938II - Electronics and communication technologies (2024/25)

4G & 5G systems

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Master's Degree in Cybersecurity [WCY-LM]

4G standards

4G standards

In the process of the standardization process, there have been two competing systems labeled as 4G technologies:

2 competing standards
was also present in 2G

- **LTE-advanced** (LTE-A), standardized by the 3rd generation partnership project (3GPP)

A GLOBAL INITIATIVE

- **IEEE 802.16m**, standardized by the Institute of Electrical and Electronic Engineers (IEEE)

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LTE-advanced (LTE-A) standard

LTE-advanced

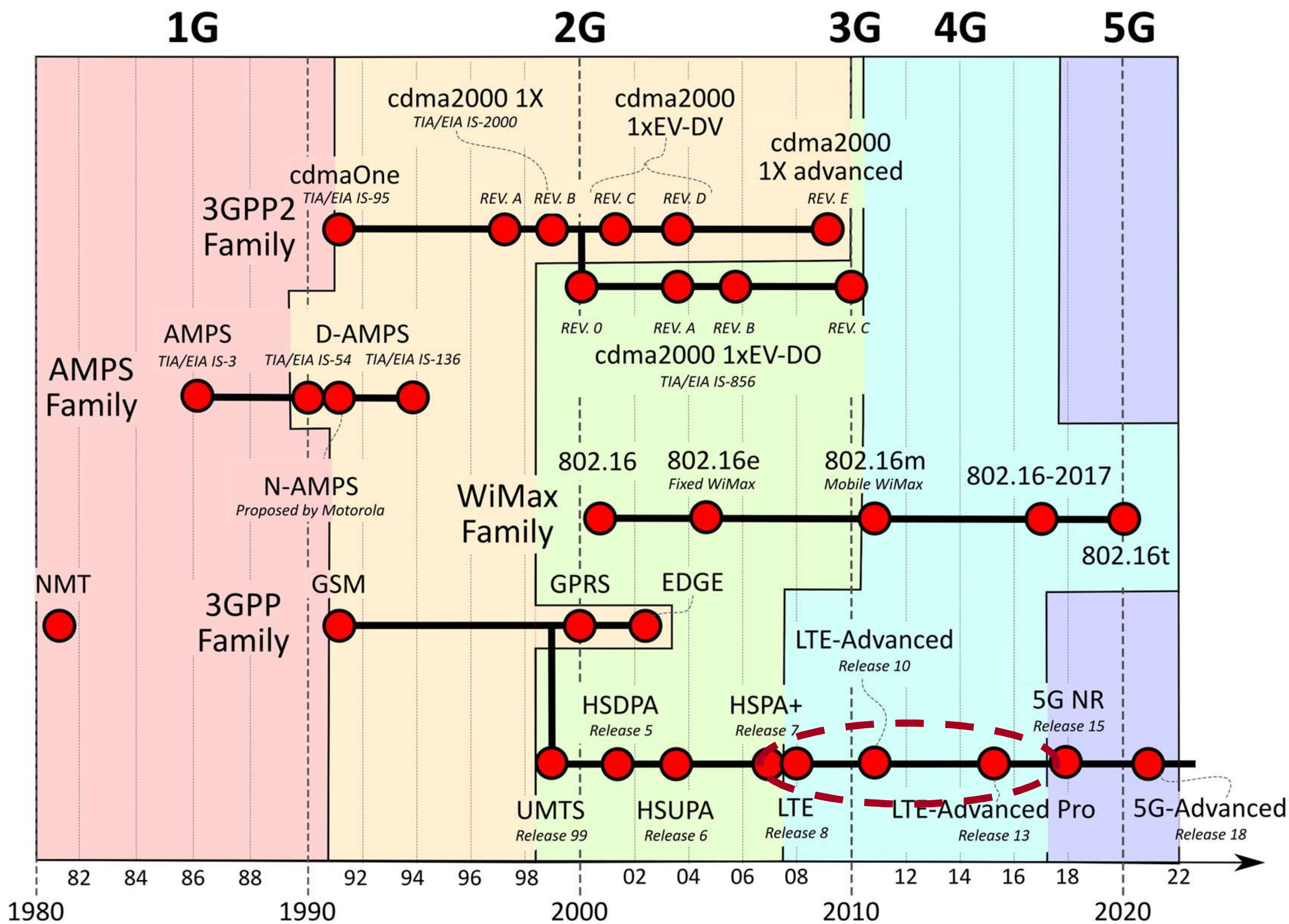
- The long-term evolution – advanced (LTE-A) has been standardized by the 3GPP in March 2011, as **3GPP Release 10** (current version: Release 13, LTE-A Pro)

  and LTE-A Pro (But you can group up to 5 chunks of 20MHz ⇒ 100 MHz)

