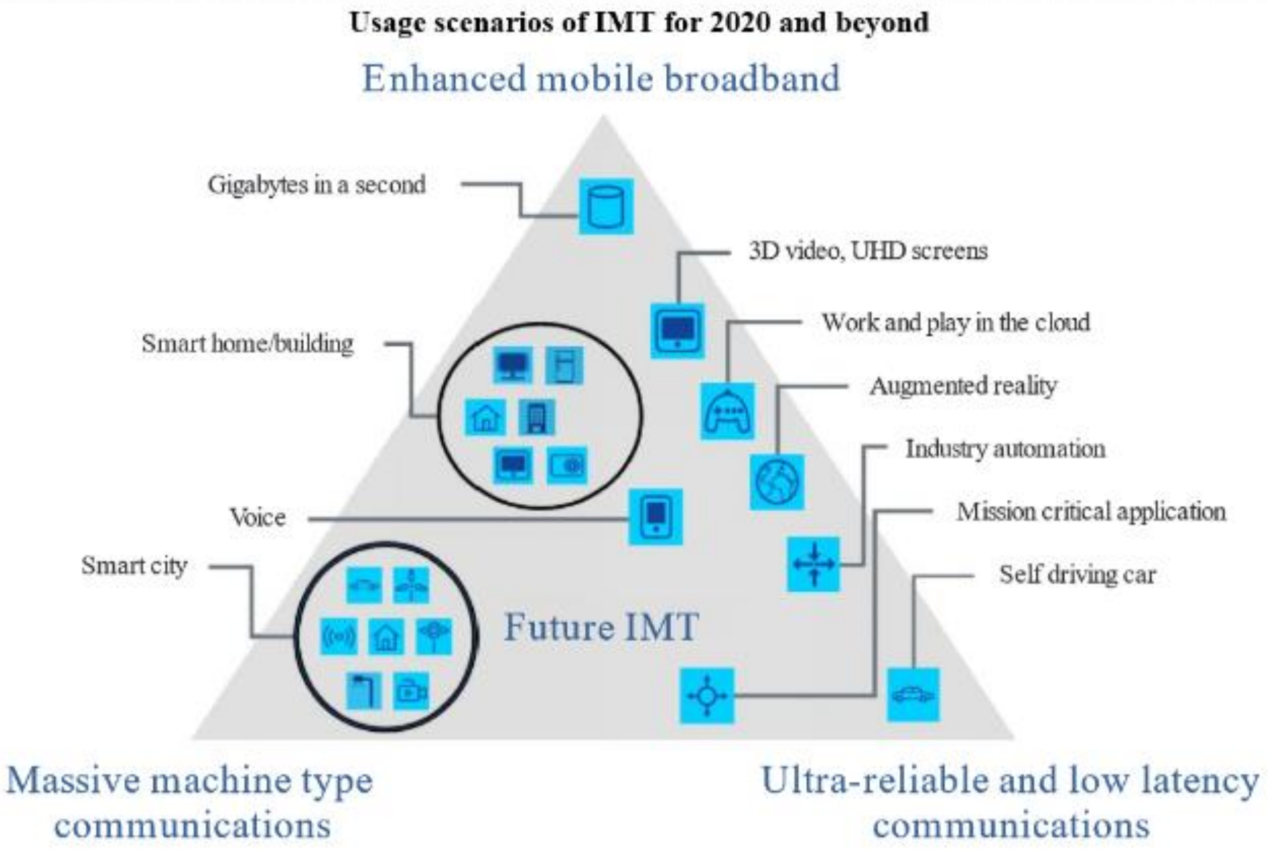
- IMT-2020
- IMT-2020 minimum requirements
- 3GPP 5G NR
- Physical layer
- MAC layer
- RRC

INTRODUCTION

- First 5G network: South Korea, April 2019
- The requirements were specified by ITU-R IMT-2020
- 3GPP defines as 5G NR (New Radio)
  - It is not a standard, only a part of the standard
  - It is more an implementation proposal
  - ITU-R has to approve
- Usage of 5G
  - eMBB – Enhanced Mobile Broadband
  - URLLC – Ultra Reliable Low Latency Communications
  - mMTC – Massive Machine Type Communications

IMT-2020

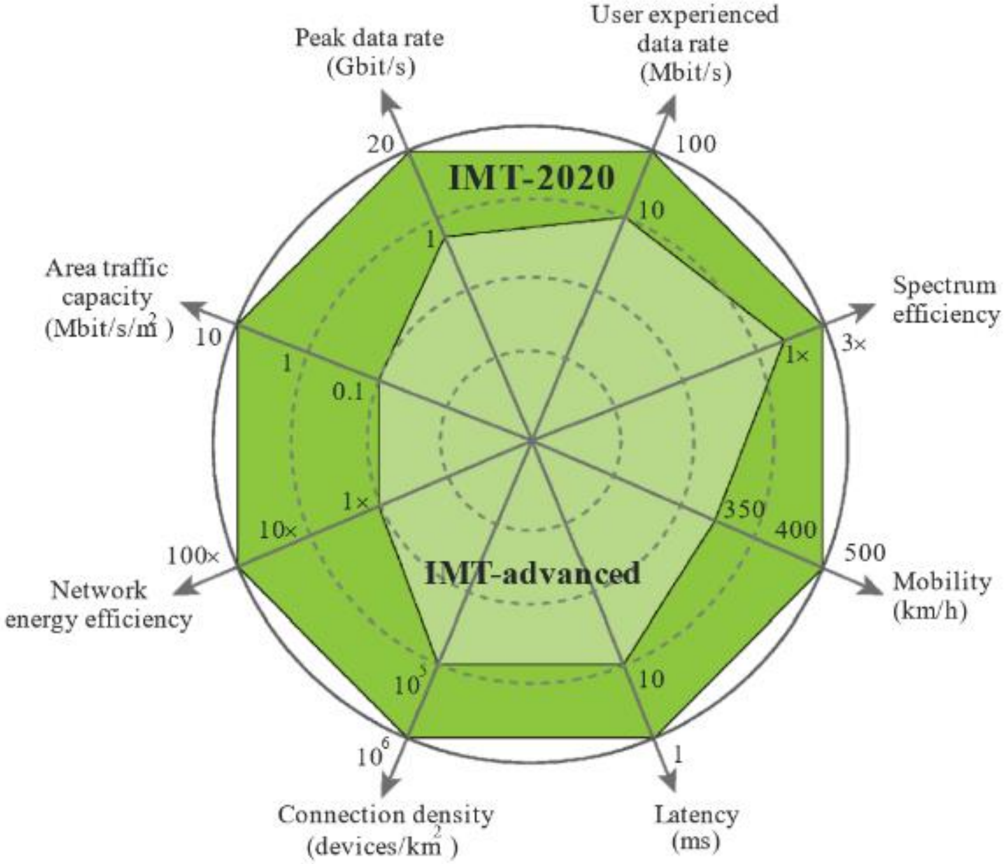
- International Mobile Telecommunications-2020 (IMT-2020) are the requirements for 5G from ITU-R (International Telecommunication Union Radiocommunication Sector)
  - It was completed in 2020; 3GPP developed the radio access technologies



IMT-2020

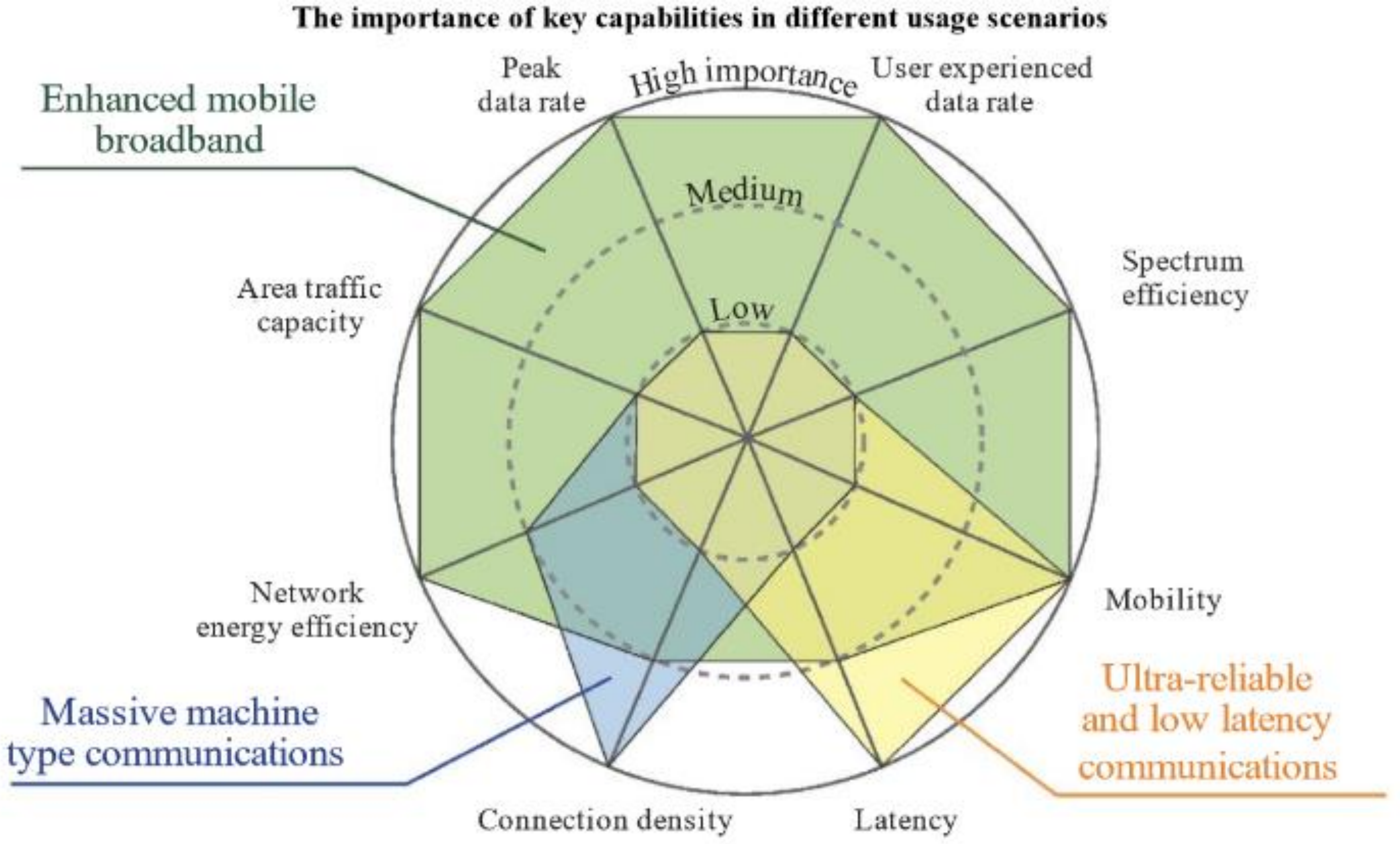
- IMT-2020 vs. IMT-advanced:
  - 10x bit rate
  - 3x spectral efficiency
  - Handover from 350km/h to 500km/h
  - 10x device density
  - 100x network energy efficiency
  - Latency from 10ms to 1ms

