# Νέες και Παλιές Προκλήσεις στα Δίκτυα Κινητών Επικοινωνιών

ΤΜΉΜΑ ΠΛΗΡΟΦΟΡΙΚΉΣ ΚΑΙ ΤΗΛΕΠΙΚΟΙΝΩΝΊΩΝ, ΕΚΠΑ

ΔΡ. ΔΗΜΗΤΡΙΟΣ ΤΣΟΛΚΑΣ & ΚΑΘ. ΛΑΖΑΡΟΣ ΜΕΡΑΚΟΣ

# Takeaways (Lecture 3)

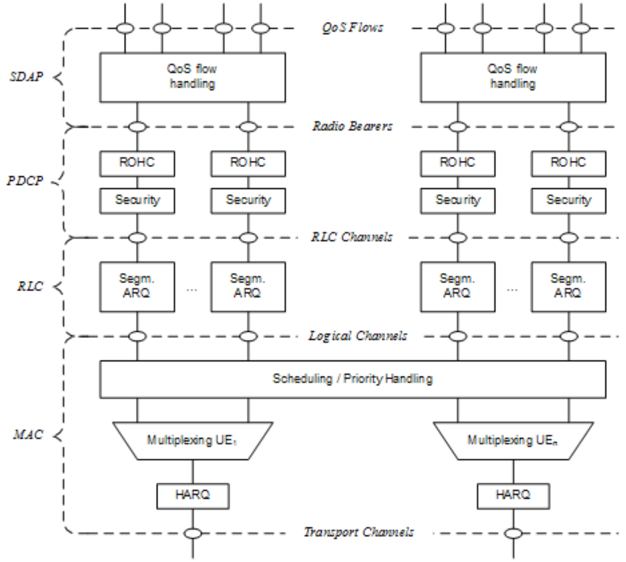
- API exposure is performed with CAPIF support
- QoS Enforcement
  - QFI concept
  - Network slice selection during the PDU session set up
- 5G New Radio (NR)
  - Deployment options: SA / NSA
  - SDAP protocol is added to realize filtering of 5G quality flows to DRB
  - The protocols stack is Split to allow central management of radio flows (concept of functional split)

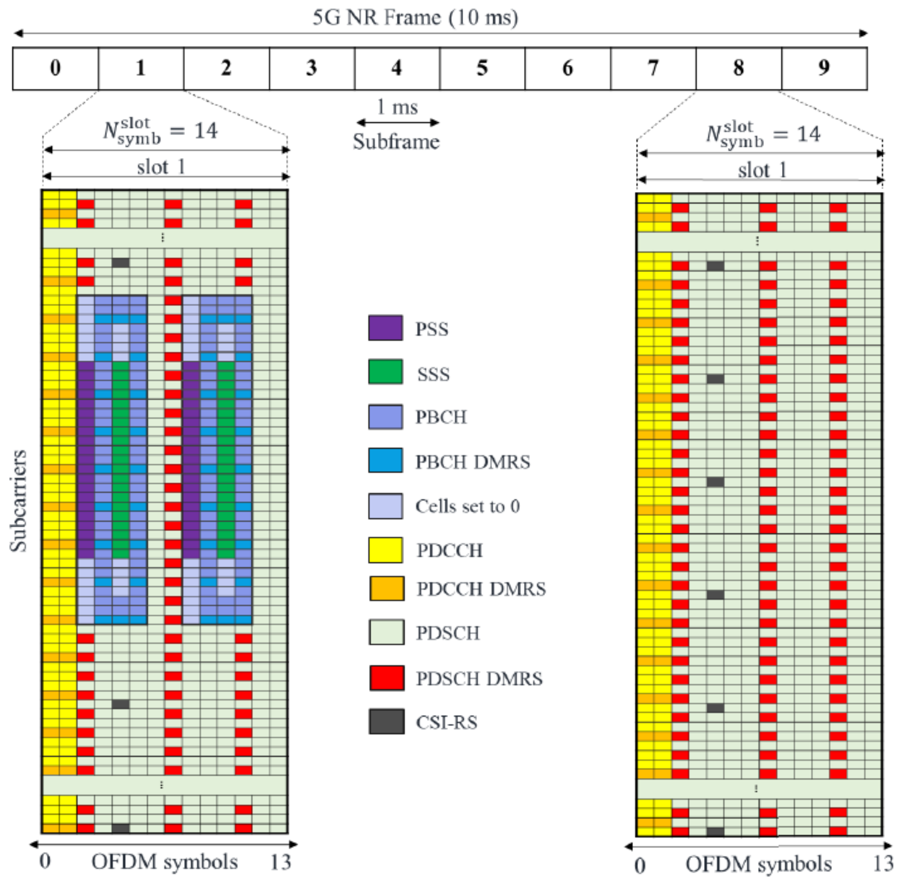
# Targets of Lecture 4

- 5G New Radio (NR)
  - Channels
  - Numerology
  - Key Performance Indicators (KPIs)

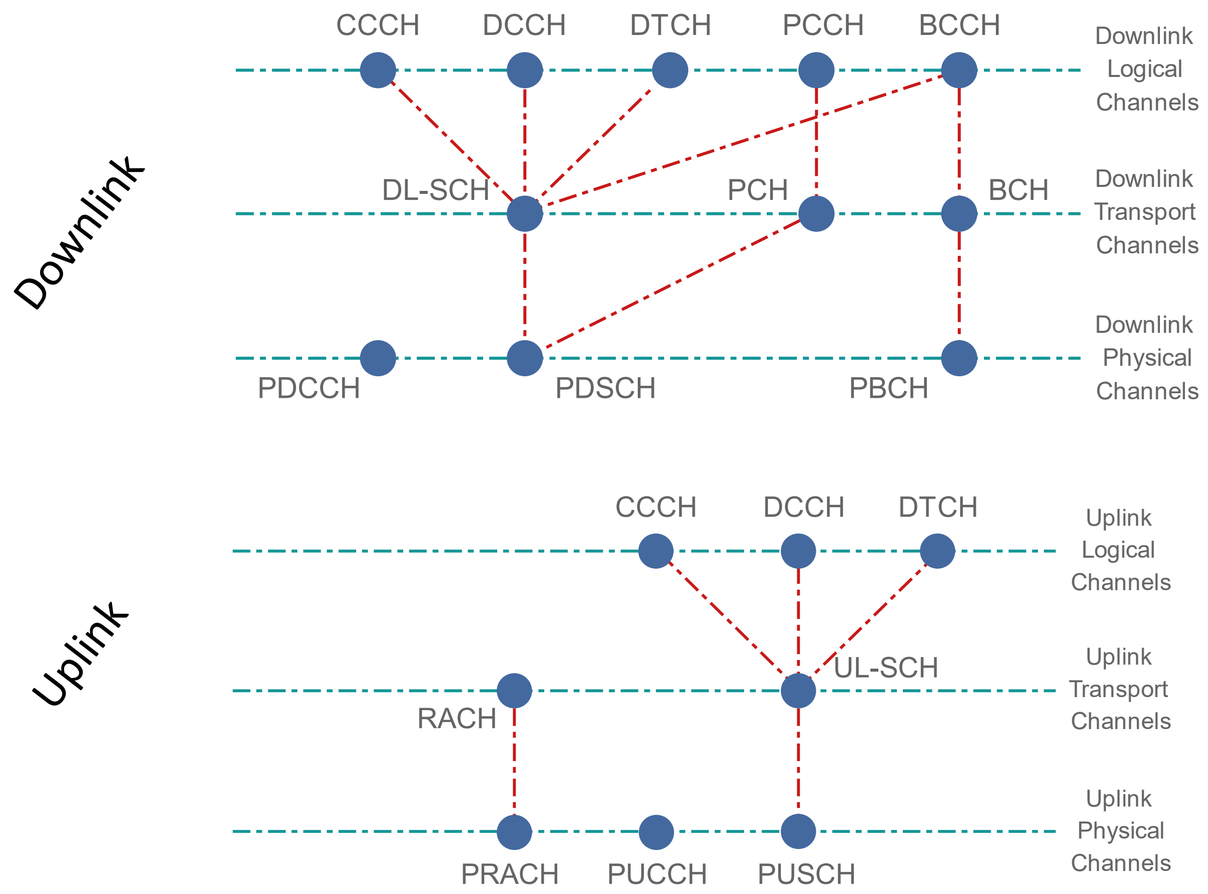
# 5G-New Radio

Physical layer numerology



# 5G NR channels

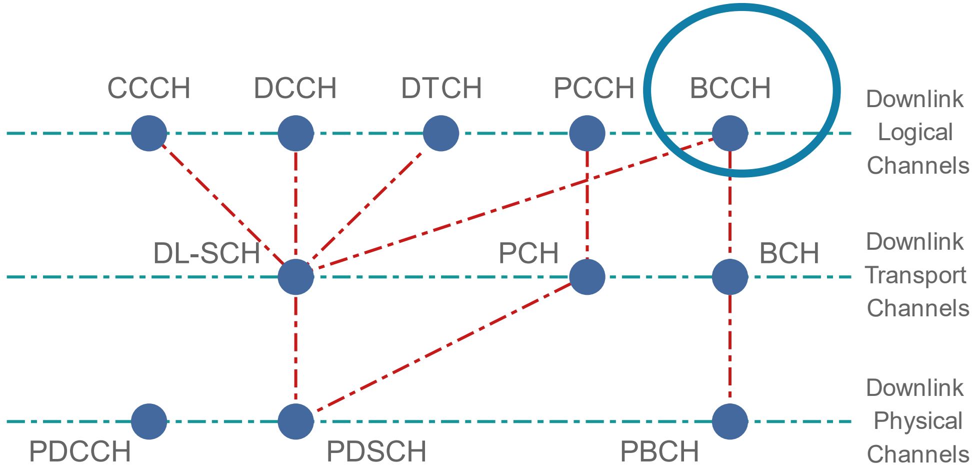


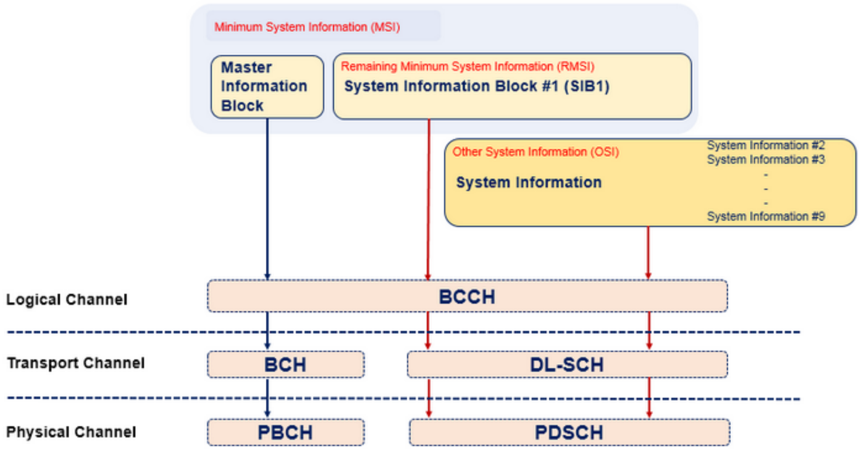

- ***Logical Channels***: Offered by MAC to RLC. *Control channels* carry CP packets. *Traffic channels* carry UP packets. Each logical channel maps to an RLC channel coming from RLC layer.
- ***Transport Channels***: Offered by PHY to MAC. MAC layer multiplexes one or more logical channels to a transport channel. Whereas logical channels describe *what is carried*, transport channels describe *how they're carried*.
- ***Physical Channels***: Channels that carry information on the air interface. Transport channels map to physical channels. There are also a few *standalone* physical channels that don't carry higher-layer information.

# Logical Channels

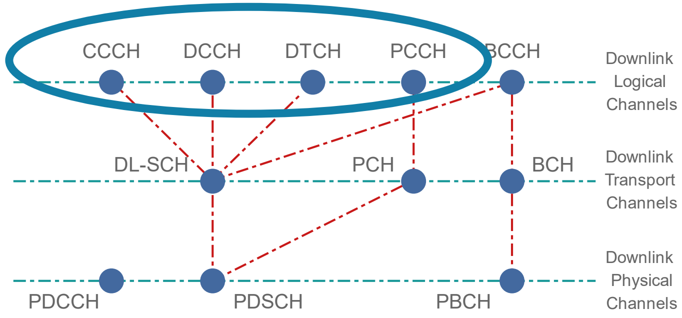
**Broadcast Control Channel, BCCH**: The BCCH is used within the downlink, and it is used for sending broadcast style information to the user equipments within that cell. The system information transmitted by the 5G NR BCCH is divided into different blocks:

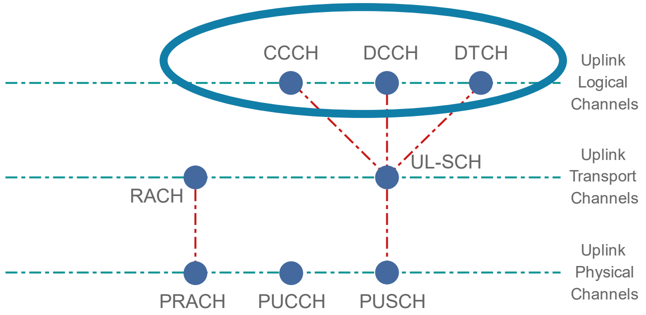
- **Master Information Block, MIB**: There is one MIB and this is mapped onto the BCH transport channel and then to the PBCH physical channel (frame information, assists for SIB decoding..)
- **System Information Block, SIB:** There are several system information blocks, SIBs. These are mapped onto the DL-SCH transport channel and then onto the PDSCH physical channel (cell specific information, cell selection priority..)