- LTE-A adopts **OFDMA for the DL**, and **SC-FDMA for the UL**, achieving **peak rates** of 3 Gb/s (DL) and 1.5 Gb/s (UL), and maximum **latency** 10 ms

- **Carrier frequencies**: 700 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2600 MHz
- **Carrier spacing**: 15 kHz (Multicarrier signal: spacing of subcarriers vs bits. Robust against time/freq. select)
  Bandwidth
- **Bandwidths**: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz (Aggregated BW, very flexible
- **Constellations**: QPSK, 16-QAM, 64-QAM Flexible: you choose these depending on channel conditions
  4 bits

History of LTE releases



Resource allocation in LTE-A

Subcarrier spacing (1/2)

In LTE-A, the subcarrier spacing Δf has been selected as a tradeoff to mitigate both frequency selectivity and time selectivity:

$$\boxed{f_{\mathrm{D}} \ll \Delta f \ll B_{\mathrm{coh}}}$$

Time selectivity: LTE-A is designed to support at most speeds of 350 km/h, at a maximum carrier frequency of 3.5 GHz

$$f_{\mathrm{D}} = \frac{v}{c} \cdot f_0 \approxeq 1.1\,\mathrm{kHz}$$

Subcarrier spacing (2/2)

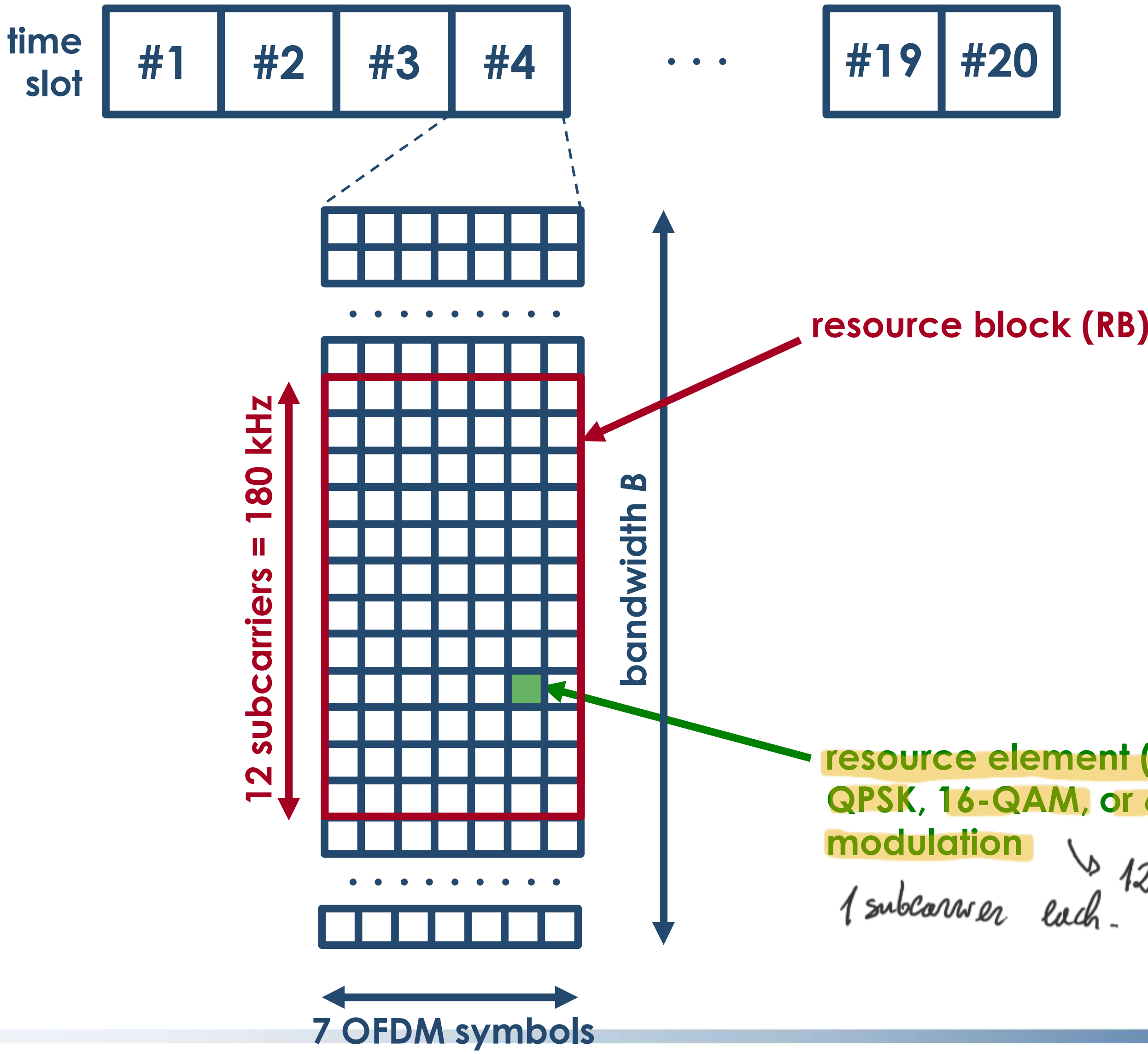
Frequency selectivity: LTE-A systems normally work with a maximum delay spread $\sigma_\tau = 4.7\,\mu\text{s}$