Enhancement of key capabilities from IMT-Advanced to IMT-2020



IMT-2020

- The importance of capabilities for various usage scenarios



MINIMUM REQUIREMENTS IMT-2020

- The maximum rate in ideal conditions at a single mobile station – for eMBB
  - W – bandwidth; SE_p – maximum spectral efficiency in the band => R_p = W*SE_p
  - For Q sub-bands: R = $\sum_{i=1}^{Q} W_i * Se_{pi}$
  - Downlink: 20 Gbps, uplink: 10 Gbps
- Maximum spectral efficiency – for eMBB
  - Downlink: 300 bit/s/Hz, uplink: 15 bit/s/Hz
- User experienced rate – for eMBB
  - W – bandwidth; SE_{user} – 5% of the spectral efficiency assigned to user => R_{user} = W*SE_{user}
  - Downlink: 100 Mbps, uplink: 50 Mbps

MINIMUM REQUIREMENTS IMT-2020

- The average spectral efficiency is the number of bits received correctly by all users divided by the bandwidth divided by no. of TRxP (Transmission Reception Point) - eMBB

$$SE_{avg} = \left(\sum_{i=1}^{N} R_i(T)\right)/(T*W*M)$$

  - N – no. users, M – no. TRxP, W – bandwidth, T – reception time duration
  - Hotspot indoor downlink: 9 bits/s/Hz/TRxP, uplink: 6.75 bits/s/Hz/TRxP
  - Dense urban downlink: 7.8 bits/s/Hz/TRxP, uplink: 5.4 bits/s/Hz/TRxP
  - Rural downlink: 3.3 bits/s/Hz/TRxP, uplink: 1.6 bits/s/Hz/TRxP
- Area traffic capacity: the number of correctly received bits per geographic area – eMBB

$$C_{area} = \rho * W * SE_{avg}$$

  - ρ is the TRxP density expressed in TRxP/m^2
  - Indoor Hotspot downlink: 10 Mbit/s/m^2

MINIMUM REQUIREMENTS IMT-2020

- Latency
  - User latency: delay due to the radio connection between the time of sending and receiving the packet
    - 4 ms for eMBB
    - 1 ms for URLLC
  - Control latency: the time required to transition from battery save mode to continuous data transfer mode
    - 20 ms, but is recommended not to be greater than 10 ms
- Connection density: maximum no. of devices with a certain QoS per unit area – mMTC
  - 1 000 000 devices/km^2

MINIMUM REQUIREMENTS IMT-2020

- Energy efficiency: the ability of radio interface technologies to minimize the energy consumption of the network/device relative to traffic capacity/traffic characteristics
  - Efficient data transmissions in case of network load
  - Low power consumption when no data is transmitted
- Robustness: the ability to transmit a given amount of information, in a predetermined period of time, with a high probability of success – URLLC
  - $1\text{-}10^{-5}$ probability of success for the transmission of layer 2 PDUs of 32 bytes in 1 ms
- Mobility: the maximum speed of the mobile station at which a certain QoS can be provided
  - Mobility classes: stationary – 0 km/h; pedestrian – 0-10 km/h; vehicular – 10-120 km/h; high speed vehicular – 120-500 km/h

MINIMUM REQUIREMENTS IMT-2020

- Disruption of mobility: the shortest period of time during which the user's terminal cannot change packets with base stations during the transition (handover) – eMBB and URLLC
  - 0 ms is the requirement
- Bandwidth: is the maximum aggregate bandwidth of the system
  - At least 100 MHz
  - Radio interface technologies should support up to 1 GHz
  - The bandwidth must be scalable; radio interface technologies must be able to work with different bandwidths

3GPP 5G NR

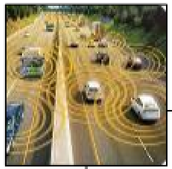
- 5G NR (New Radio) is developed by 3GPP for the global 5G standard
- The 38 series of 3GPP specifications describe the technical details of 5G NR

Enhanced Mobile Broadband (eMBB)

- 10-20 Gbps peak
- 100 Mbps whenever needed
- 10000x more traffic
- Macro and small cells
- Support for high mobility (500 km/h)
- Network energy saving by 100 times

Massive Machine Communication (mMTC)

- High density of devices ($2x10^5$ - $10^6/km^2$)
- Long range
- Low data rate (1 - 100 kbps)
- M2M ultra low cost
- 10 years battery
- Asynchronous access

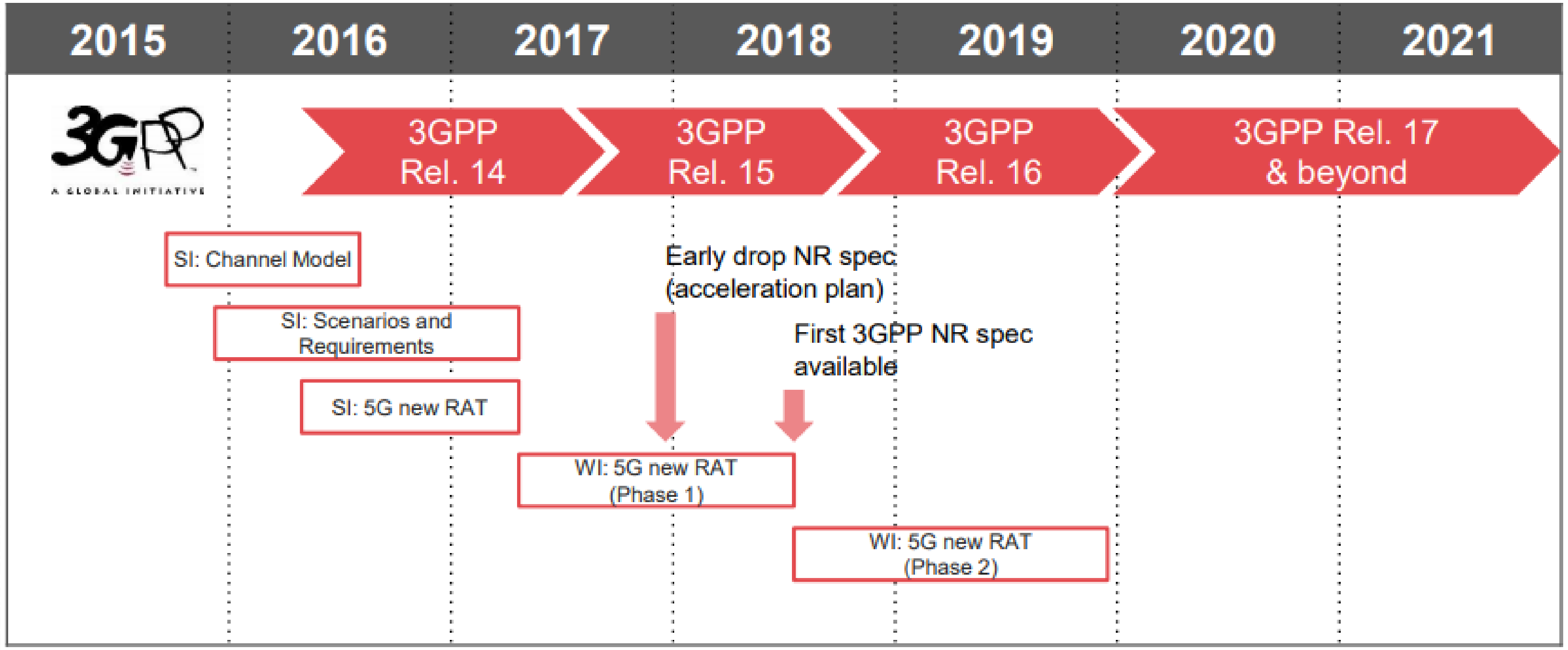


Ultra Reliability and Low Latency (URLLC)

- Ultra responsive
  - <1 ms air interface latency
  - 5 ms E2E latency
- Ultra reliable and available (99.9999%)
- Low to medium data rates (50 kbps - 10 Mbps)
- High speed mobility