# Logical Channels



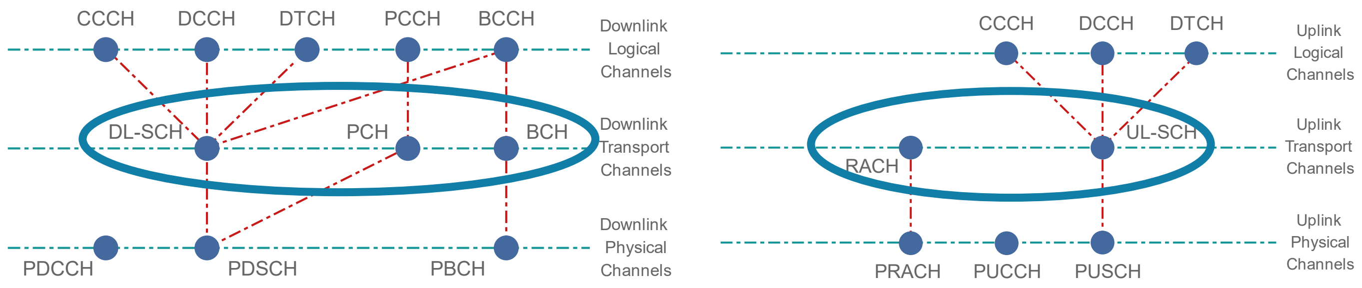

**Paging Control Channel, PCCH**: This is a **Downlink** channel. It is used to page the UEs whose location at cell level is not known to the network. As a result, the paging message needs to be transmitted in multiple cells. The PCCH is mapped to the PCH transport channel and then to the PDSCH physical channel.

**Common Control Channel, CCCH**: This 5G channel is used on both the downlink and uplink for transmitting control information to and from the user equipment or mobiles. The channel is used for **initial access**, i.e. those mobiles that do not have a radio resource control, RRC connection.

**Dedicated Control Channel, DCCH**: The DCCH is used within the uplink and downlink to carry dedicated control information between the UE or mobile and the network. It is used by the UE and the network after a radio resource control, RRC connection has been established.

**Dedicated Traffic Channel, DTCH**: This 5G channel is present in both the uplink and downlink. It is dedicated to one UE and is used for carrying user information to and from a specific UE and the network.

# Transport Channels




- **Broadcast Channel, BCH:** The BCH 5G channel is used in the downlink only for transmitting the BCCH system information and specifically the Master Information Block, MIB, information. In order that the data can be utilised, it has a specific format.

- **Paging Channel, PCH:** The PCH is used for carrying paging information from the PCCH logical channel. The PCH supports **discontinuous reception, DRX**, to enable the UE to save battery power by waking up at a specific time to receive the PCH. In order that the PCH is received by all mobiles / UEs in the cell, the PCH must be broadcast over the entire cell as a single message, or where beam forming is used, this can be done using several different PCH instances.

- **Downlink Shared Channel, DL-SCH:** As the name indicates, this is a downlink only channel. It is the main transport channel used for transmitting downlink data and it supports all the key 5G NR features. These include: dynamic rate adaptation; HARQ, channel aware scheduling, and spatial multiplexing. The DL-SCH is also used for transmitting some parts of the BCCH system information, specifically the SIB. Each UE has a DL-SCH for each cell it is connected to.

- **Uplink Shared Channel, UL-SCH:** This is the uplink counterpart to the DLSCH that is, the uplink transport channel used for transmission of uplink data.

- **Random-Access Channel, RACH:** The RACH is a transport channel, which carries the random access preamble which is used to overcome the message collisions that can occur when UEs access the system simultaneously.

# Physical DL Channels

- **Physical Broadcast Channel (PBCH):** transmits the static part of the system information, known as the Master Information Block (MIB), to all UEs requiring to access the network
  - The *PBCH uses **QPSK** modulation* and it transmits a cell specific demodulation reference signal – DMRS pattern for beamforming

- **Physical Downlink Control Channel (PDCCH):** specifies the data scheduling and allocation by means of Downlink Control Information (DCI) for every User Equipment (UE) and to configure other aspects such as HARQ retransmissions, link adaptation and MIMO;
  - The *PDCCH uses QPSK as its modulation* format and polar coding as the coding scheme

- **Physical Downlink Shared Channel (PDSCH)** that transmits the data content to UEs
  - The *PDSCH uses an adaptive modulation* format dependent upon the link conditions, i.e., signal to noise ratio.

*Four types of reference signals:*

- **Primary and Secondary Synchronization Signals (PSS, SSS),** needed by UEs to access the network and, more specifically, to receive radio frame timing information and cell ID;
- **Demodulation Reference Signals (DMRS**), used for channel estimation to retrieve data in PBCH, PDCCH and PDSCH;
- **Phase Tracking Reference Signals (PT-RS)** to estimate the phase noise in the PDSCH (only used at FR2);
- **Channel State Information Reference Signals (CSI-RS),** used to provide CSI needed for link adaptation

# QPSK ?

(a) μη διαμορφωμένο (ψηφιακό) σήμα

(b) διαμόρφωση εύρους (AM)

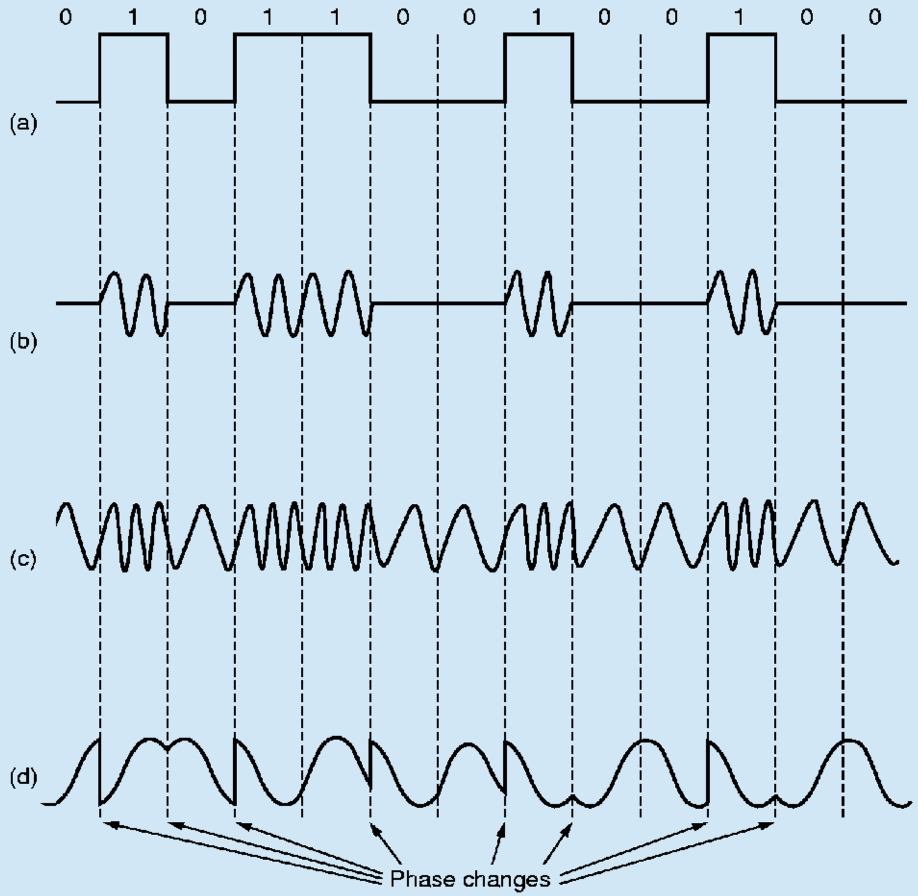
(c) διαμόρφωση συχνότητας (FM)

- FSK (frequency shift keying)
  - τεχνική για ψηφιακά σήματα

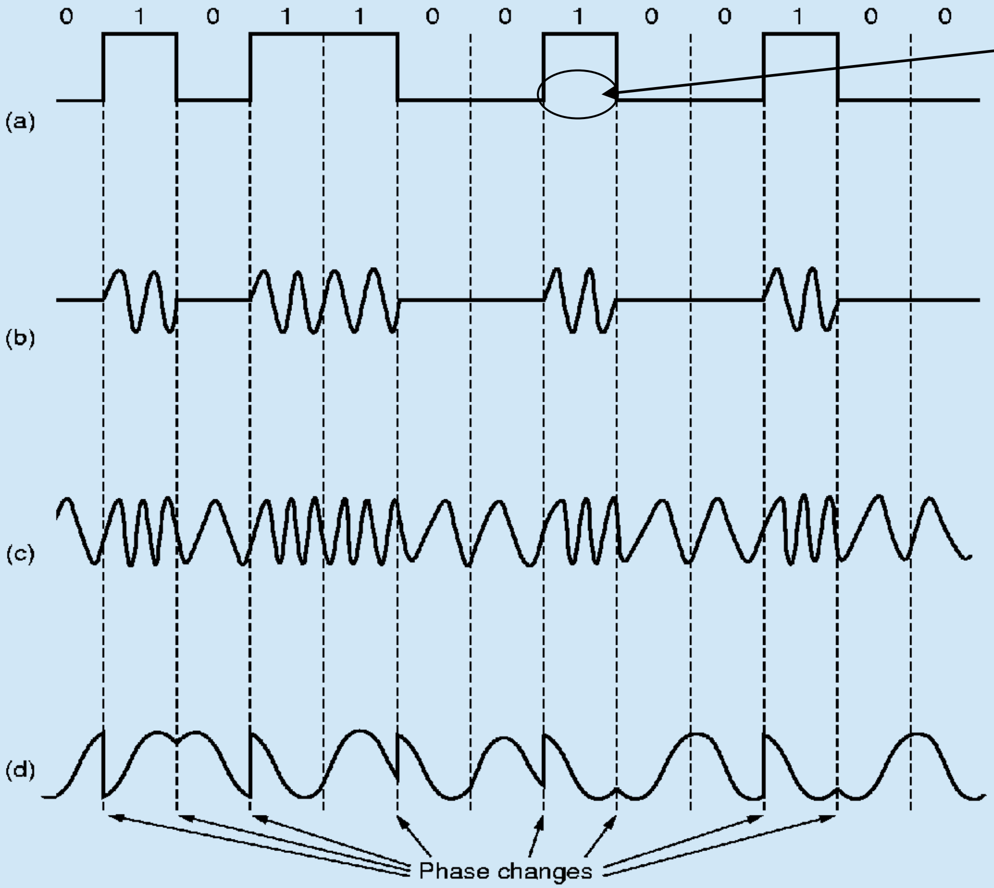
(d) διαμόρφωση φάσης (PM)

- *PSK* (phase shift keying)
  - τεχνική για ψηφιακά σήματα

*f* : φέρουσα συχνότητα



# QPSK ?




**Sample**

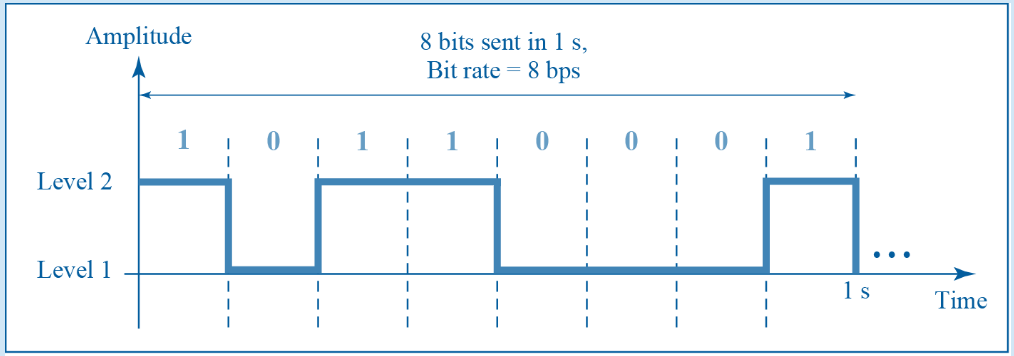
- Sample Rate=Samples/sec (Baud Rate)
- Κατά τη διάρκεια ενός Sample στέλνεται ένα Symbol