$$B_{\text{coh}} = \frac{1}{\sigma_\tau} \approxeq 212\,\text{kHz}$$

A good tradeoff (which also allows us to maintain some backward compatibility with UMTS parameters) is choosing a carrier spacing $\Delta f = 15\,\text{kHz}$

$$\frac{f_{\text{D}}}{\Delta f} \approxeq 7\%, \qquad \frac{\Delta f}{B_{\text{coh}}} \approxeq 7\%$$

Frame structure type I (FDD)



↳ 12×7 resource element.
1 subcarrier each.

Resource block: composed by 12 subcarriers (freq. dom.) times 7 slot in the time domain. 180 KHz per block in the frequency domain.

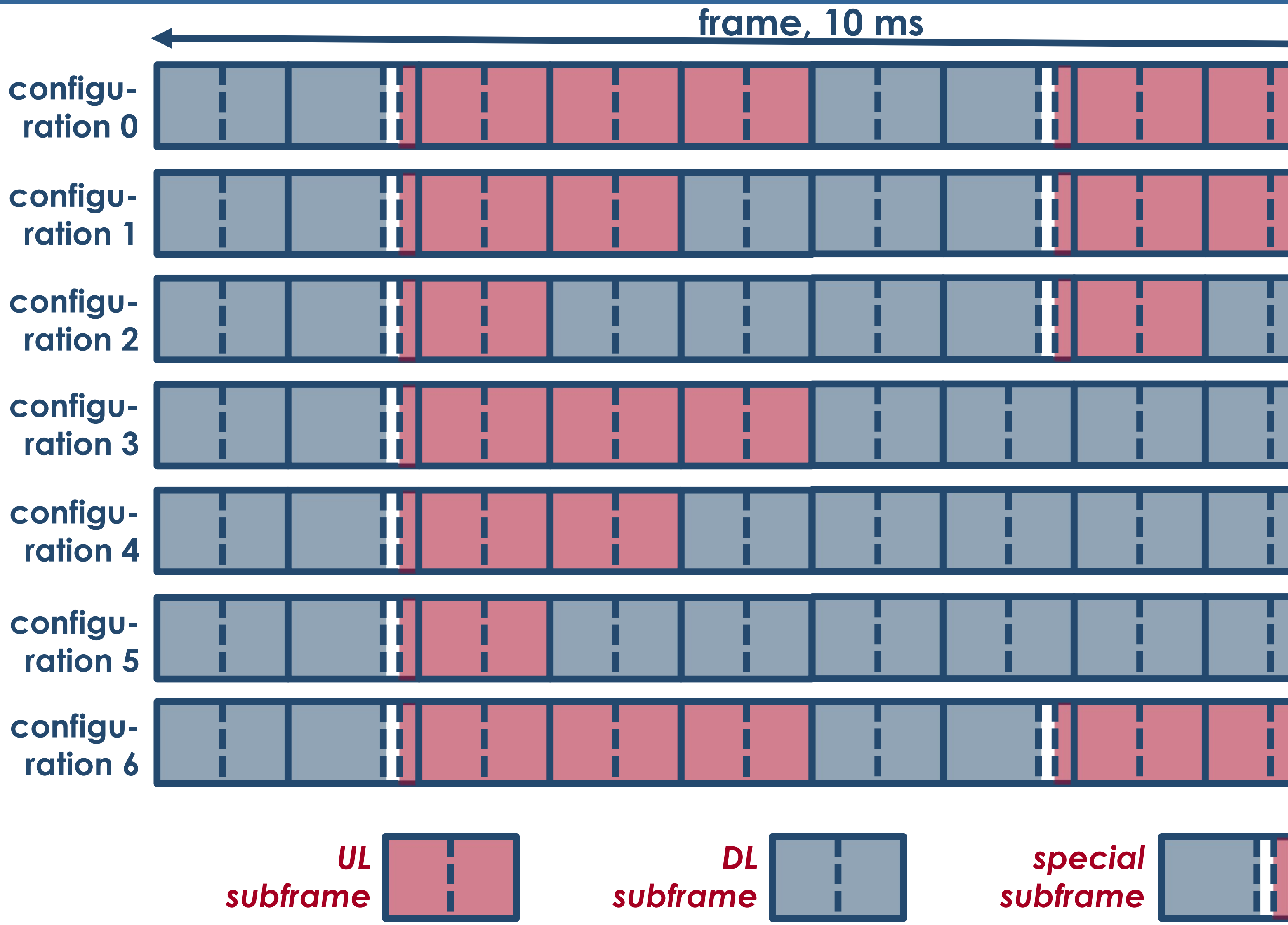
In principle you could assign each resource elements to different users. But that's too complex. So LTE assigns a resource block to a user.

In this way, it's better because the $B_{coh} = 200 kHz$, and resource blocks are 180kHz in bandwidth. So it's comparable and it's good for estimation because the channel doesn't change that much, and it's easier for the channel allocation. If you worked subcarrier by subcarrier the users would need a more complete estimation of the channel.

This is for FDD mode.

Frame structure type II* (TDD)

You can balance uplink and downlink.



→ guard interval for the electronic switch +

+ defense against inter symbol interference.