3GPP 5G NR

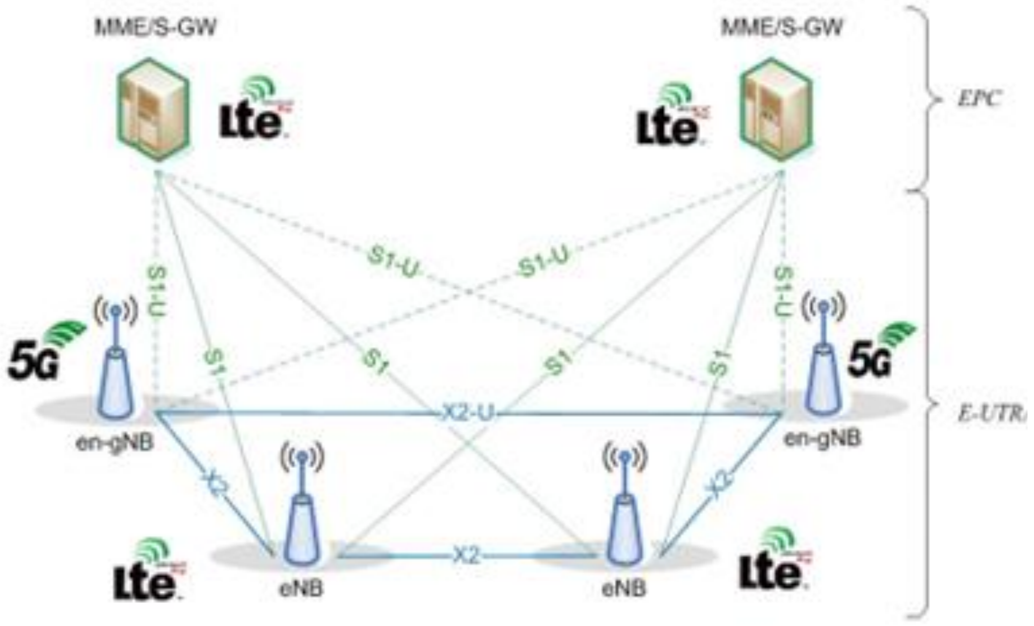
- The 5G NR study started in 2015, the first specifications being available in 2017
- Release 17 with full 5G specifications completed in 2022



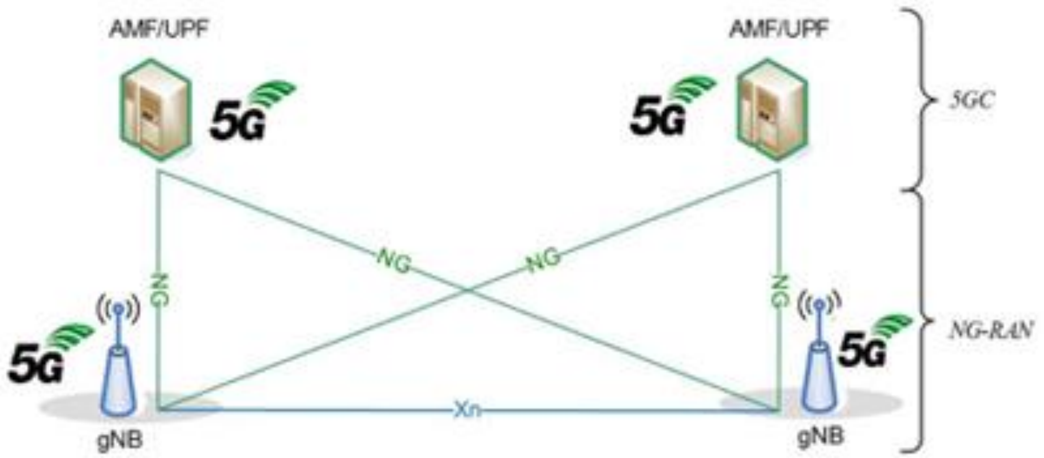
3GPP 5G NR

- 5G NR uses two main frequency bands:
  - <6GHz
  - >6GHz
- There are two ways to implement 5G networks:
  - NSA (Non-Standalone Mode)
    - Uses the LTE control plane, 5G NR is implemented only on the user plane
    - LTE core network is used
  - SA (Standalone Mode)
    - 5G is also used for signaling
    - The core network is 5G and has no LTE dependency

3GPP 5G NR



NSA architecture (*3GPP)



SA architecture (*3GPP)

5G NR PHYSICAL LAYER

- Numerology
  - 5G NR uses OFDM and allows scalable spacing of subcarriers: $\Delta f = 2^{\mu} 15$kHz
  - A numerology is defined by the spacing of the subcarriers and the cyclic prefix
  - The selection depends on the cell size and frequency band
  - The duplexing method can be TDM and/or FDM in UL and DL

μ	$\Delta f = 2^{\mu} \cdot 15$ kHz	Cyclic Prefix
0	15 kHz	Normal
1	30 kHz	Normal
2	60 kHz	Normal, Extended
3	120 kHz	Normal
4	240 kHz	Normal

Sync < 6 GHz (μ = 0, 1)

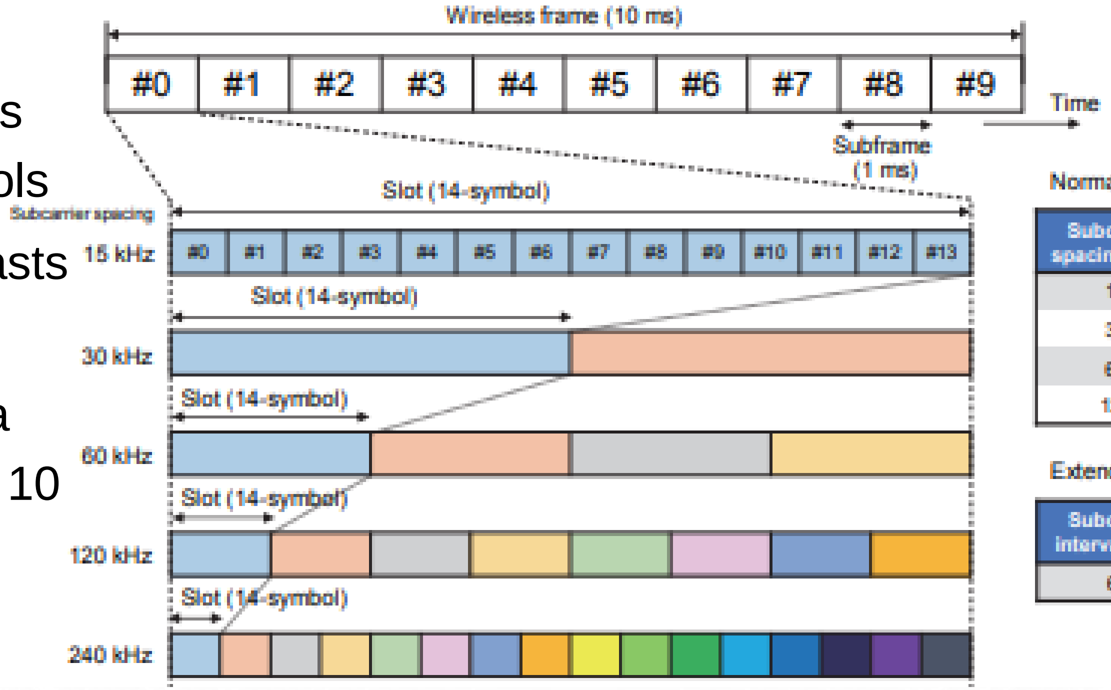
Sync > 6 GHz (μ = 3, 4)

Data < 6 GHz (μ = 0, 1, 2)

Data > 6 GHz (μ = 2, 3, 4)

5G NR PHYSICAL LAYER – FRAMES

- 5G NR frame structure
  - One slot contains 14 OFDM symbols
  - One subframe lasts 1ms
  - One frame has a fixed duration of 10 ms



Normal cyclic prefix

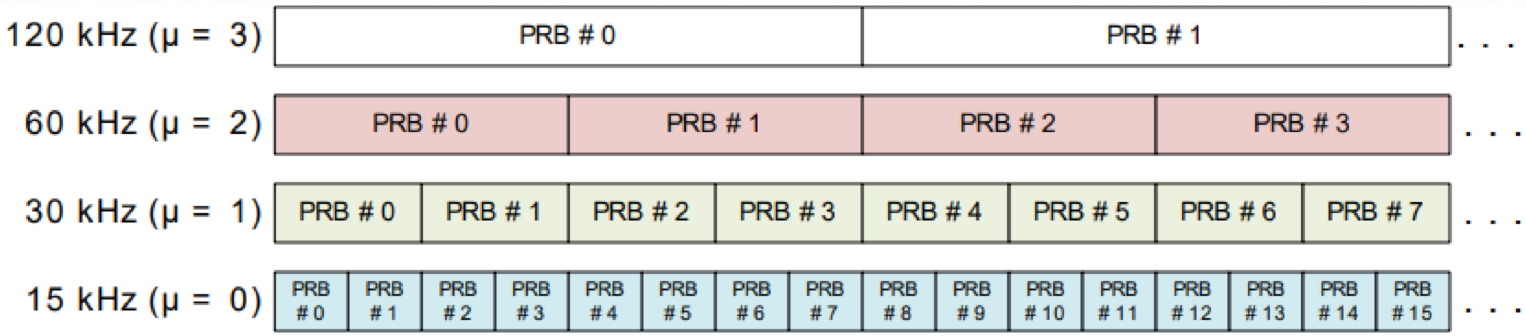
Subcarrier spacing [kHz]	No. of symbols per slot	No. of slots per subframe	No. of subframes per frame
15	14	1	10
30	14	2	10
60	14	4	10
120	14	8	10