**Symbol**

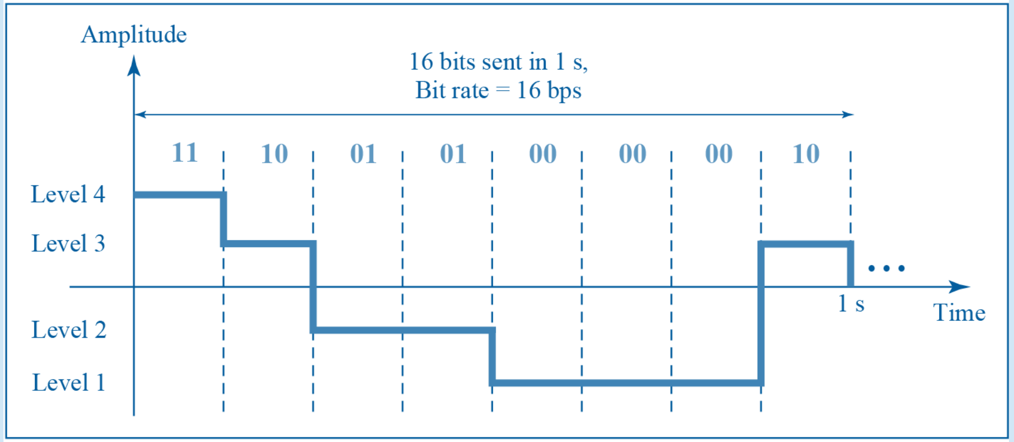
- Symbol= Ελάχιστο τμήμα που φέρει πληροφορία
- Πως θα αυξάνατε το ρυθμό μετάδοσης?
  - Αύξηση των διαθέσιμων Symbols

(περισσότερα symbols = περισσότερες στάθμες στο AM)

# QPSK ?



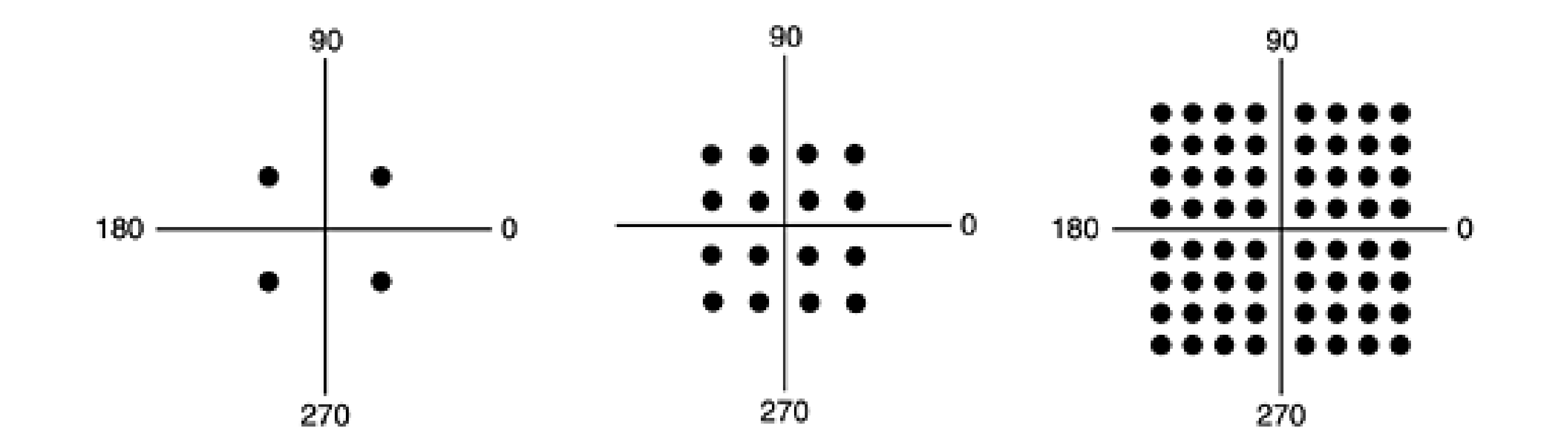

a. A digital signal with two levels




b. A digital signal with four levels

# QPSK ?

QPSK (Quadrature Phase Shift Keying) = 4 phase shifts, 1 amplitude level, 2 bits/symbol
QAM-16 = 4 phase shifts, 4 amplitude levels, 4 bits/symbol
QAM-64 = 4 phase shifts, 16 amplitude levels, 6 bits/symbol




QPSK QAM-16 QAM-64

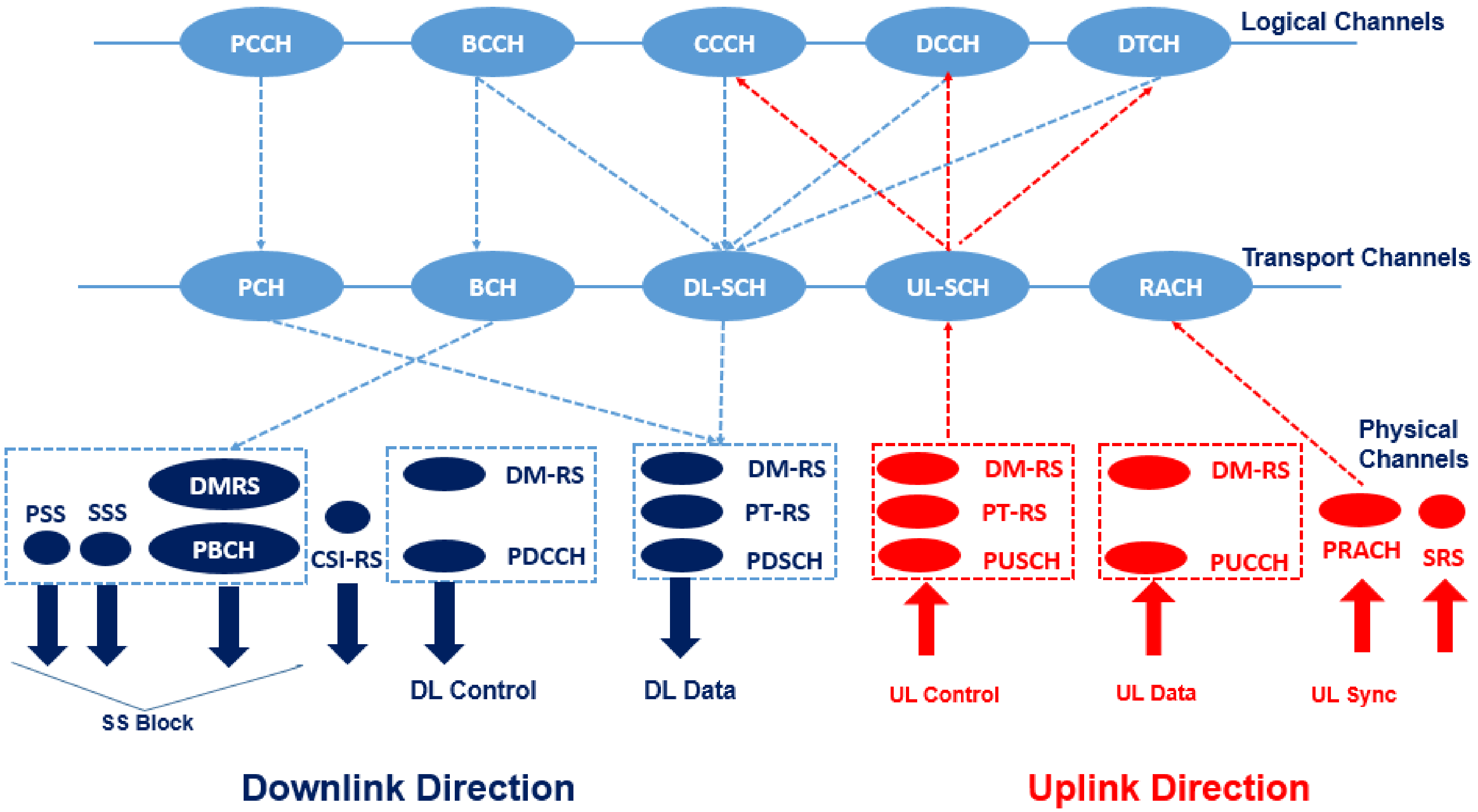
# Physical UL Channels

- **Physical Random Access Channel (PRACH),** used by the UE to request initial access as well as during the beam management process;
- **Physical Uplink Control Channel (PUCCH),** which carries Uplink Control Information (UCI) and contains different information such as CSI, HARQ or scheduling requests;
- **Physical Uplink Shared Channel (PUSCH),** which transmits the data content to the gNB.

*UL reference signals are used:*

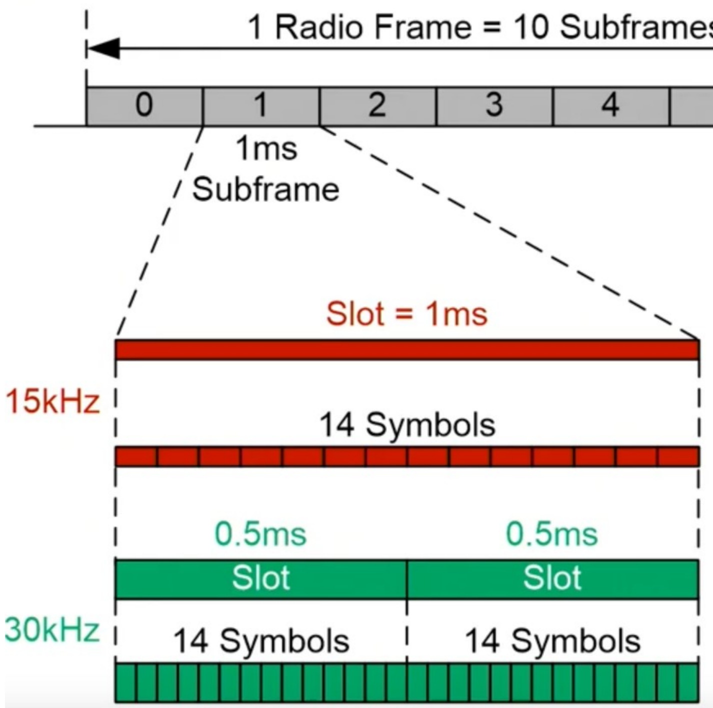
- **DMRS**, **PT-RS** and Sounding Reference Signals (**SRS**), equivalent to CSI-RS in the DL

# Mapping among logical/transport/physical channels



# 5G NR structure

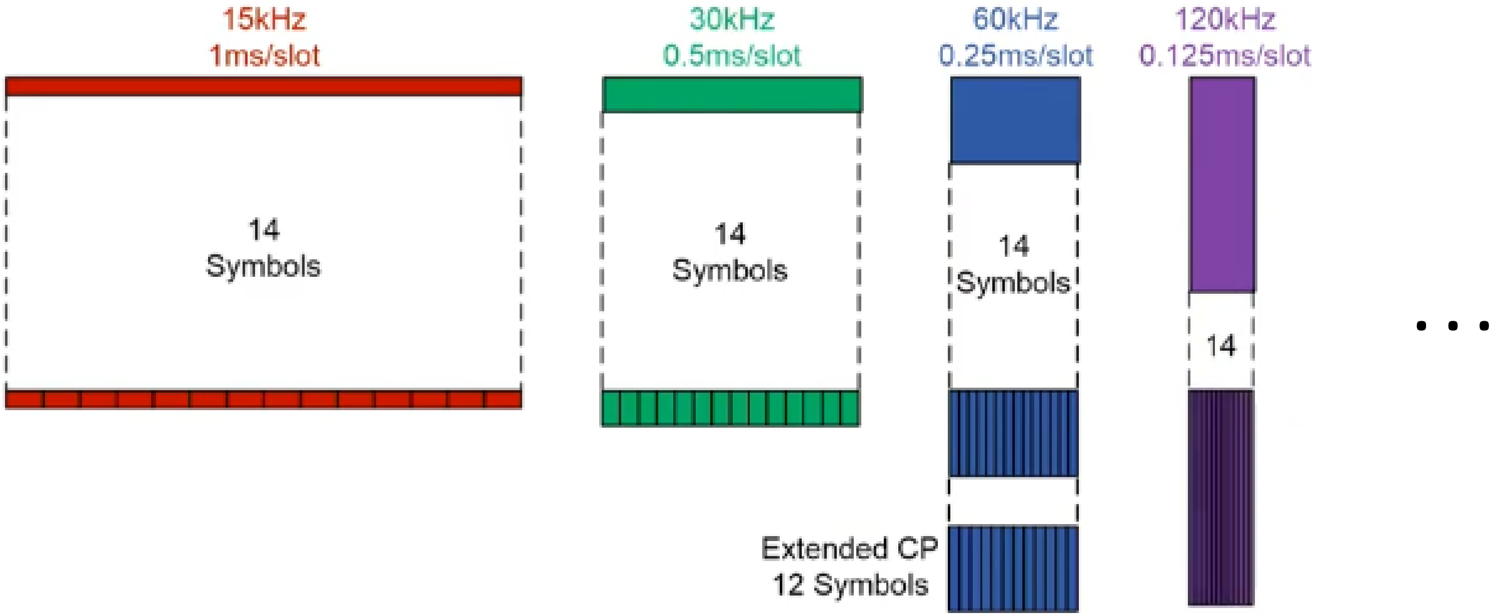
Frames / subframes / slots/ OFDM symbols




| $\mu$ | $N_{symb}^{slot}$ | $N_{slot}^{frame,\mu}$ | $N_{slot}^{subframe,\mu}$ |
|---|---|---|---|
| 0 | 14 | 10 | 1 |
| 1 | 14 | 20 | 2 |
| 2 | 12/14 | 40 | 4 |
| 3 | 14 | 80 | 8 |
| 4 | 14 | 160 | 16 |

# 5G NR structure

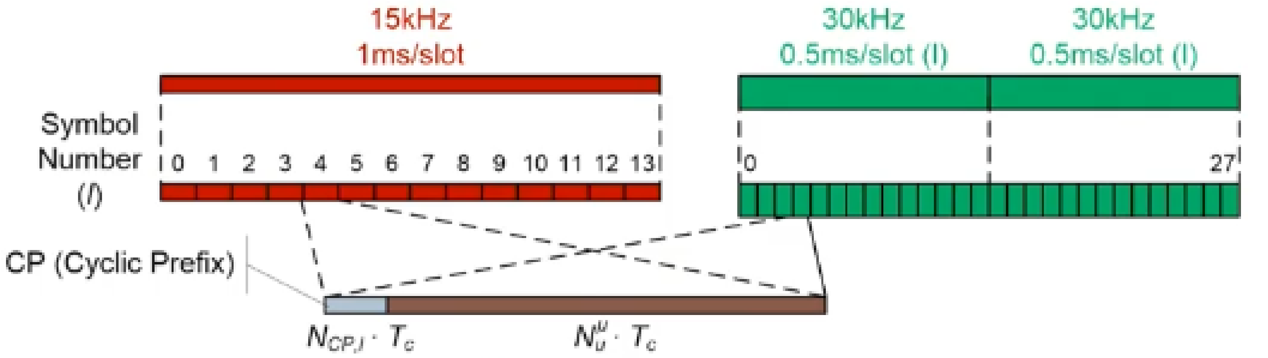
OFDM symbols per slot (with CP normal and extended)



# 5G NR structure

OFDM symbols per slot (with CP normal and extended)

Time units $T_c = 1/(\Delta f_{max} \cdot N_f)$ where $\Delta f_{max} = 480 \cdot 10^3$ Hz and $N_f = 4096$.