Bandwidth options

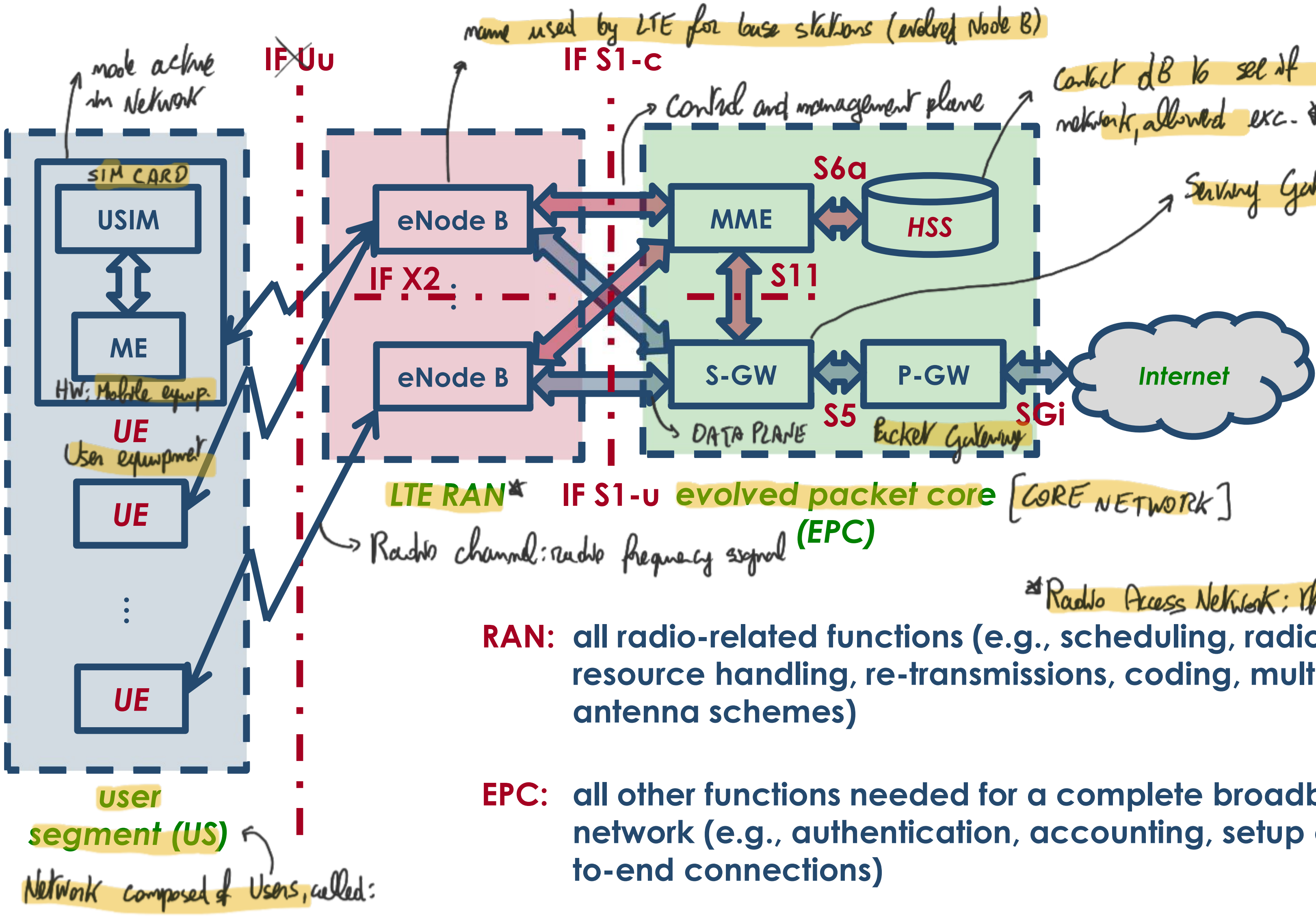
channelization [MHz]	# RBs	# sub-carriers	bandwidth B [MHz]	guard bands [MHz]
1.4	6	72	1.08	2×0.16
3	15	180	2.7	2×0.15
5	25	300	4.5	2×0.25
10	50	600	9	2×0.5
15	75	900	13.5	2×0.75
20	100	1200	18	2×1

0.18kHz

1MHz right and left of virtual subcarriers

UNIT OF MEASURE

System architecture evolution (SAE) (1/2)



*Radio Access Network: there's a radio interface between Base Stat. and user.

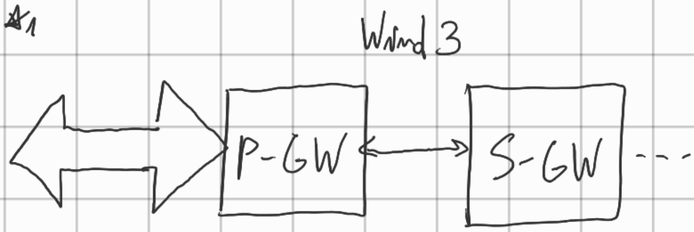
RAN: all radio-related functions (e.g., scheduling, radio resource handling, re-transmissions, coding, multi-antenna schemes)

EPC: all other functions needed for a complete broadband network (e.g., authentication, accounting, setup of end-to-end connections)

*Ex: if you are calling a user in the same network the eNodeB ns told who to contact (which other eNodeB). If you are calling another service provider, you go over the internet to reach another network (TIM, WIND...)

How is the network composed?