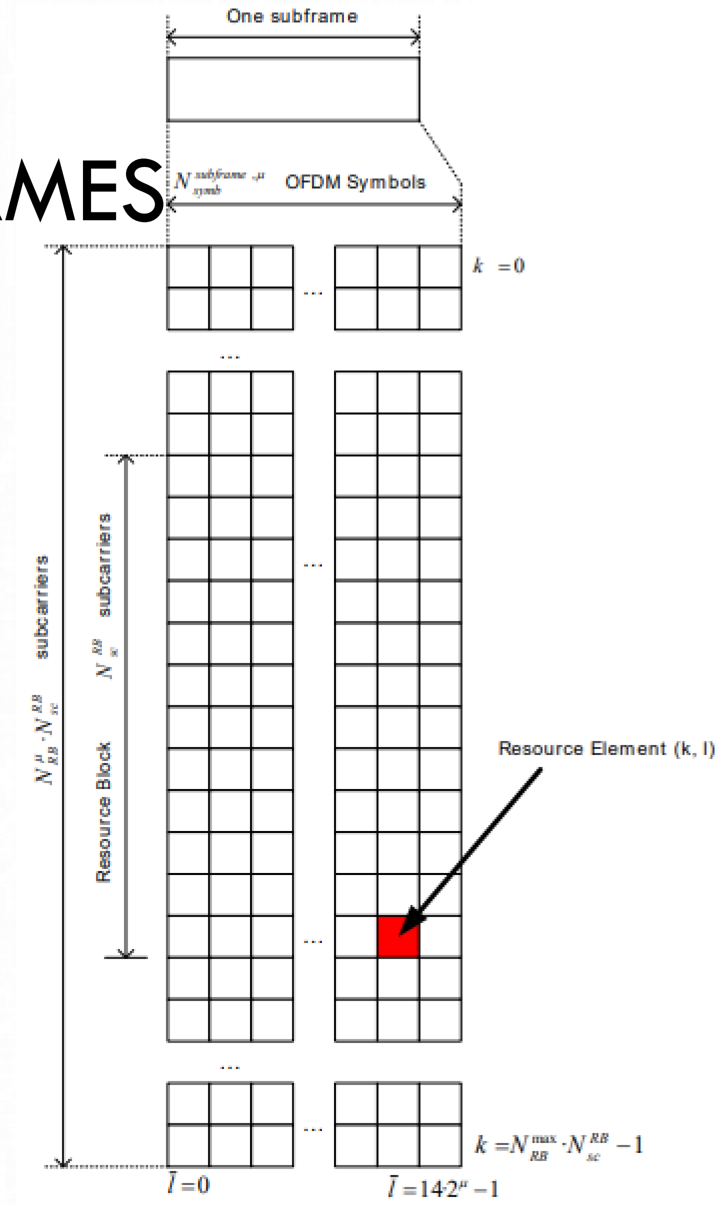
Extended cyclic prefix

Subcarrier interval [kHz]	No. of symbols per slot	No. of slots per subframe	No. of subframes per frame
60	12	4	10

5G NR PHYSICAL LAYER – FRAMES

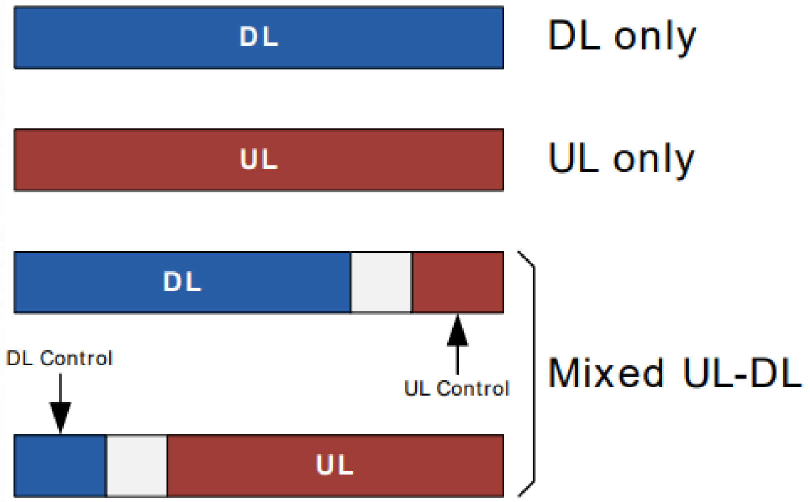
- In the frequency domain one resource block (PRB – Physical Resource Block) 12 consecutive subcarriers
- The frame structure does not depend on duplexing
- For each carrier and numerology, a resource matrix is defined with $N_{RB}^{max,\mu} N_{SC}^{RB}$ subcarriers with $N_{symb}^{subframe,\mu}$ OFDM symbols





5G NR PHYSICAL LAYER – FRAMES

- A slot can be used for:
  - Only for DL
  - Only for UL
  - Mixed for UL and DL
- SFI (Slot Format Indication) transmits to the UE if a slot is UL, DL or flexible
  - SFI can be dynamic or static
  - Contains an index to a UE-specific preconfigured table

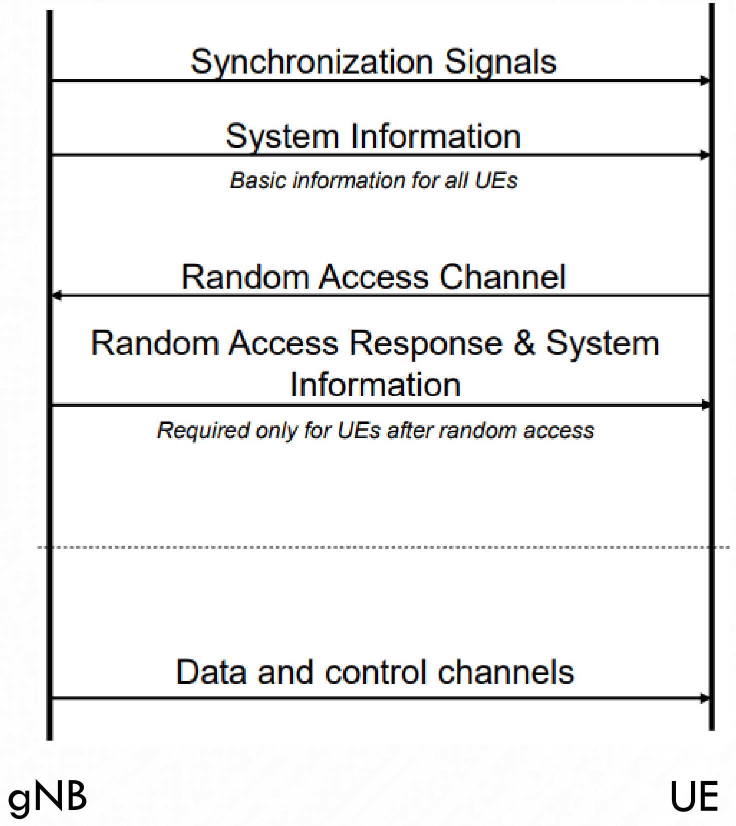


5G NR PHYSICAL LAYER – INITIAL ACCESS

- Initial UE access is achieved in three steps:
  - Synchronization Signal (SS) detection
  - Obtaining broadcast information
  - Establishing the connection by random access
- SS detection
  - SS consists of 2 signals
    - PSS – Primary Synchronization Signal
    - SSS – Secondary Synchronization Signal
  - SS with PBCH (Physical Broadcast Channel) and DMRS (DeModulation Reference Signal) forms an SS/PBCH block

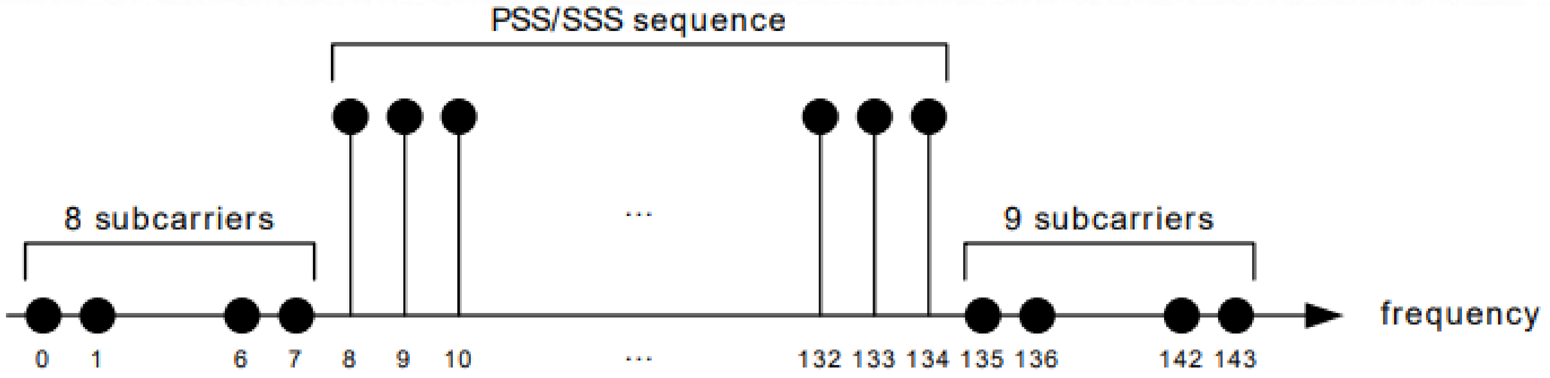
5G NR PHYSICAL LAYER – INITIAL ACCESS

- gNB uses the SS/PBCH block to transmit the information needed for the UE to detect NR cells, to synchronize, to measure the quality of DL transmissions
- gNB sets the transmission period for SS/PBCH
- UE identifies SS blocks by:
  - Index indicated by DMRS and PBCH
- A minimum bandwidth is defined for PSS, SSS and PBCH:
  - < 6GHz: 15kHz spacing → 5MHz, 30kHz spacing → 10MHz
  - > 6GHz: 120kHz spacing → 50MHz, 240kHz spacing → 100MHz