*$T_c$ NR Time Unit*
*$= 1/(\Delta f_{max} \cdot N_f) = 0.5086263$ns*

Where: $\Delta f_{max} = 480 \cdot 10^3$ Hz and $N_f = 4096$

$\kappa = T_s/T_c = 64$

$N_u^\mu = 2048\kappa \cdot 2^{-\mu}$

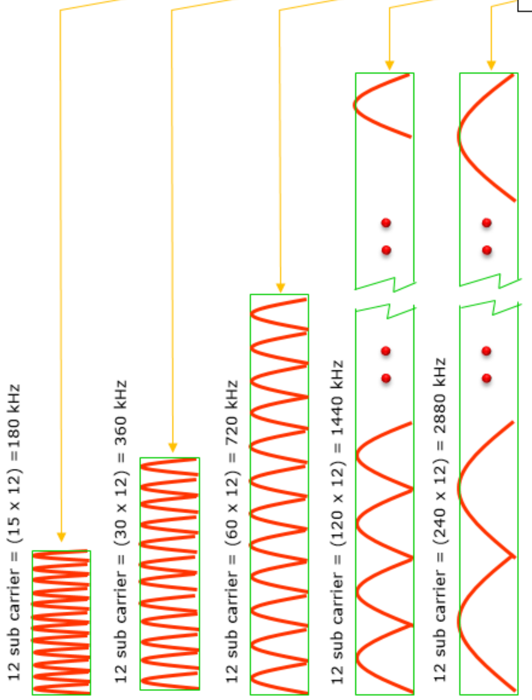
$$N_{CP,l}^{\mu} = \begin{cases} 512\kappa \cdot 2^{-\mu} & \text{Extended CP} \\ 144\kappa \cdot 2^{-\mu} + 16\kappa & \text{Normal CP, } l = 0 \text{ or } l = 7 \cdot 2^{\mu} \\ 144\kappa \cdot 2^{-\mu} & \text{Normal CP, } l \neq 0 \text{ or } l \neq 7 \cdot 2^{\mu} \end{cases}$$

| Parameters | 5G | LTE | LTE-A (5 CCs) | 802.11ac | |
|---|---|---|---|---|---|
| Carrier Bandwidth [Mhz] | 200 | 20 | 100 | 20 | 160 |
| Subcarrier spacing [kHz] | 60 | 15 | 15 | 312.5 | 312.5 |
| Symbol Length [us] | 16.67 | 66.67 | 66.67 | 4 | 4 |
| FFT size | 4096 | 2048 | 5 x 2048 | 64 | 512 |
| Effective subcarriers | 3300 | 1200 | 6000 | 56 | 484 |
| TTI duration [ms] | 0.25 | 1 | 1 | variable | variable |
| Number of GPs | 3 | 2 | 2 | none | none |
| Number of symbols per frame | 14 | 14 | 14 | n.a | n.a |
| CP duration [us] | 1 | 4.7 (short) | 4.7 (short) | 0.4 (short) | 0.4 (short) |
| GAP duration [us] | 0.89 | 66.67 (min) | 66.67 (min) | none | none |
| Overhead (CP+GAP) [%] | 6.67 | 7.25 | 7.25 | 11 | 11 |
| HARQ Process | 4 | up to 15 | up to 75 | none | none |

# 5G NR structure

38.211 Table 4.2-1

| $\mu$ | $\Delta f = 2^{\mu} \cdot 15$ [kHz] | Cyclic prefix |
|---|---|---|
| 0 | 15 | Normal |
| 1 | 30 | Normal |
| 2 | 60 | Normal, Extended |
| 3 | 120 | Normal |
| 4 | 240 | Normal |



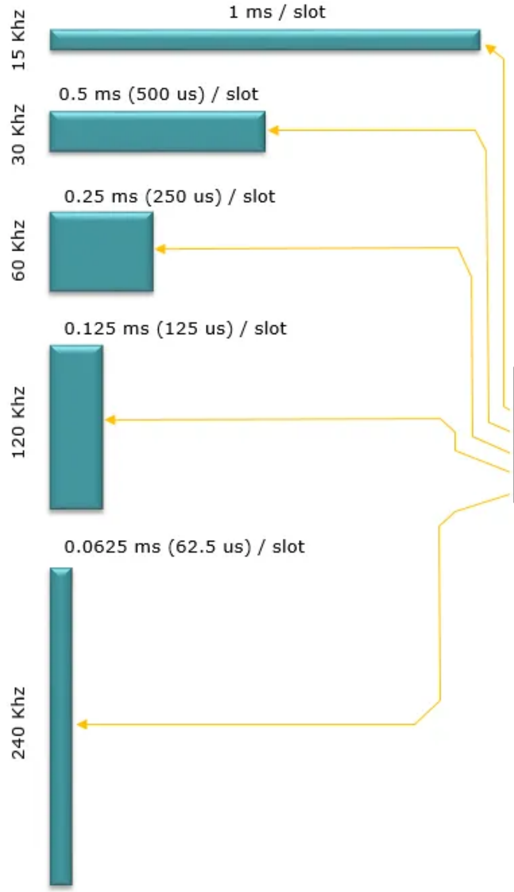

The NR subcarrier spacing is defined as 15 x $2^n$ kHz, where n can take positive values at the moment

- n = 0, 15 x $2^0$ = 15 kHz
- n = 1, 15 x $2^1$ = 30 kHz
- n = 2, 15 x $2^2$ = 60 kHz
- n = 3, 15 x $2^3$ = 120 kHz
- n = 4, 15 x $2^4$ = 240 kHz

In future n can take both positive and negative values

- n = -1, 15 x $2^{-1}$ = 7.5 kHz
- n = -2, 15 x $2^{-2}$ = 3.75 kHz → same as LTE NB-IoT subcarrier spacing

NOTE : In LTE, there is only type of subcarrier spacing (15 Khz), whereas in NR multiple types of subcarrier spacing are available. This is the biggest difference between LTE and NR numerology




< 38.211 – Table 4.3.2-1 >

| $\mu$ | $N_{symb}^{slot}$ | $N_{slot}^{frame,\mu}$ | $N_{slot}^{subframe,\mu}$ |
|---|---|---|---|
| 0 | 14 | 10 | 1 |
| 1 | 14 | 20 | 2 |
| 2 | 14 | 40 | 4 |
| 3 | 14 | 80 | 8 |
| 4 | 14 | 160 | 16 |

**Mini-slot** occupies 2, 4 or 7 OFDM symbols. It enables non-slot based scheduling. It is minimum scheduling unit used in 5G NR. They can be positioned asynchronously with respect to the beginning of a standard slot.

# 5G NR structure

- Resource block = 12 subcarriers
- Resource Element = 1 subcarrier x 1 OFDM symbol

38.211 Table 4.2-1

| $\mu$ | $\Delta f = 2^{\mu} \cdot 15$ [kHz] | Cyclic prefix |
|---|---|---|
| 0 | 15 | Normal |
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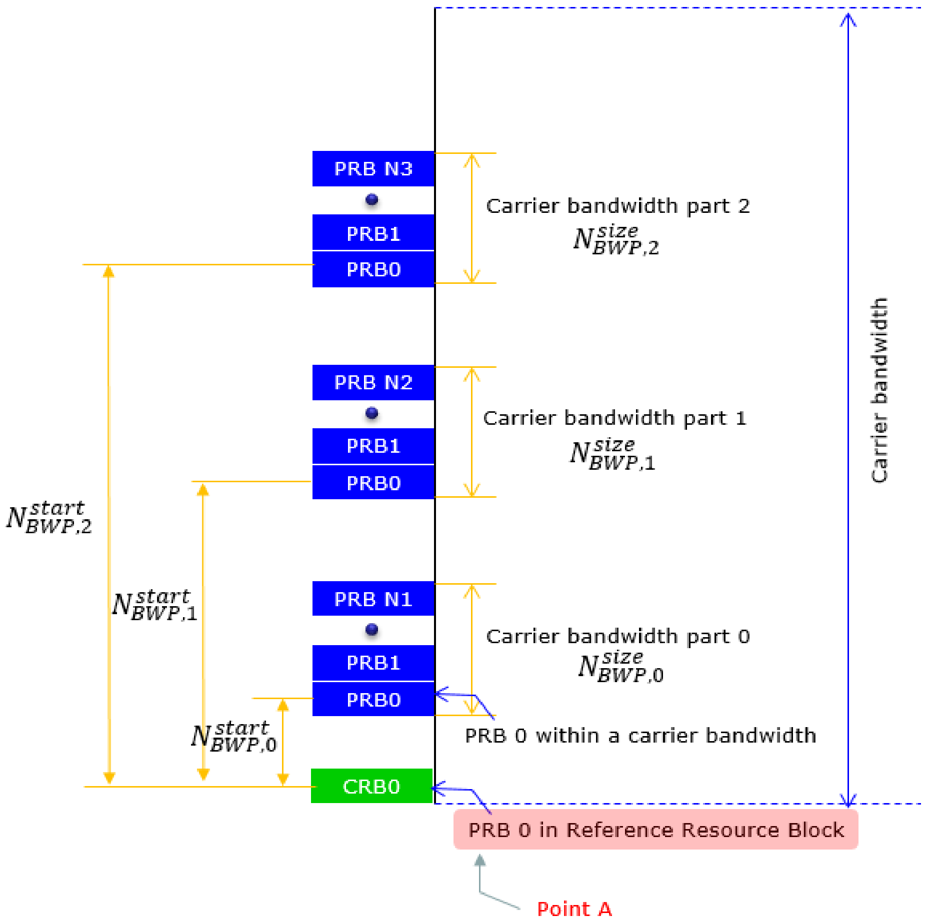
| 2 | 60 | Normal, Extended |
| 3 | 120 | Normal |
| 4 | 240 | Normal |

- Bandwidth parts (BWP)