*1

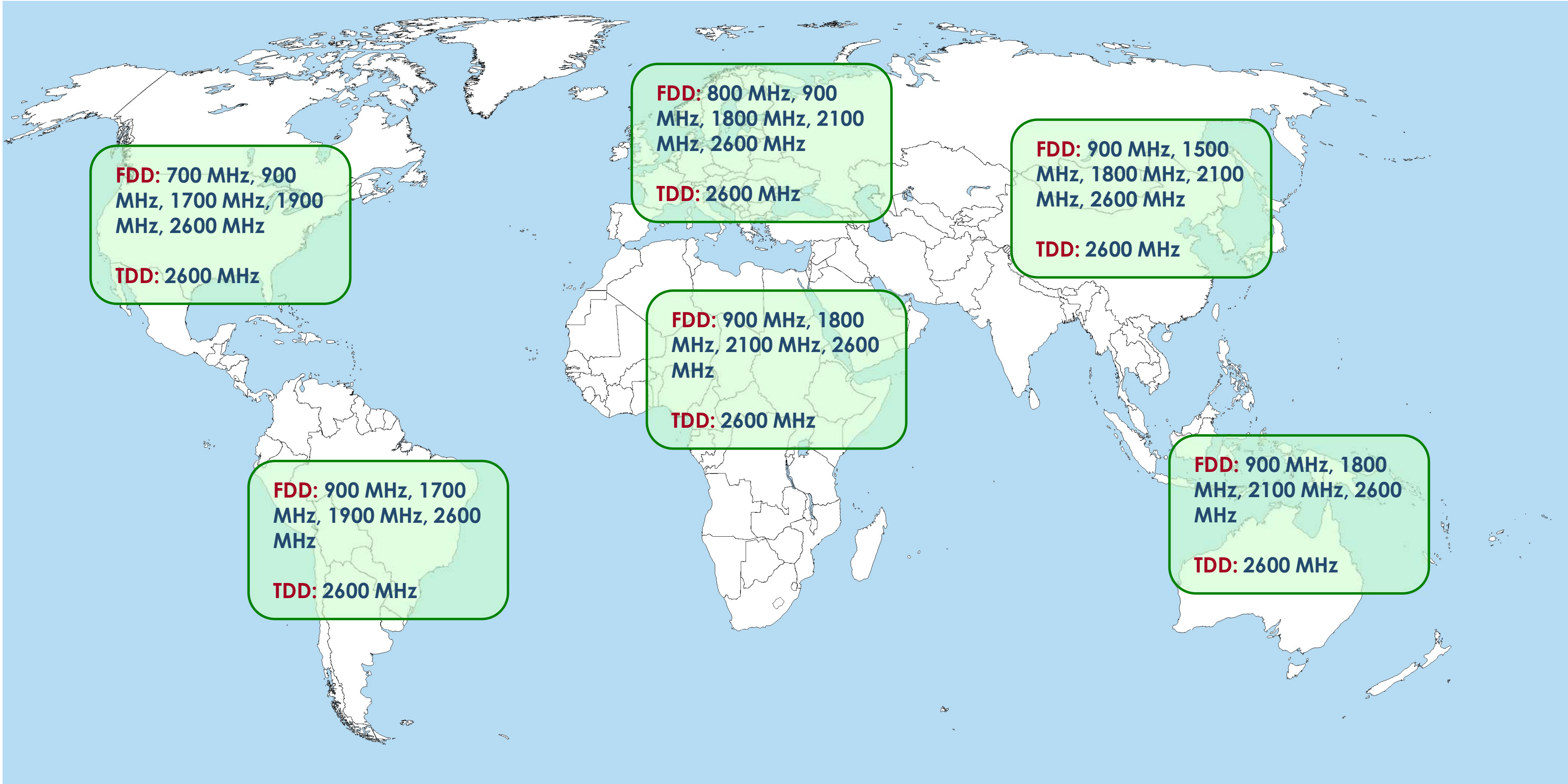


System architecture evolution (SAE) (2/2)

Acronyms

- EPC: evolved packet core
- HSS: home subscriber service
- ME: mobile equipment
- MME: mobility management entity
- P-GW: packet data network gateway
- RAN: radio access network
- S-GW: serving gateway
- UE: user equipment
- US: user segment
- USIM: UMTS subscriber identity module