5G NR PHYSICAL LAYER – INITIAL ACCESS

- The PSS/SSS sequence is mapped on 127 subcarriers
- The center frequency of PSS/SSS is aligned with the center frequency of the PBCH
- Transmission on PBCH:
  - TTI 80ms
  - Payload 56 bits
  - Polar codes are used



5G NR PHYSICAL LAYER – INITIAL ACCESS

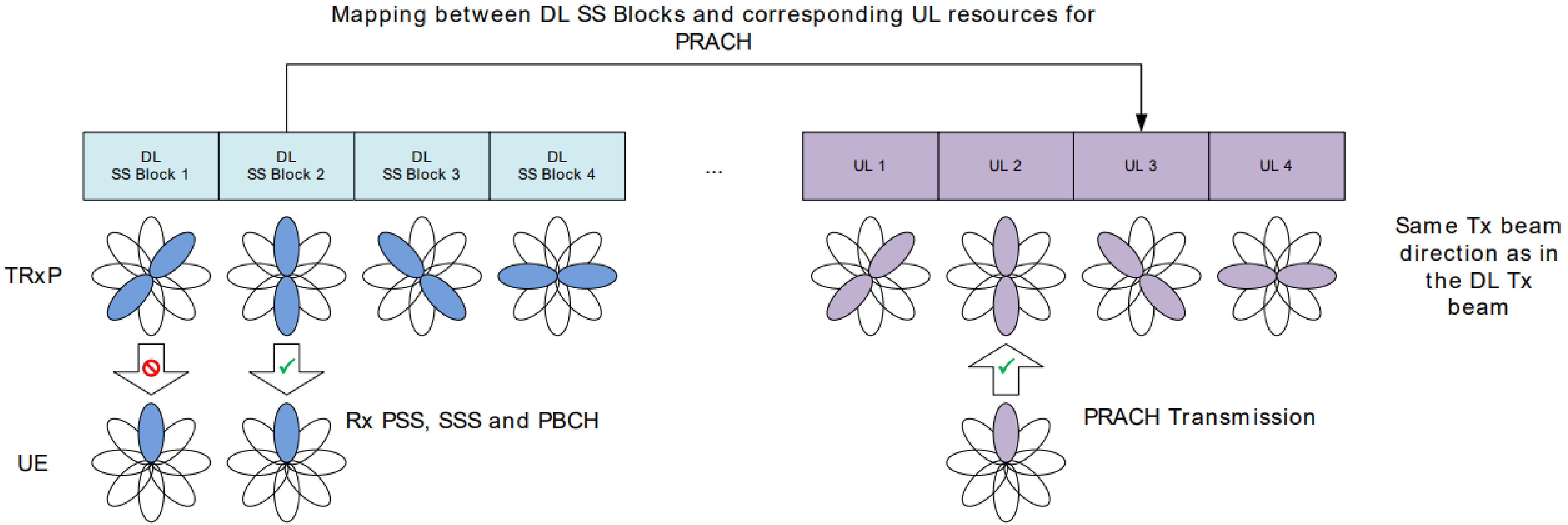
- System Information Notification
  - The broadcast information sent by gNB is of 3 types:
    - Broadcast information sent on PBCH
    - System information required for initial access
    - Other system information
  - PBCH includes SFN (System Frame Number) and other information that the UE uses for frame synchronization after SS detection
  - The UE will receive SIB (System Information Block) which contains information about the UL carrier and the configuration of random-access signals

5G NR PHYSICAL LAYER – INITIAL ACCESS

- Random access
  - The UE identifies the best SS block
  - The UE uses PRACH (Physical Random Access Channel) to transmit a set of resources:
    - The association between the selected SS block and the PRACH parameters configured based on the system information
    - UE announces gNB about best SS block
  - 5G NR defines 13 PRACH formats
  - PRACH sequences are based on Zadoff-Chu sequences

Format number	Sequence length	No. of OFDM symbol repetitions	Subcarrier spacing	Time duration	Bandwidth
0	839	1	1.25 kHz	1 subframe	1.05 MHz
1		2		3 subframe	
2		4		3.5 subframe	
3		4	5 kHz	1 subframe	4.20 MHz
A1	139	2	{15, 30, 60, 120} kHz	2 symbols	{2.09, 4.17, 8.34, 16.68} MHz
A2		4		4 symbols	
A3		6		6 symbols	
B1		2		2 symbols	
B2		4		4 symbols	
B3		6		6 symbols	
B4		12		12 symbols	
C0		1		2 symbols	
C2		4		6 symbols	

5G NR PHYSICAL LAYER – INITIAL ACCESS



5G NR PHYSICAL LAYER – MIMO

- In high frequency bands it is necessary to use multiple antennas
  - The beamforming gain compensates for the effects of radio attenuation
- Hybrid beamforming MIMO with up to 256 gNB antenna elements and up to 32 UE antennas
- Hybrid beamforming:
  - Digital beamforming for control of baseband signals
  - Analog beamforming for RF signal control
- Spatial multiplexing is used to increase spectral efficiency

5G NR PHYSICAL LAYER – MIMO

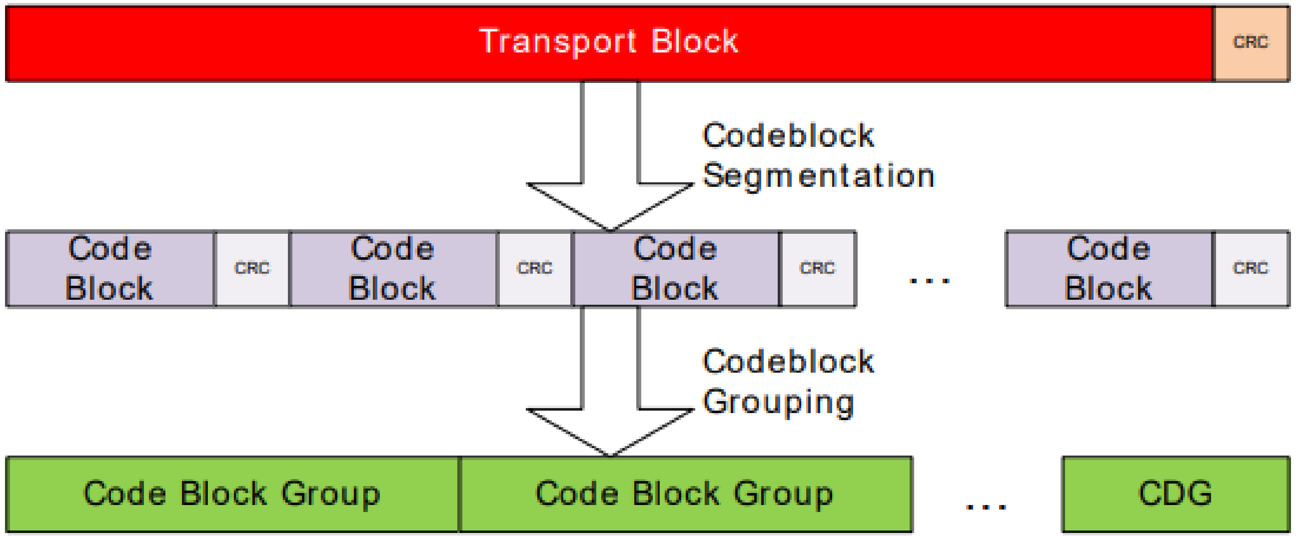
	< 6 GHz	mmWave
Deployment Scenario	Macro cells High user mobility	Small cells Low user mobility
MIMO Order	Up to 8x8	Less MIMO order (typically 2x2)
Number of Simultaneous Users	Tens of users Large coverage area	A few users Small coverage area
Main Benefit	Spatial multiplexing	Beamforming for single user
Channel Characteristics	Rich multipath propagation	A few propagation paths
Spectral Efficiency	High due to the spatial multiplexing	Low spectral efficiency (few users, high path loss)
Transceiver	Digital transceiver	Hybrid

5G NR PHYSICAL LAYER – SCHEDULING

- DL channel scheduling is based on DCI (Downlink Control Information)
  - DCI is transmitted on the PDCCH (Physical Downlink Control Channel)
  - gNB allocates a PDSCH (Physical Downlink Shared Channel) to the UE
  - UE sends a HARQ-ACK message via PUCCH (Physical Uplink Control Channel)
  - The UE also sends SR (Scheduling Request) and CSI (Channel State Information)
  - gNB allocates resources based on the received information

5G NR PHYSICAL LAYER – HARQ

- HARQ retransmissions allow two operations
  - Retransmission of the entire block originally transmitted
  - CBG (Code Block Group) retransmission – only erroneous code blocks are retransmitted and not the entire transport block