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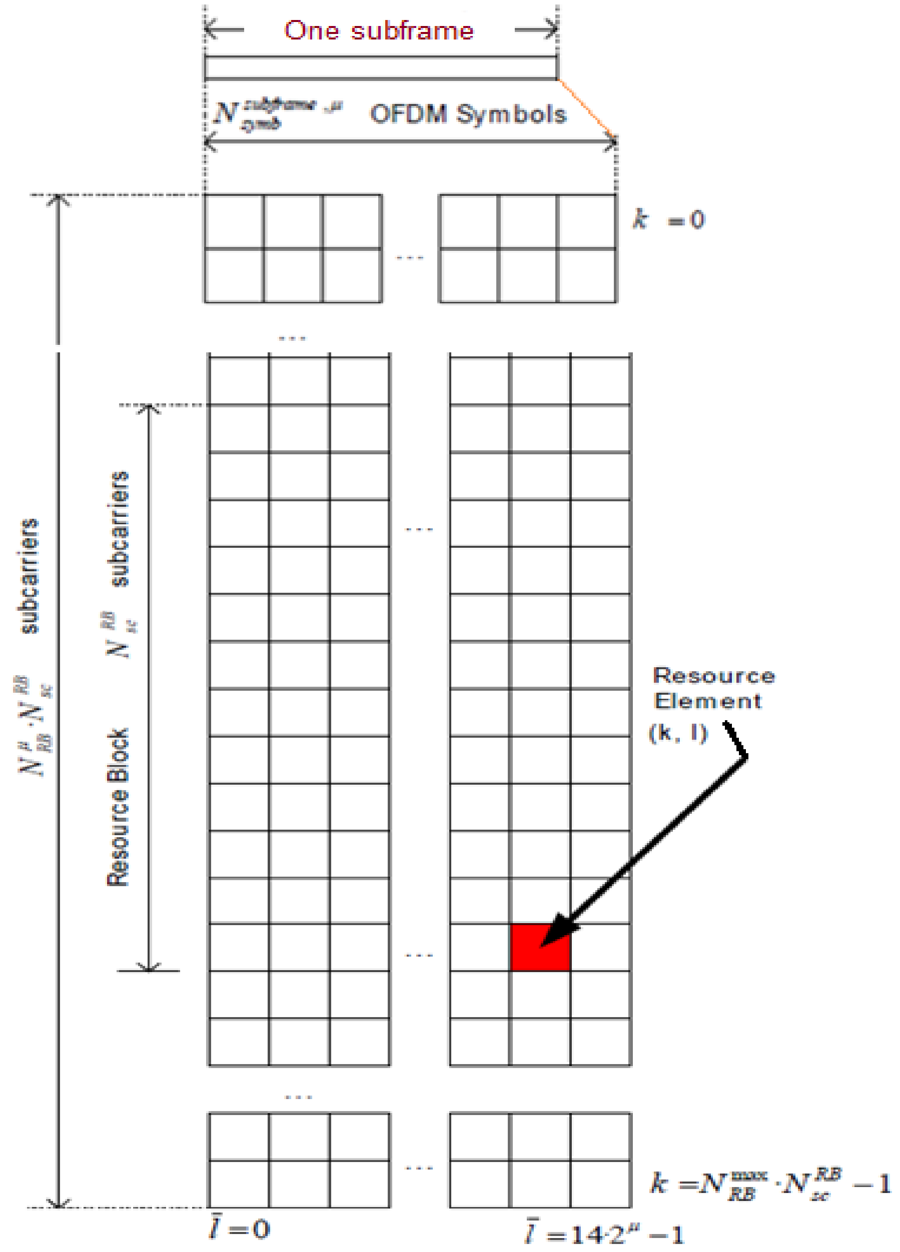
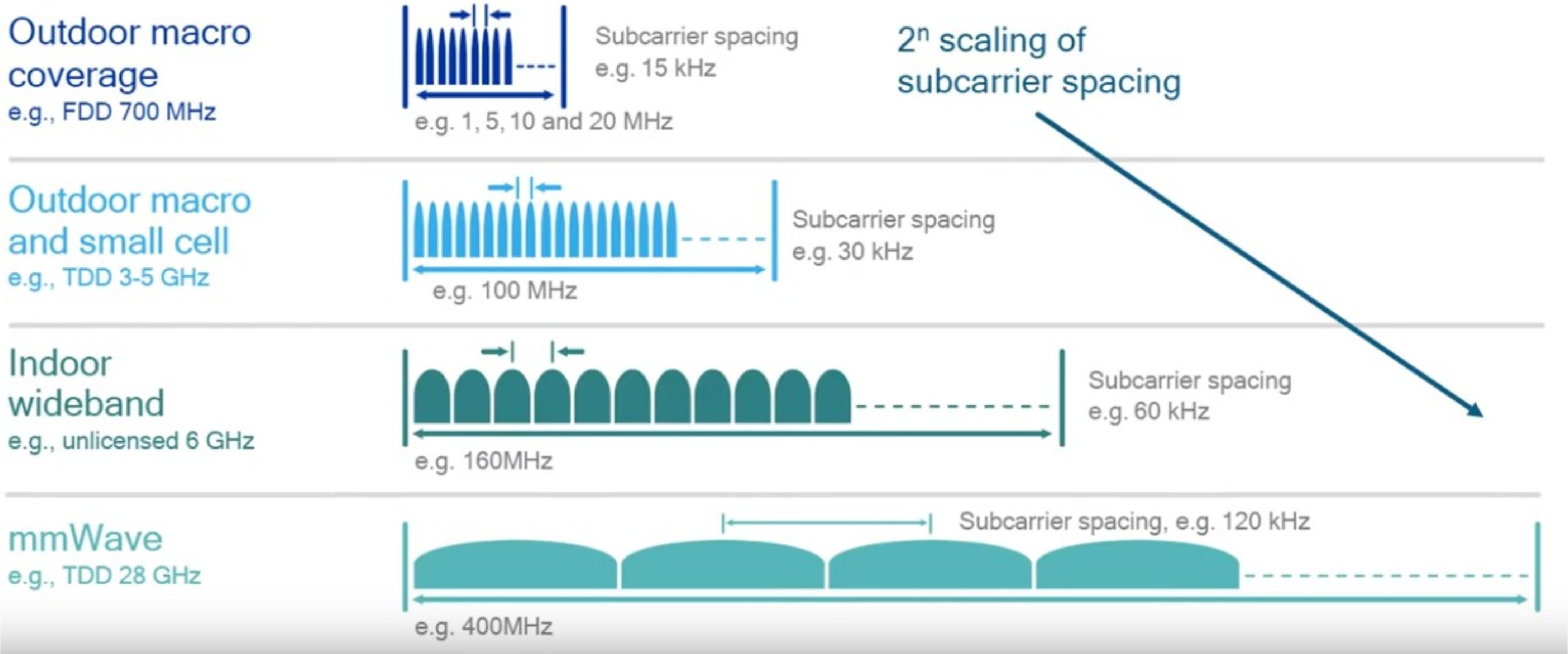
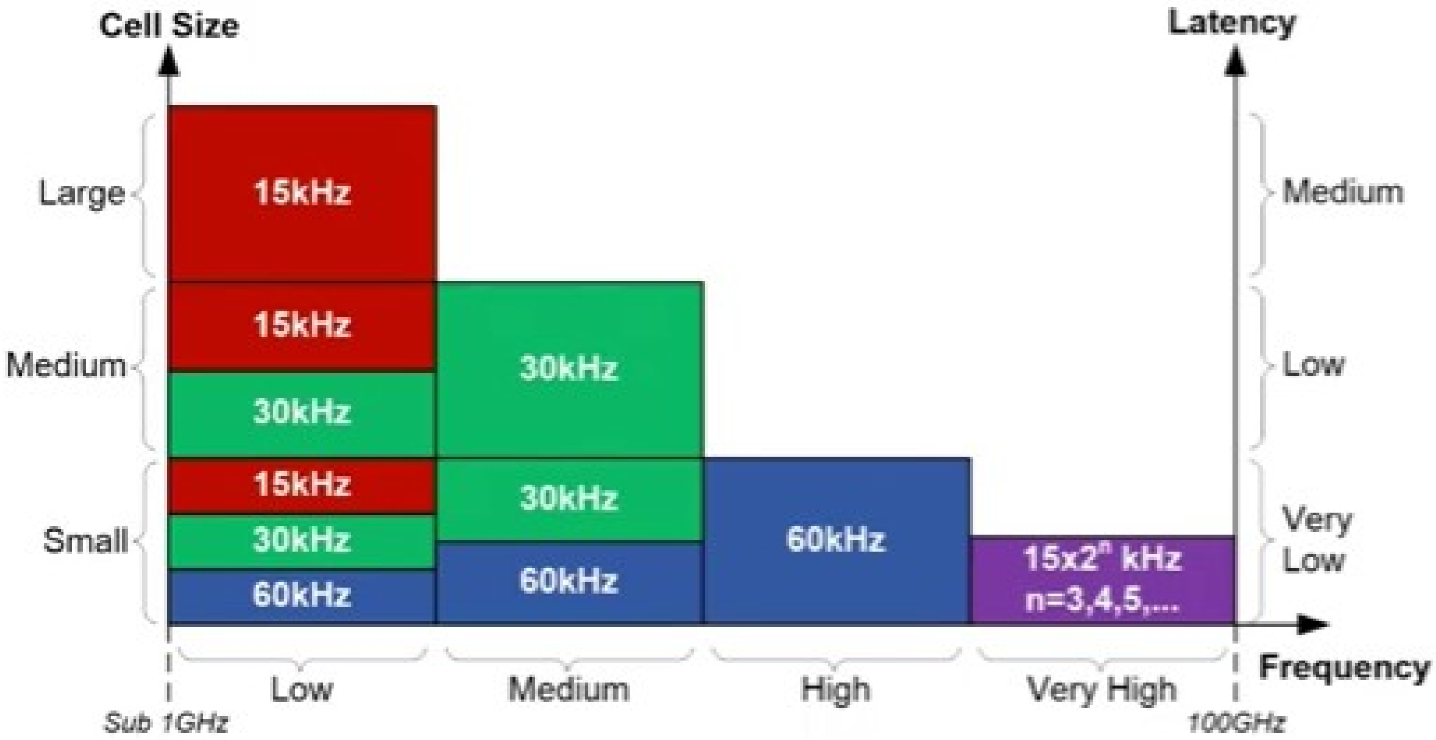


# 5G NR structure



# Selecting the numerology



# 5G NR structure

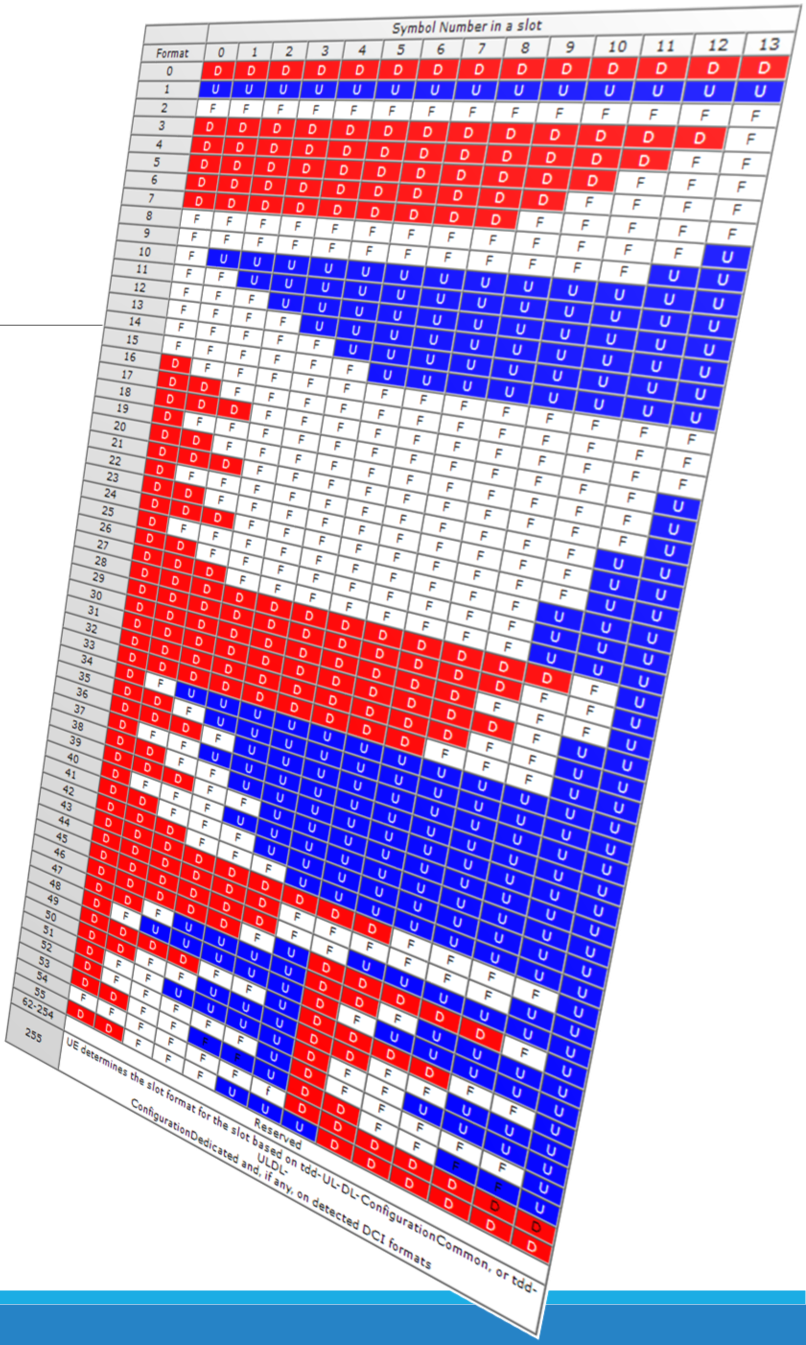
## Slot Frame Indicator

| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DL-heavy transmission with UL part | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Slot (e.g, slot format 28) | | | | | | | | | | | | | | Slot(e.g, slot format 28) | | | | | | | | | | | | | |
| D | D | D | D | D | D | D | D | D | D | D | D | F | U | D | D | D | D | D | D | D | D | D | D | D | D | F | U |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UL-heavy transmission with DL Control | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Slot(e.g, slot format 34) | | | | | | | | | | | | | | Slot(e.g, slot format 34) | | | | | | | | | | | | | |
| D | F | U | U | U | U | U | U | U | U | U | U | U | U | D | F | U | U | U | U | U | U | U | U | U | U | U | U |