Spectrum allocation



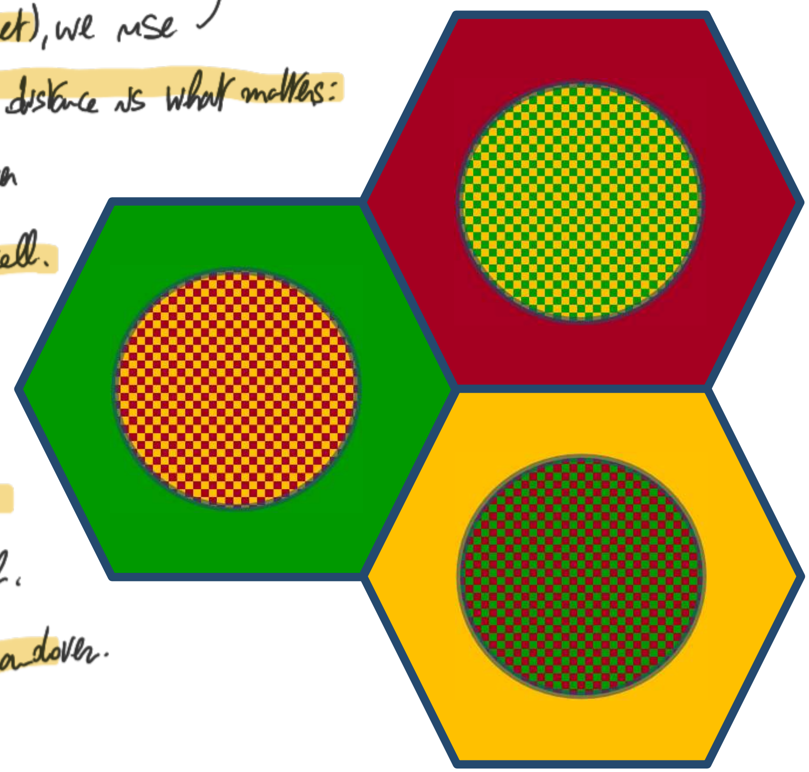
Fractional frequency reuse (FRR)

To boost the performance of the LTE-A network in terms of robustness against multiple-access interference, BSs coordinate across the X2 interface to implement the fractional frequency reuse:

In 4G, suppose a cluster of 3 cells (so 3 subset), we use
Classical frequency reuse is the classic. But reuse distance is what matters:
if we reuse frequency more we can gain on user
density. You divide cell in 2 regions: inner/outer cell.
In the outer cell you assign frequencies in the

available channels

classical mode. In the inner you use all the
frequencies but the ones used in the outer cell.
You need to be good to manage mobility for handover.



Mobility management

The choice of **mobility management** procedures depends on the UE state:

- if the UE is connected, it measures the received power of the reference signal of the serving cell and sends a report; based on this, the network concludes whether a **handover** should take place

user

we can distinguish. Handover is less time critical so you adopt less strict schemes.

- if the UE is idle, the network uses a mobile-triggered procedure known as **cell reselection**, whose objective is to maximize the UE battery life and to minimize the load on the network

Network becomes more efficient

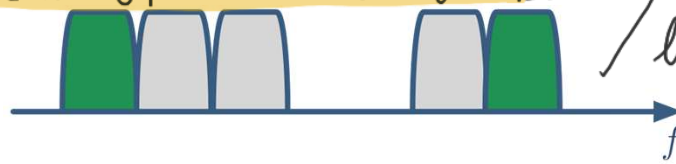
Enabling technologies for 4G standards

Enabling technologies for 4G standards

LTE-A PRO uses:

- carrier aggregation

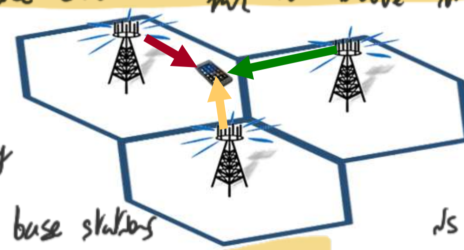
if you need more throughput we can use more slots.



This is what allowed LTE to be compliant with 4G standards.

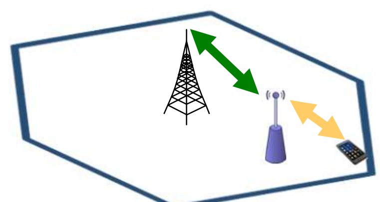
Advantage: you have to place antennas far to have independent

- network MIMO (base station with large # of antenna) You make BTS cooperate, with many antennas build more throughput. Gain by grouping base stations cooperate, but BTS have to exchange much info between base stations.
  ↳ Quick estimation, computation.