5G NR PHYSICAL LAYER – MODULATION

- BPSK, QPSK, 16QAM, 64QAM, 256QAM modulations are used as primary modulation schemes
- Secondary modulation schemes:
  - CP-OFDM: OFDM with cyclic prefix, adds a guard period for protection against inter-symbol interference
    - It is used with MIMO
  - DFTS-OFDM (Discrete Fourier Transform Spreading OFDM): suppresses PAPR to allow wider coverage
    - Used with single (antenna) layer transmissions

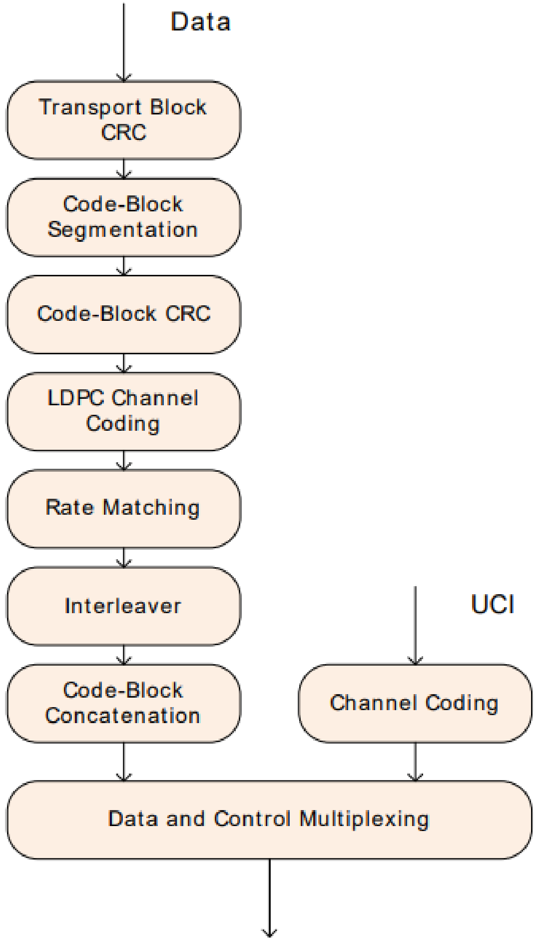
5G NR PHYSICAL LAYER – MODULATION

Secondary modulation scheme	Primary modulation scheme	Downlink	Uplink
CP-OFDM	π/2-BPSK	—	—
	BPSK	—	PUCCH format 1
	QPSK	PBCH, PDCCH, PDSCH	PUCCH format 1/2, PUSCH
	16QAM	PDSCH	PUSCH
	64QAM	PDSCH	PUSCH
	256QAM	PDSCH	PUSCH
DFTS-OFDM	π/2-BPSK	—	PUCCH format 3/4, PUSCH
	QPSK	—	PUCCH format 3/4, PUSCH
	16QAM	—	PUSCH
	64QAM	—	PUSCH
	256QAM	—	PUSCH

5G NR PHYSICAL LAYER – CHANNEL CODING

- LDPC and polar codes are used
- LDPC codes are used for data channels
  - Allow parallel processing – reduces the decoding delay
- Polar codes are used in control channels

	Downlink	Uplink
LDPC	DL-SCH, PCH	UL-SCH
Polar coding	BCH, DCI	UCI (payload size ≥ 12)
Block coding	—	UCI (payload size < 12)

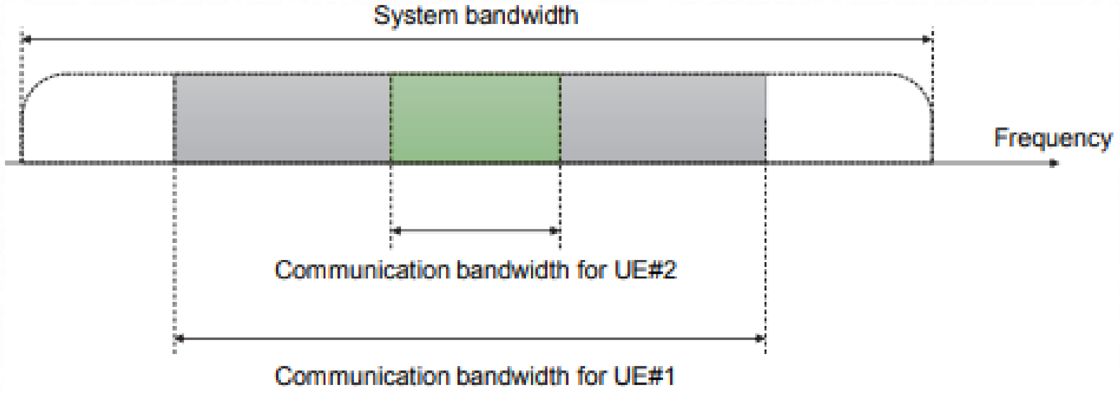


5G NR PHYSICAL LAYER – TRANSMISSION POWER

- Transmission power control takes into account the beamforming operations
  - The UE uses reference signals to compute the attenuation
  - For each transmitted/received beam the power control can be configured according to the channel attenuation
  - gNB configures the maximum transmission power for each group of cells
  - Power control in the UE depends on whether it is capable to dynamically divide the transmission power between LTE and NR

5G NR PHYSICAL LAYER – BWP

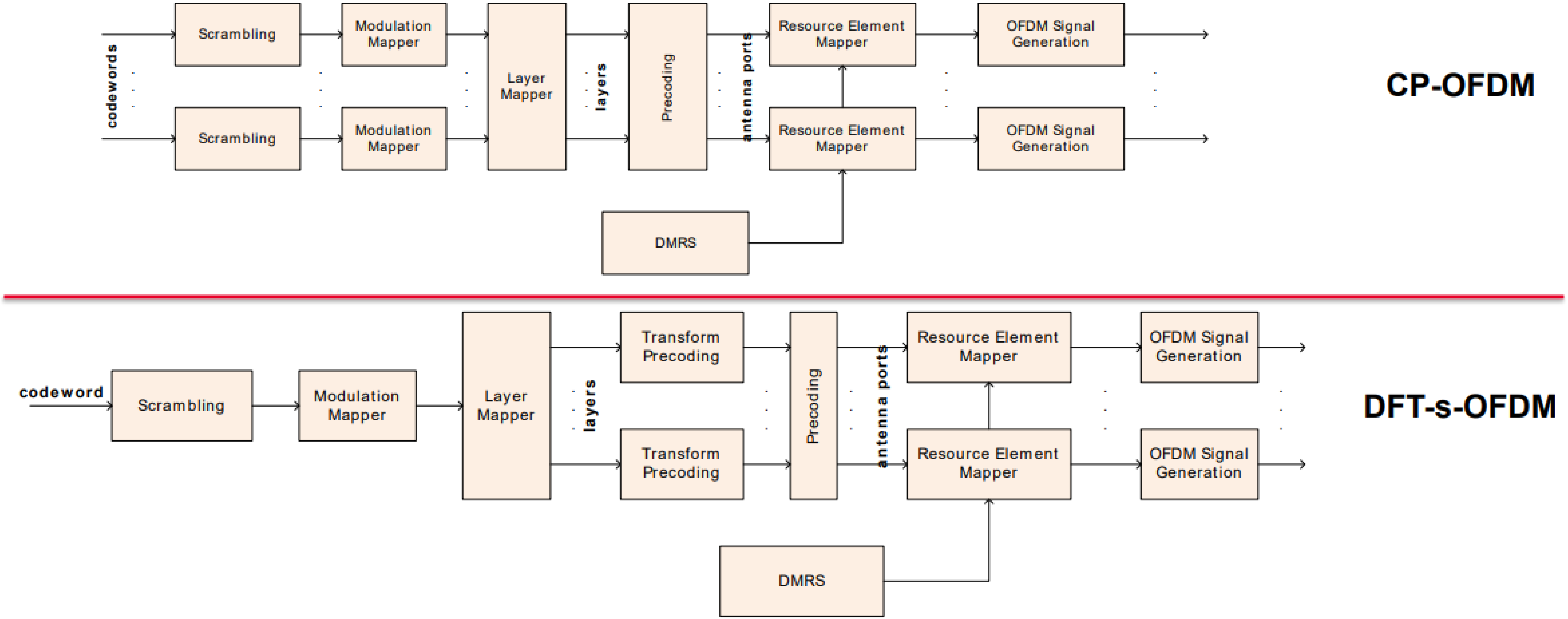
- NR carrier bandwidth is 100MHz at frequencies lower than 6GHz and 400MHz at higher frequencies
- The BWP (Bandwidth Parts) concept allows the UE to use smaller bandwidths than those used by the gNB
  - BWP configuration is set by the gNB
  - It can be also applied if there is no data to be transmitted to reduce power consumption



5G NR PHYSICAL LAYER – UL CHANNELS

- **PRACH** – Physical Random Access Channel
  - Used for initial access
- **PUSCH** – Physical Uplink Shared Channel
  - Carries user data
  - Modulated symbols are associated with code words
  - Allows CP-OFDM or DFTS-OFDM
  - Transmission schemes may or may not be based on the codebook
  - DMRS sequence is transmitted (Gold sequence for CP-OFDM, Zadoff-Chu sequence for DFTS-OFDM)

5G NR PHYSICAL LAYER – UL CHANNELS



5G NR PHYSICAL LAYER – UL CHANNELS

- **PUCCH** – Physical Uplink Control Channel
  - Carries UCI (Uplink Control Information), HARQ-ACK and/or SR
  - There are two types of PUCCH: short and long
  - For PUCCH 5 different formats are defined