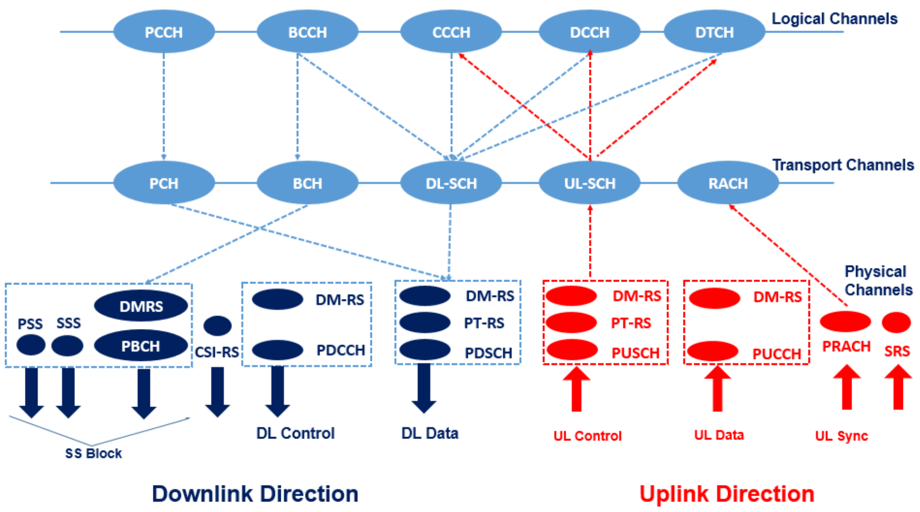
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slot aggregation for DL-heavy transmission (e.g, for eMBB) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Slot(e.g, slot format 0) | | | | | | | | | | | | | | Slot (e.g, slot format 28) | | | | | | | | | | | | | |
| D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | F | U |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slot aggregation for UL-heavy transmission (e.g, for eMBB) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Slot | | | | | | | | | | | | | | Slot | | | | | | | | | | | | | |
| D | F | U | U | U | U | U | U | U | U | U | U | U | U | D | U | U | U | U | U | U | U | U | U | U | U | U | U |

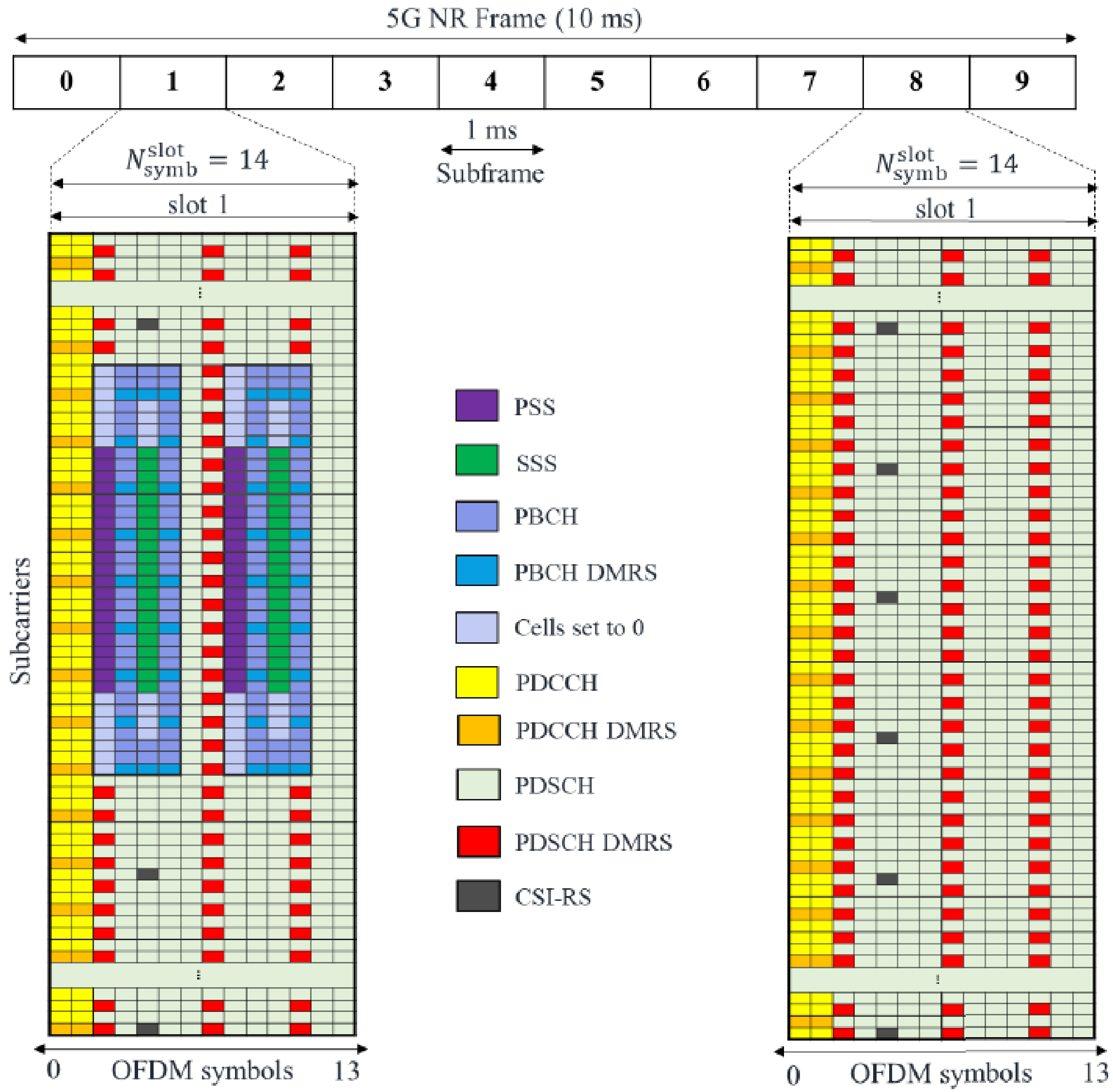



**Transmission Time Interval (TTI):** It is composed of consecutive OFDM symbols in the time domain in a particular transmit direction

# Filling in the RE




| Numerology | Subcarrier Spacing (kHz) | CP type | Supported for Data (PDSCH, PUSCH etc) | Supported for Sync (PSS,SSS,PBCH) | PRACH |
|---|---|---|---|---|---|
| N/A | 1.25 | | No | No | Long Preamble |
| N/A | 5 | | No | No | Long Preamble |
| 0 | 15 | Normal | Yes | Yes | Short Preamble |
| 1 | 30 | Normal | Yes | Yes | Short Preamble |
| 2 | 60 | Normal,Extended | Yes | No | Short Preamble |
| 3 | 120 | Normal | Yes | Yes | Short Preamble |
| 4 | 240 | Normal | No | Yes | |



# KPI calculation methodologies

- Inspection
  - Review of functionalities and parameters of the technology under evaluation
- Analysis
  - Mathematical procedures
- Link level Simulations (PHY/MAC, single user)
  - Simulation that target KPIs that dependent on the physical layer and radio channels (e.g., BER).
  - Link-level simulations are used to determine the performance between the gNB and the UE under specific channel conditions
- System level Simulations (Full stack, multiple users)
  - Simulations that are applied to KPIs that depend on instantaneous network conditions such as available infrastructure, radio resources, number of users or radio conditions

# Evaluation of selected KPI list

- Bandwidth
- Peak data rate
- Peak spectral efficiency
- User plane latency
- Control plane latency
- Energy Efficiency
- X% percentile spectral efficiency
- User experienced data rate
- Average spectra efficiency
- Area traffic capacity
- Mobility

# Bandwidth

- In FR1 (450 MHz - 6 GHz), 5G allows bandwidths from 5 MHz to 100 MHz
- In FR2 (24.25 GHz - 52.6 GHz), 5G offers values from 50 MHz to 400 MHz

| FR | $\mu$ | BW (MHz) | $N_{RB}^{max}$ | CA CC | CA BW (GHz) |
|---|---|---|---|---|---|
| FR1 | 0 | 50 | 270 | 16 | 0.8 |
| | 1 | 100 | 273 | | **1.6** |
| | 2 | 100 | 135 | | **1.6** |
| FR2 | 2 | 200 | 264 | | 3.2 |
| | 3 | 400 | 264 | | **6.4** |

# Peak data rate calculation

| SCS (kHz) | 5MHz | 10MHz | 15MHz | 20 MHz | 25 MHz | 30 MHz | 40 MHz | 50MHz | 60 MHz | 80 MHz | 90 MHz | 100 MHz |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $N_{RB}$ | $N_{RB}$ | $N_{RB}$ | $N_{RB}$ | $N_{RB}$ | $N_{RB}$ | $N_{RB}$ | $N_{RB}$ | $N_{RB}$ | $N_{RB}$ | $N_{RB}$ | $N_{RB}$ |
| 15 | 25 | 52 | 79 | 106 | 133 | 160 | 216 | 270 | N/A | N/A | N/A | N/A |
| 30 | 11 | 24 | 38 | 51 | 65 | 78 | 106 | 133 | 162 | 217 | 245 | 273 |
| 60 | N/A | 11 | 18 | 24 | 31 | 38 | 51 | 65 | 79 | 107 | 121 | 135 |

#of RB in the available BW

$$\gamma_p = \sum_{j=1}^{J} \left( \alpha \cdot \nu \cdot Q_m \cdot f \cdot R_{max} \frac{12 \cdot N_{PRB}^{BW,\mu}}{T_s^{\mu}} (1 - OH) \right)$$

OFDM symbol duration

$$T_s^{\mu} = \frac{10^{-3}}{14 \cdot 2^{\mu}}$$

(e.g., 16.6μs)

Coding rate (948/1024)

Scaling Factor (1,0.8, 0.75)

Modulation order (2,4,6,8 for QPSK/16/64/256 QAM )

#Layers for Multiple Antennas

DL/UL factor

#Component Carrier

$$N_{SS/PBCH} = N_{sf}^{SS/PBCH} \times N_{slot}^{sf} \times N_{SS/PBCH}^{slot} \times N_{RE}^{SS/PBCH} \times N_{P}^{SS/PBCH}$$ (Periodicity)

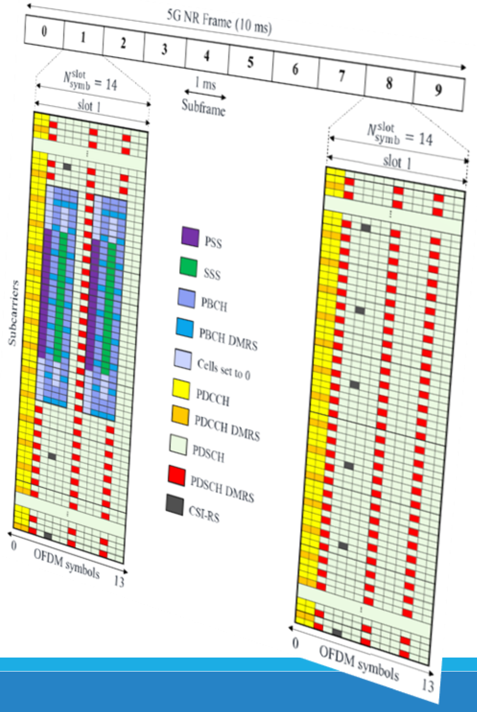
$$N_{PDCCH} = N_{sf}^{CORESET} \times N_{slot}^{sf} \times N_{CORESET}^{slot} \times N_{RE}^{CORESET}$$ (Control resource sets)

$$N_{RE}^{CORESET} = N_{CCE} \times N_{RB}^{CCE} \times N_{RE}^{RB}$$

$$N_{RS} = N_{sf}^{PDSCH} \times N_{slot}^{sf} \times (N_{DMRS} + N_{CSI} + N_{PT\text{-}RS})$$

$$OH = \frac{N_{SS/PBCH} + N_{PDCCH} + N_{RS}}{N_{RE\text{-}DL}}$$

$$N_{RE\text{-}DL} = N_{sf} \times N_{slot}^{sf} \times N_{symb}^{slot} \times N_{RB}^{max} \times N_{RE}^{RB}$$



# Peak data rate calculation

| | $\mu$ | Overhead | $\gamma_P$ SISO | $\gamma_P$ MIMO | $\gamma_P$ SISO+CA | $\gamma_P$ MIMO+CA |
|---|---|---|---|---|---|---|
| DL | 0 | 0.1037 | 0.30 | 2.40 | 4.81 | 38.54 |
| | 1 | 0.1036 | 0.60 | 4.87 | 9.75 | **78.05** |
| | 2 | 0.1076 | 0.59 | 4.78 | 9.57 | 76.62 |
| UL | 0 | 0.0834 | 0.30 | 1.22 | 4.90 | 19.60 |
| | 1 | 0.0815 | 0.62 | 2.49 | 9.99 | **39.99** |
| | 2 | 0.0826 | 0.62 | 2.49 | 9.98 | 39.54 |

| Frequency range | SCS | Bandwidth | DL | UL | Efficiency DL | Efficiency UL |
|---|---|---|---|---|---|---|
| FR1 | 15 kHz | 50 MHz | 288.9 Mbit/s | 309.1 Mbit/s | 5.78 bit/s/Hz | 6.18 bit/s/Hz |
| FR1 | 30 kHz | 100 MHz | 584.3 Mbit/s | 625.0 Mbit/s | 5.84 bit/s/Hz | 6.25 bit/s/Hz |
| FR1 | 60 kHz | 100 MHz | 577.8 Mbit/s | 618.1 Mbit/s | 5.78 bit/s/Hz | 6.18 bit/s/Hz |
| FR2 | 60 kHz | 200 MHz | 1.08 Gbit/s | 1.18 Gbit/s | 5.40 bit/s/Hz | 5.90 bit/s/Hz |
| FR2 | 120 kHz | 400 MHz | 2.15 Gbit/s | 2.37 Gbit/s | 5.38 bit/s/Hz | 5.93 bit/s/Hz |
| Comparison with LTE | | | | | | |
| All bands | 15 kHz | 20 MHz | 100 Mbit/s | 100 Mbit/s | 5.00 bit/s/Hz | 5.00 bit/s/Hz |
| Comparison with 3G | | | | | | |
| All bands | - | 5 MHz | 21.1 Mbit/s | 17.2 Mbit/s | 4.22 bit/s/Hz | 3.44 bit/s/Hz |

# Peak Spectral Efficiency

$$\eta_p = \frac{\gamma_p}{\alpha \cdot BW}$$

$$\gamma_p = \sum_{j=1}^{J} \left( \alpha \cdot \nu \cdot Q_m \cdot f \cdot R_{max} \frac{12 \cdot N_{PRB}^{BW,\mu}}{T_s^{\mu}} (1 - OH) \right)$$

The IMT-2020 requirement is 30 bit/s/Hz in the DL and 15 bit/s/Hz in the UL

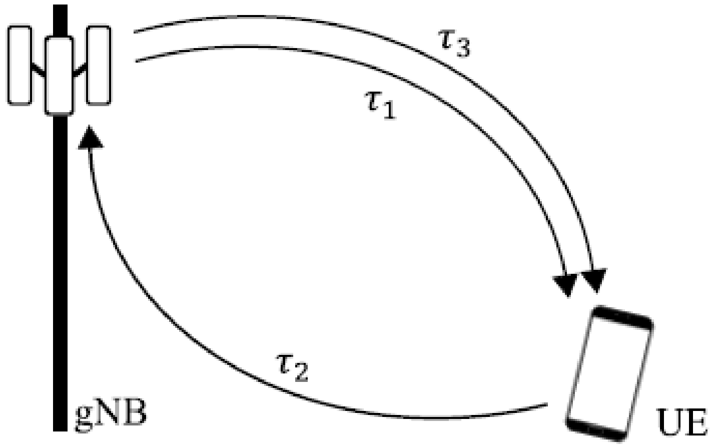
| | | DL | | UL | |
|---|---|---|---|---|---|
| | $\mu$ | $\eta_p$ SISO | $\eta_p$ MIMO | $\eta_p$ SISO | $\eta_p$ MIMO |
| FR1 | 0 | 6.02 | 48.17 | 6.12 | 24.51 |
| | 1 | 6.09 | **48.78** | 6.24 | **24.99** |
| | 2 | 5.98 | 47.89 | 6.17 | 24.71 |

ITU-R defined the average SE minimum requirements for all three eMBB test environments for IMT-2020, i.e., 9 bit/s/Hz/TRxP for **InH**, 7.8 bit/s/Hz/TRxP for **UMa** and 3.3 bit/s/Hz/TRxP for **Rma**

**Hotspot (InH), Dense Urban (UMa) and Rural (RMa)**

# User Plane Latency

- Transmission time (t1) + probability of retransmission (HARQ t2 + Retransmission time t3)




$$\tau = \tau_1 + p(\tau_2 + \tau_3)$$

$$\tau_3 = t_{gNB,tx} + t_{FA3} + t_{TTI} + t_{UE,rx}$$

$$\tau_2 = t_{UE,tx} + t_{FA2} + t_{HARQ} + t_{gNB,rx}$$

$$\tau_1 = t_{gNB,tx} + t_{FA1} + t_{TTI} + t_{UE,rx}$$

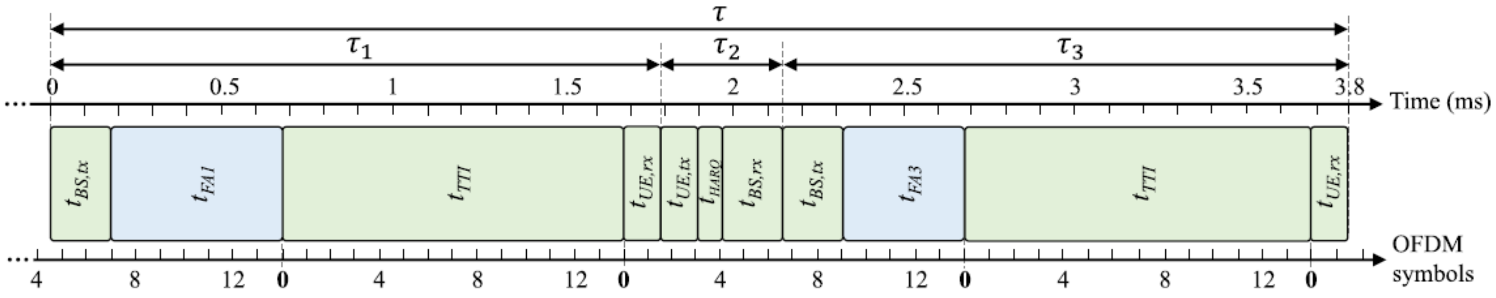
UE processing
Data transmission
Frame alignment
gNB processing

$$t_{gNB,tx} = \frac{\max\left[N_2(2048+144)\cdot\kappa\cdot 2^{(-\mu)}\cdot\frac{T_c}{2048\cdot\Delta_f}, 0\right]}{2}$$

eMBB ➔ 4ms URLLC ➔ 1ms

# User Plane Latency

- Transmission time (t1) + probability of retransmission (HARQ t2 + Retransmission time t3)




The total amount of time needed for the data transmission without HARQ retransmissions, is 1.8 ms

| Slot configuration | HARQ probability | $\mu = 0$ | $\mu = 1$ | $\mu = 2$ |
|---|---|---|---|---|
| 2 symbols | $p = 0$ | 0.50 | 0.27 | **0.23** |
| | $p = 0.1$ | 0.58 | 0.32 | 0.27 |
| | $p = 1$ | 1.35 | 0.77 | 0.66 |
| 4 symbols | $p = 0$ | 0.71 | 0.38 | 0.28 |
| | $p = 0.1$ | 0.82 | 0.44 | 0.34 |
| | $p = 1$ | 1.85 | 0.95 | 0.78 |
| 7 symbols | $p = 0$ | 1.03 | 0.54 | 0.36 |
| | $p = 0.1$ | 1.18 | 0.62 | 0.41 |
| | $p = 1$ | 2.53 | 1.29 | 0.86 |
| 14 symbols | $p = 0$ | 1.80 | 0.92 | 0.55 |
| | $p = 0.1$ | 1.98 | 1.02 | 0.63 |
| | $p = 1$ | 3.78 | 1.91 | 1.30 |

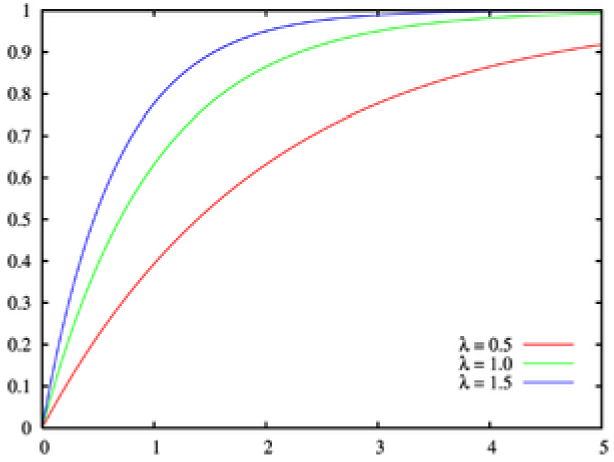
# Support of URLLC

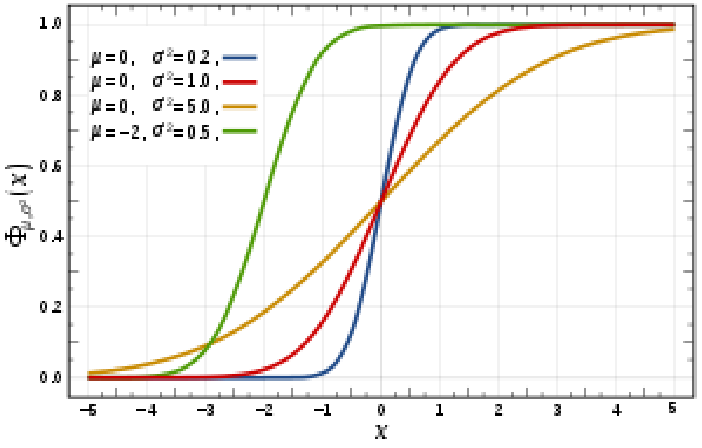
Some key techniques in the PHY/MAC layer to reduce the latency include the following:

- Frequent transmission opportunities that minimize waiting time
  - Frequent monitoring occasions for DL control channel
  - Frequent opportunities for UE to transmit Scheduling Request (SR) on the uplink (UL)
  - Flexible scheduling timing between the Physical Downlink Control Channel (PDCCH) and the Physical Downlink Shared Channel/Physical Uplink Shared Channel (PDSCH/PUSCH)
- Grant-free (or configured grant) UL transmission
  - gNB to configure periodic UL resources for a UE; when the UE has data, it can transmit on the configured resources without the need for dynamic UL grant
- Flexible transmission duration (short duration for both data and control channel) - **minislots**
- Flexible frame structure for Time Division Duplexing (TDD)
- Short UE processing time
- Short next-generation NodeB (gNB) processing time

https://www.5gamericas.org/wp-content/uploads/2019/07/5G_Americas_URLLC_White_Paper_Final__updateJW.pdf

# $5^{th}$ percentile of user spectral efficiency




**Percentiles:** Let $0 < p < 100$. The $p$th percentile of the RV $X$ is the value $x_p$ which separates the smallest $p$% of $X$'s values from the largest $(100 - p)$%. In probabilistic terms, the $p$th percentile satisfies the equation $P(X \leq x_p) = p/100$. Thus we have

$$\begin{aligned} \frac{p}{100} &= P(X \leq x_p) && (1)\\ &= P(-\infty < X \leq x_p) && (2)\\ &= \int_{-\infty}^{x_p} f_X(x)dx && (3)\\ &= F_X(x_p) && (4) \end{aligned}$$

From lines 3 and 4 above, we see that we can compute $x_p$ from either the density function $f_X$ or the CDF $F_X$ of $X$.

**Example 1:** In example 2.45, pp. 109-110 in your book, the author computes the 50th percentile $x_{50}$ and the 60th percentile $x_{60}$ for the RV with density

$$f_X(x) = \begin{cases} 0.1e^{-0.1x}, & x > 0 \\ 0, & x \leq 0 \end{cases}$$

To compute $x_{50}$ using $f_X$ we use (3) above:

$$\begin{aligned} \frac{50}{100} &= \int_{-\infty}^{x_{50}} f_X(x)dx \\ &= \int_{0}^{x_{50}} 0.1e^{-0.1x}dx \\ &= -e^{-0.1x}\Big|_0^{x_{50}} \\ &= 1 - e^{x_{50}} \end{aligned}$$

Solving this yields $x_{50} = 6.931$.