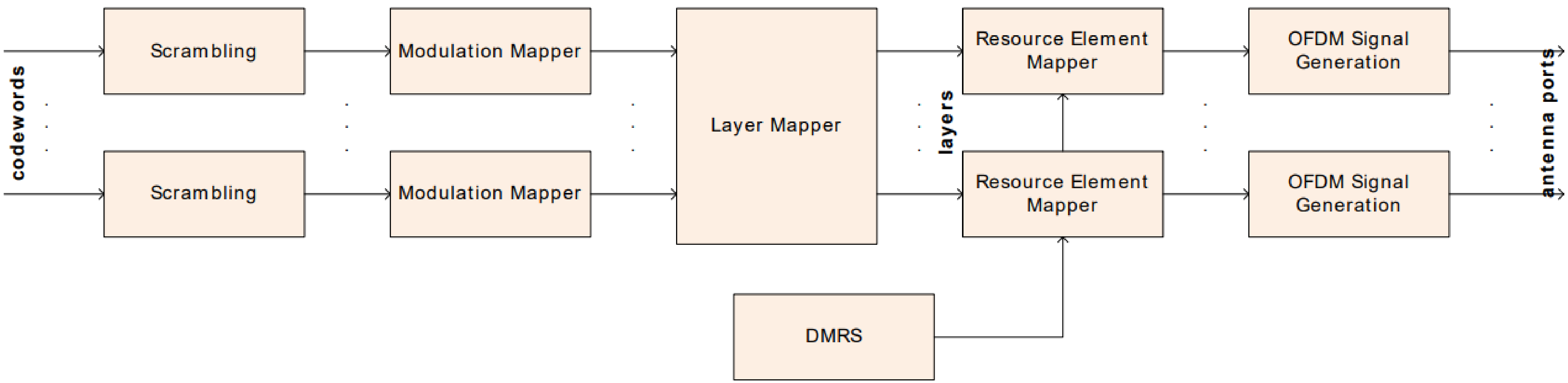
Format Types	Lengh of Symbols	Number of bits	Descriptions (based on 38.300 - 5.3.3)
Format 0	1~2	<= 2	Short PUCCH. with UE multiplexing in the same PRB. Based on sequence selection.
Format 1	4~14	<= 2	Long PUCCH. with multiplexing in the same PRB. time-multiplex the UCI and DMRS
Format 2	1~2	> 2	Short PUCCH. with no multiplexing in the same PRB. frequency multiplexes UCI and DMRS
Format 3	4~14	> 2	Long PUCCH. with moderate UCI payloads and with some multiplexing capacity in the same PRB. time-multiplex the UCI and DMRS
Format 4	4~14	> 2	Long PUCCH. with large UCI payloads and with no multiplexing capacity in the same PRB

5G NR PHYSICAL LAYER – DL CHANNELS

- **PBCH** – Physical Broadcast Channel
  - Used for initial access
- **PDCCH** – Physical Downlink Control Channel
  - Carries DCI (Downlink Control Information)
  - QPSK modulation is used
  - PDCCH consists of one or more Control Channel Elements (CCE)
    - 1 CCE consists of 6 REG (Resource Element Group)
    - 1 REG consists 1 resource block during 1 OFDM symbol
  - CORESET (Control Resource Set): is the basic allocation unit for PDCCH and consists of the corresponding REG and CCE

5G NR PHYSICAL LAYER – DL CHANNELS

- **PDSCH** – Physical Downlink Shared Channel
  - Carries user data



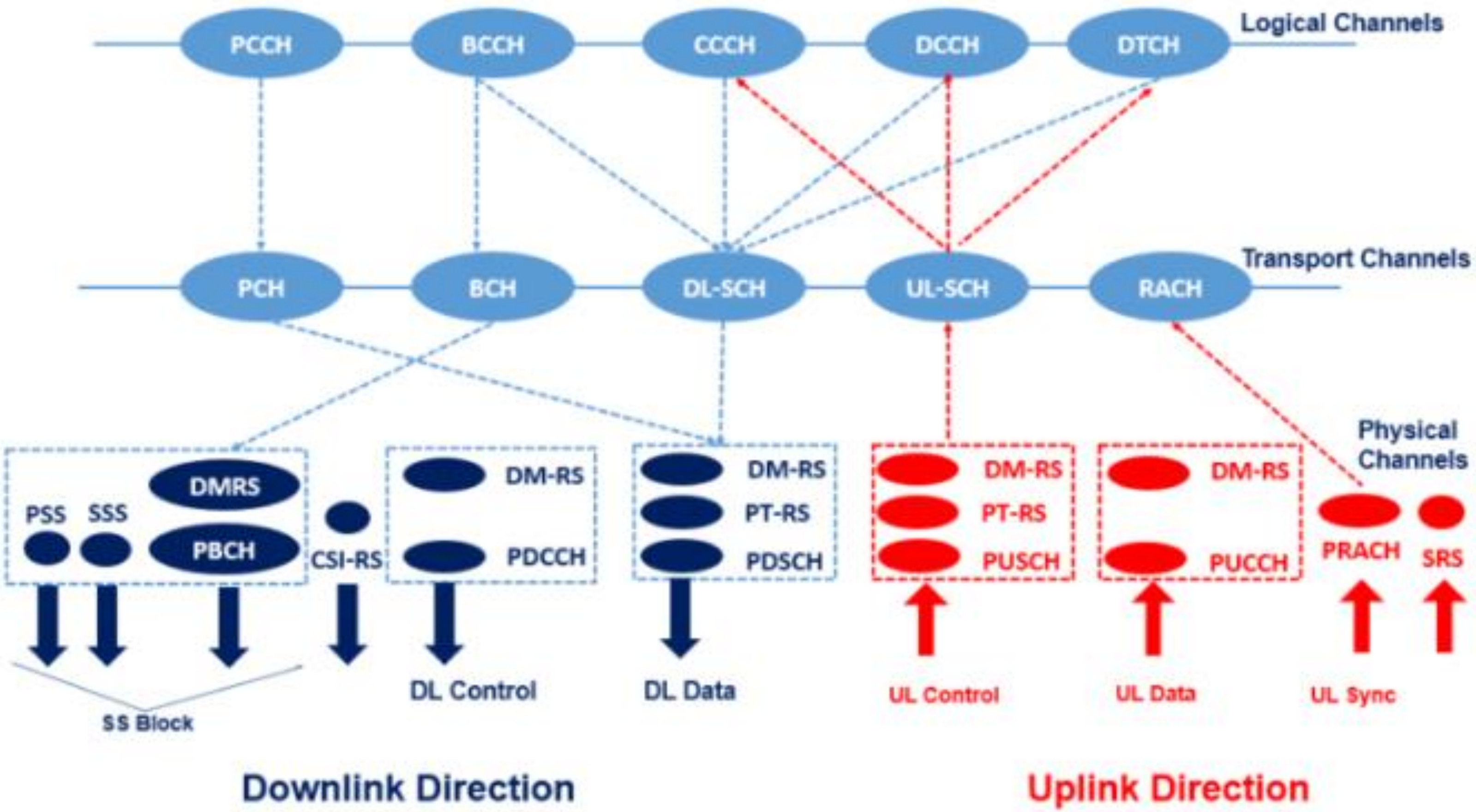
5G NR MAC

- Services provided by the MAC layer:
  - Mapping of logical and transport channels
  - MAC SDU multiplexing in transport blocks
    - SDUs belong to logical channels, while transport blocks to transport channels
  - MAC SDU demultiplexing from transport blocks
  - Reporting scheduling information
  - HARQ error correction
  - Prioritization of logical channels in UL

5G NR MAC – CHANNELS

- Transport channels:
  - **BCH** – Broadcast Channel
  - **DL-SCH** – Downlink Shared Channel
  - **PCH** – Paging Channel
  - **UL-SCH** – Uplink Shared Channel
  - **RACH** – Random Access Channel
- Logical channels:
  - **BCCH** – Broadcast Control Channel
  - **PCCH** – Paging Control Channel
  - **CCCH** – Common Control Channel
  - **DCCH** – Dedicated Control Channel
  - **DTCH** – Dedicated Traffic Channel

5G NR MAC – CHANNEL MAPPING



5G NR MAC – PROCEDURES

- Random-access procedure:
  - Gets the initial UE transmission grant
  - Helps synchronization with the gNB
  - Includes: initialization of random-access, selection of resources, transmission of the random-access preamble, reception of the response
- DL-SCH data transfer
  - Performs the operations necessary for DL data transmission
- UL-SCH data transfer
  - Performs the operations necessary for UL data transmission
- SR (Scheduling Request)
  - It is used by the UE to send a request for a UL grant to the gNB