# 5th percentile of user spectral efficiency

user spectral efficiency

$$r_i = \frac{R_i(T_i)}{T_i \cdot \alpha \cdot BW}$$

The IMT-2020 requirements for 5th percentile user spectral efficiency are 0.3 bit/s/Hz for **InH**, 0.225 bit/s/Hz for **UMa** and 0.12 bit/s/Hz for **RMa**

- Throughput is defined as the rate of correctly received bits.
- For the normalized user throughput, $r_i$, of user $i$, the correctly received bits $R_i(T_i)$, meaning the bits contained in the Service Data Units (SDUs) delivered to upper layers, are added up over a certain period of time $T_i$ and
- Divided by $T_i$ as well as the effective channel bandwidth, $BW$

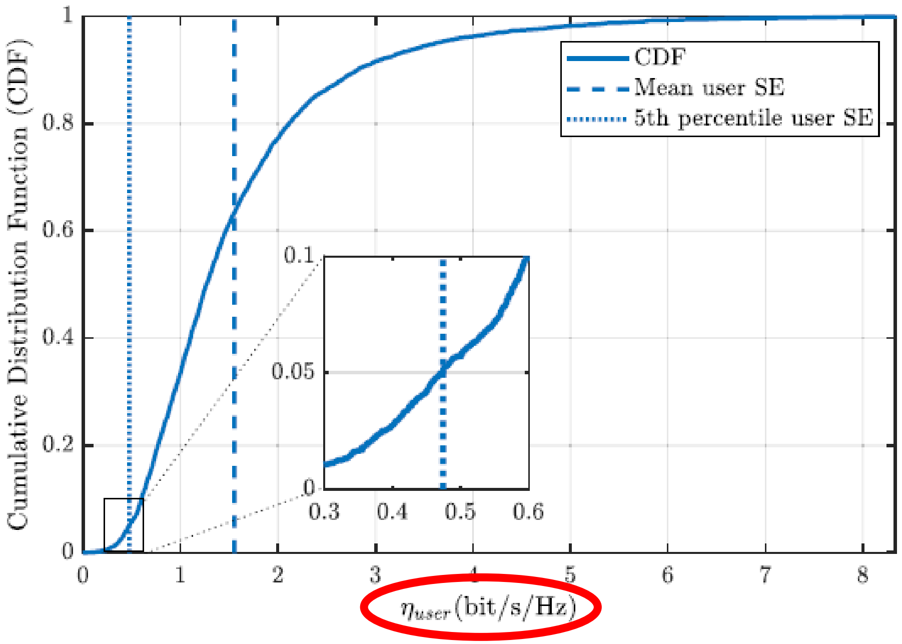
# $5^{th}$ percentile of user spectral efficiency

user spectral efficiency

$$r_i = \frac{R_i(T_i)}{T_i \cdot \alpha \cdot BW}$$

The IMT-2020 requirements for $5^{th}$ percentile user spectral efficiency are 0.3 bit/s/Hz for **InH**, 0.225 bit/s/Hz for **UMa** and 0.12 bit/s/Hz for **RMa**

- Throughput is defined as the rate of correctly received bits.
- For the normalized user throughput, *ri*, of user *i*, the correctly received bits *Ri*(*Ti*), meaning the bits contained in the Service Data Units (SDUs) delivered to upper layers, are added up over a certain period of time *Ti* and
- Divided by *Ti* as well as the effective channel bandwidth, *BW*

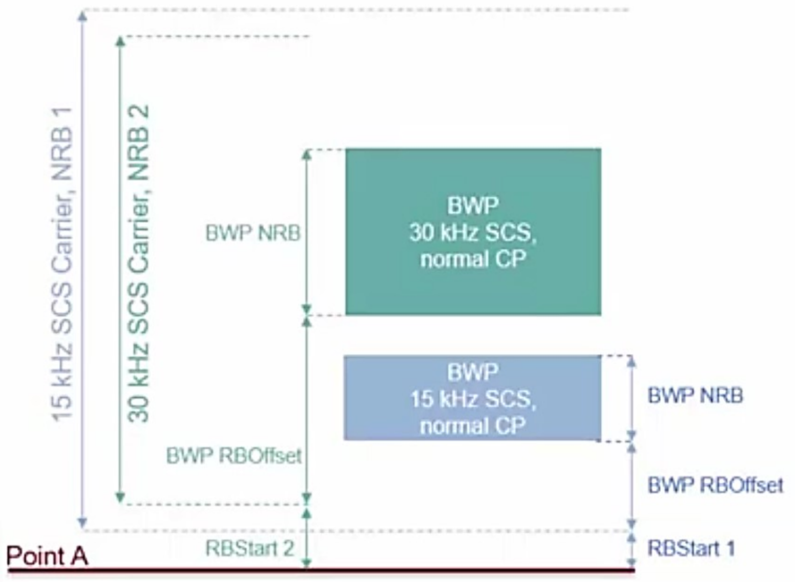


# $5^{th}$ percentile of user experienced data rate

user spectral efficiency

$$\gamma_{\text{user}} = BW \cdot \eta_{\text{user}}$$

The ITU-R requirements for $5^{th}$ percentile for DL a minimum requirement of 100 Mbit/s for IMT-2020 in UMa test environment



# 5th percentile area traffic capacity

Average spectral efficiency

$$C_{\text{area}} = \rho \cdot BW \cdot \eta_{\text{avg}}$$

Density of the reception points

The IMT-2020 requirement for this KPI is 10 Mbit/s/m2 for DL in **InH** test environment

# Evaluation of selected KPI list

- Bandwidth
- Peak data rate
- Peak spectral efficiency
- User plane latency
- Control plane latency
- Energy Efficiency
- X% percentile spectral efficiency
- User experienced data rate
- Average spectra efficiency
- Area traffic capacity
- Mobility

| KPI | IMT-2020 | 5G NR | Fulfillment |
|---|---|---|---|
| Bandwidth (GHz) | 1 | 6.4 | ✓ |
| Peak data rate (Gbit/s) | 20 | 78.05 | ✓ |
| Peak SE (bit/s/Hz) | 30 | 48.78 | ✓ |
| User plane latency (ms) | 1 | 0.23 | ✓ |
| Control plane latency (ms) | 20 | 11.6 | ✓ |
| Energy efficiency (%) | Qualitative | 99.73 | ✓ |
| 5th perc. user SE (bit/s/Hz) | 0.3 | 0.47 | ✓ |
| User exp. data rate (Mbit/s) | 100 | 247.6 | ✓ |
| Average SE (bit/s/Hz/TRxP) | 9 | 15.5 | ✓ |
| Traffic capacity (Mbit/s/$m^2$) | 10 | 37.5 | ✓ |
| Mobility SE (bit/s/Hz) | 0.45 | 2.64 | ✓ |

# Online calculators

**5G NR:** 5G NR Throughput calculator, 5G NR Link budget calculator, 5G NR ARFCN Calculator, 5G NR GSCN Calculator, 5G NR TBS Calculator, Spectral Efficiency 5G NR calculator, 5G NR SSB SSS EPRE Power Calculator, 5G Neighbor planning calculator, QoS for 5G NR
**4G LTE:** 4G LTE Throughput calculator, 4G LTE Link budget calculator, 4G LTE EARFCN calculator, 4G LTE RS RE Power calculator, 4G LTE Users (CCE) calculator, 4G LTE Timing Advance Distance Calculator, 4G Neighbor planning calculator, QoS for 4G LTE
**NB-IoT:** NB-IoT Link budget calculator

# From theory to practice

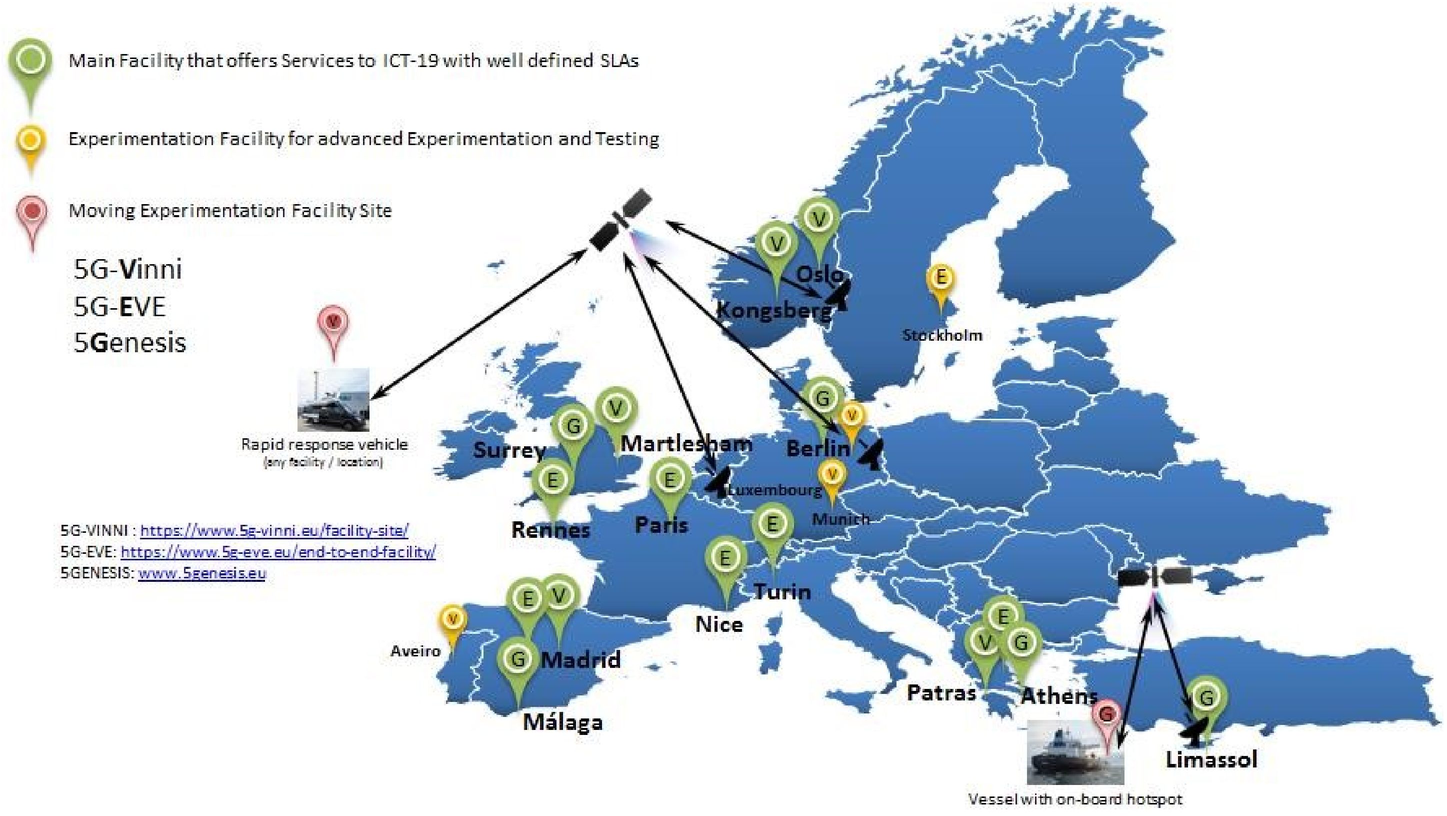
In real implementations used for KPIs measurements the performance impact factors can be classified into three main categories, namely:

- *The deployment and configuration aspects*, referring to the technology that is selected for each domain of the service provisioning chain (Core, Transport, and Radio domains) and, also, to set-up configurations, such as the selection of bandwidth size and antenna layers.
- *The scenario under which an experiment/measurement is performed*, referring to run-time factors that affect the performance values, such as the mobility of end devices, the channel conditions, and the traffic type used.
- *The testing/experimentation procedure,* referring to the methodology used for collecting measurements and calculating the KPI values, such as experiment repetitions applied, outlier values identification, and mean values calculation process, i.e., factors that affect the reliability of the measurements.

# 5G experimentation platforms/ testbeds

https://5g-ppp.eu/5g-ppp-platforms-cartography/

https://www.ip45g.de/en/5g-testbeds/



# 5G experimentation results

| Technology Set (identifier) | 3GPP Standardization | | Radio access configuration | | | | | |
|---|---|---|---|---|---|---|---|---|
| | *3GPP Release* | *3GPP Architecture option* | *Band* | *BW (MHz)* | *Pattern* | *MIMO Layers* | *Max Modulation* | *Aggregation* |
| #TS_Malaga | Rel 15 | NSA | 5GNR:n78<br>4GRadio:B7 | NR:40<br>4GRadio:20 | NR:TDD<br>4GRadio:FDD | NR:2x2<br>4GRadio:4x4 | NR:256QAM<br>4GRadio:256QAM | Single Carrier<br>*NR+LTE* |
| #TS_Athens | Rel 15 | NSA | NR:n78<br>4GRadio:1 | NR:50<br>4GRadio:10 | NR:TDD<br>4GRadio:FDD | NR:2x2<br>4GRadio:2x2 | NR:256QAM<br>4GRadio:256QAM | Single Carrier<br>*NR+LTE* |
| #TS_Surrey | Rel 15 | NSA | 5GNR:n78<br>4GRadio:38 | NR:100<br>4GRadio:20 | NR:TDD<br>4GRadio:TDD | NR:64x64<br>4GRadio:8x8 | NR:256QAM<br>4GRadio:256QAM | Single Carrier<br>*NR+LTE* |

| KPI measurements (identifier) | Tech&SetUp | Scenario | Target KPI | | | Complementary Measurements |
|---|---|---|---|---|---|---|
| | *(identifier)* | *(identifier)* | *Name* | *Mean Value* | *Best/peak Value* | *Name &Value of complementary measurements, if any* |
| #KPIset_1 | #TS_Malaga | #SC2_Iperf_indoor_UDP | DL Throughput | 264.74 Mbps | 269.88 Mbps | Mean SINR 21.4 dB, Mean RSRQ -10.8 dB, Mean RSRP -58 dBm |
| #KPIset_3 | #TS_Athens | #SC2_Iperf_indoor_UDP | DL Throughput | 369.27 Mbps | 372.47 Mbps | Mean RSSI -51 dB, Mean RSRQ -6.5 dB, Mean RSRP -70.48 dBm |
| #KPIset_10 | #TS_SurreyNSA | #SC3_Iperf_outdoorNLOS_TCP | DL Throughput | 492.08 Mbps | 738.08 Mbps | n/a |
| #KPIset_11 | #TS_SurreyNSA | #SC3_Iperf_outdoorNLOS_TCP | UL Throughput | 59.34 Mbps | 73.40 Mbps | n/a |
| #KPIset_12 | #TS_SurreyNSA | #SC4_Iperf_outdoorNLOS_UDP | UL Throughput | 119.55 Mbps | 125.08 Mbps | n/a |