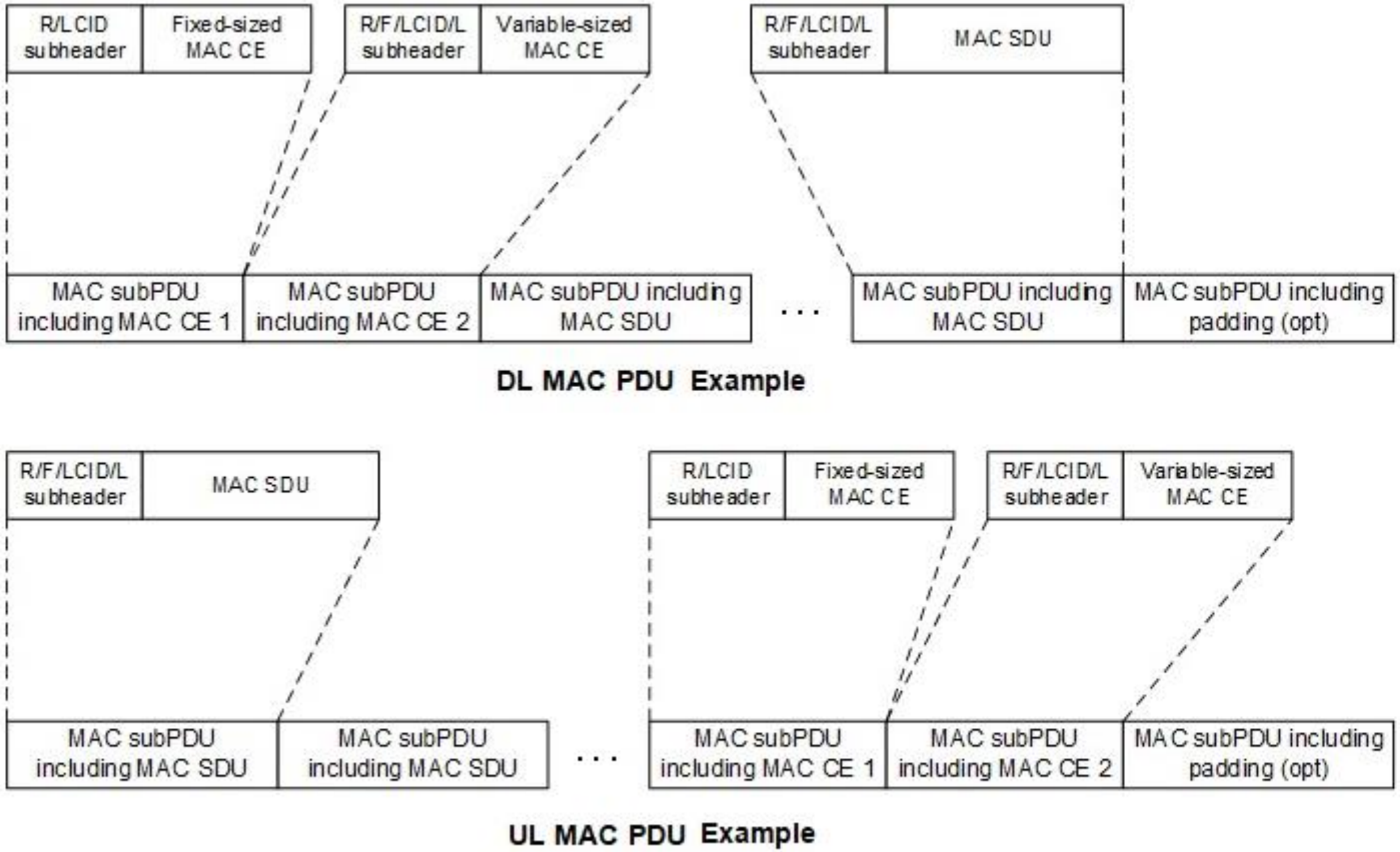
5G NR MAC – PROCEDURES

- PCH reception
  - Monitors paging messages
- BCH reception
  - Carries basic information about 5G NR cell
- DRX (Discontinous Reception)
  - Allows PDCCH monitoring
- Other procedures:
  - Transmission/reception without dynamic scheduling, BWP operations, MAC reconfiguration, data inactivity monitoring, erroneous protocol data processing, etc.

5G NR MAC – MAC PDU

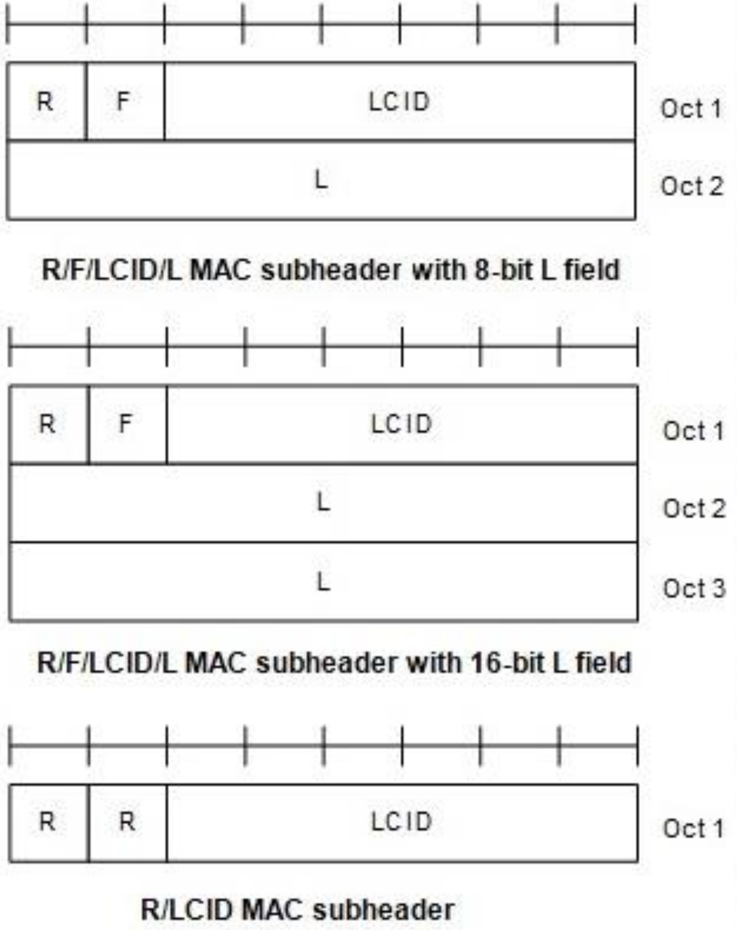
- A MAC PDU consists of one or more sub-PDUs
- Each sub-PDU has one of the following fields:
  - Sub-header MAC
  - Sub-header MAC and MAC SDU
  - Sub-header MAC and MAC CE (Control Element)
  - Sub-header MAC and padding
- MAC SDUs have variable dimensions
  - Each MAC sub-header corresponds to a MAC SDU, MAC CE or padding

5G NR MAC – MAC PDU



5G NR MAC – MAC PDU

- The MAC sub-header contains the fields:
  - LCID: Logical Channel ID
    - Identifies the appropriate MAC SDU logical channel
    - Length: 6 bits
  - L: is the length field of the MAC SDU
  - F: the length of field L
    - Value 0 → 8-bit L field
    - Value 1 → 16-bit L field
  - R: reserved, set to 0

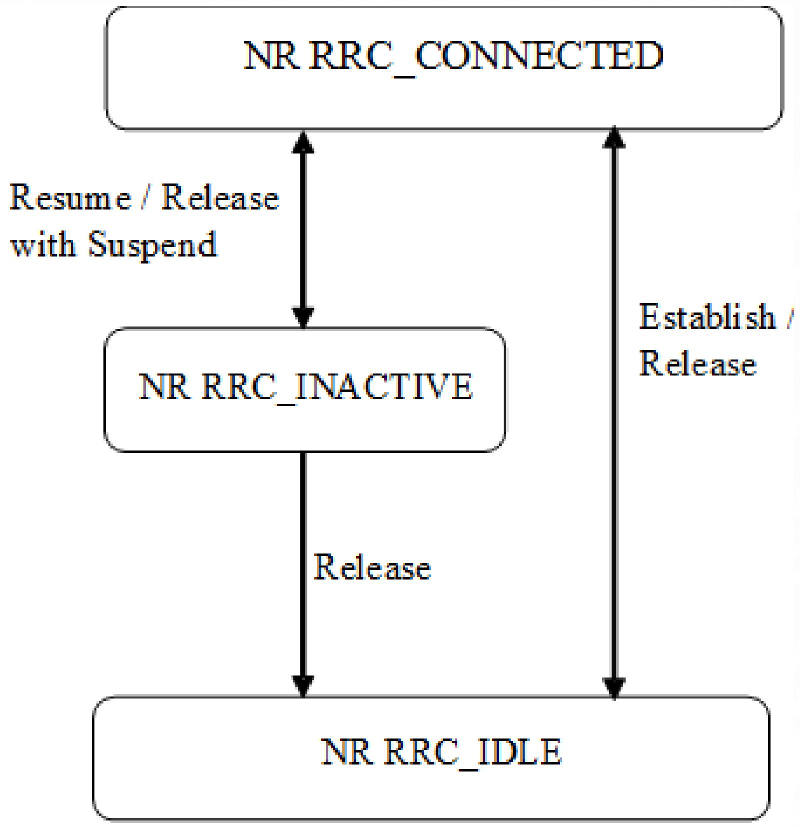


RADIO RESOURCE CONTROL

- RRC (Radio Resource Control) – is responsible of managing gNB-UE signaling messages
- 5G RRC functions:
  - Establishing, restoring and disconnecting the RRC connection
  - Transfer of SIB (System Information Block) at UE request
  - Suspend/resume RRC connection
  - Handover signaling: measurements, handover commands
  - RLF (Radio Link Failure) management

RADIO RESOURCE CONTROL

- In 5G NR a new state, RRC Inactive, is added compared to LTE
- RRC Connected
  - The UE stores the context
  - Network-controlled measurements and handover
  - DRX configured by the gNB
  - Support for carrier aggregation and dual connection
  - Feedback about the CSI



RADIO RESOURCE CONTROL

- RRC Inactive
  - It serves to minimize the time required for the UE transition to the Connected state from other states
  - Contributes to the UE battery lifetime increase
  - The UE and the gNB store the context
  - Support for cell reselection
  - Paging messages monitoring
  - SIB acquisition or SIB request from the gNB
- RRC Idle
  - Cell reselection
  - Paging
  - SIB acquisition or SIB request from the gNB