If distance between antennas is larger, the independence between paths is more applicable. So you can better separate the users. You can build cells that better separate users (less MA interference)

- relaying



Use of relays: small base stations between cells to be relays between Base Station and device. Power to reach relay much smaller than the one to reach BTS, but you need to manage them.

Network MIMO in 4G lets a base station use multiple antennas to send different parts of the same data to your phone, which also has multiple antennas. This allows your phone to combine the data streams, making downloads faster and the connection more reliable. It also reduces interference from other users by focusing the signal better, especially if you're far from the base station. Think of it as splitting data into smaller packets, sending them through different paths, and reassembling them on your phone.

Carrier aggregation

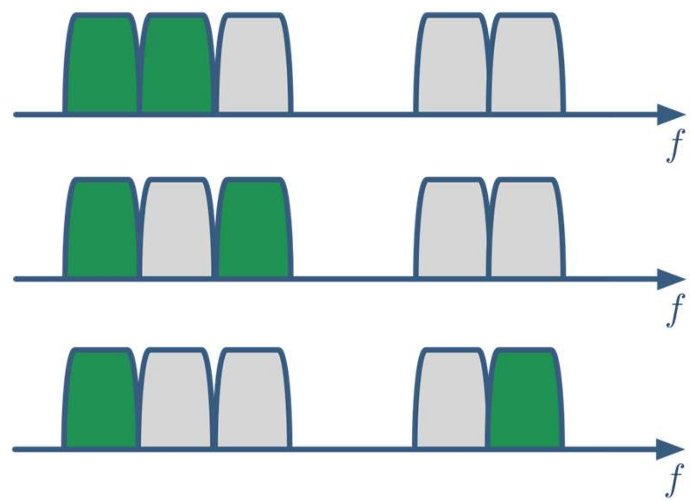
With carrier aggregation (Rel. 10) we can increase the signal bandwidth by grouping physical channels, in both TDD and FDD configurations

Better to do 5 times the same op with 1000 carriers than one with 5000. OPs don't scale linearly.
Plus you don't need 100MHz in a row. You are more flexible.
Front-end will need to be able to work on different bandwidth.

intraband, contiguous CA:

intraband, non-contiguous CA:

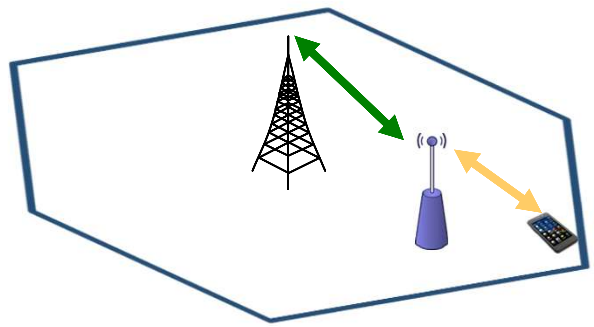
interband CA:



By grouping up to 5 carriers, we can obtain a 100-MHz bandwidth

Relaying*

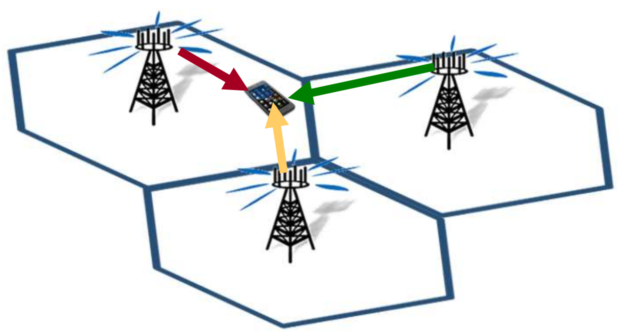
Since Release 10, **relay nodes** can be introduced in the network as **low-power BTSs**, to provide enhanced system performance



- improved **network coverage**
- increased **energy efficiency**
- increased **spectral efficiency**
- some form of **coordination** between the relays and the network is required

Network MIMO*

Network MIMO, known as **coordinated multipoint** (CoMP) in LTE-A, and **coordinated MIMO** (CO-MIMO) in IEEEE 802.16m, consists in coordinating (at the transmit side) or combining (at the receive side) signals using **multiple antennas**



- this form of **distributed MIMO** achieves significant performance improvements, especially for **cell-edge users** (improving coverage and cell-edge rates)
- it requires a significant **feedback overhead** to exchange CSI across BTSs

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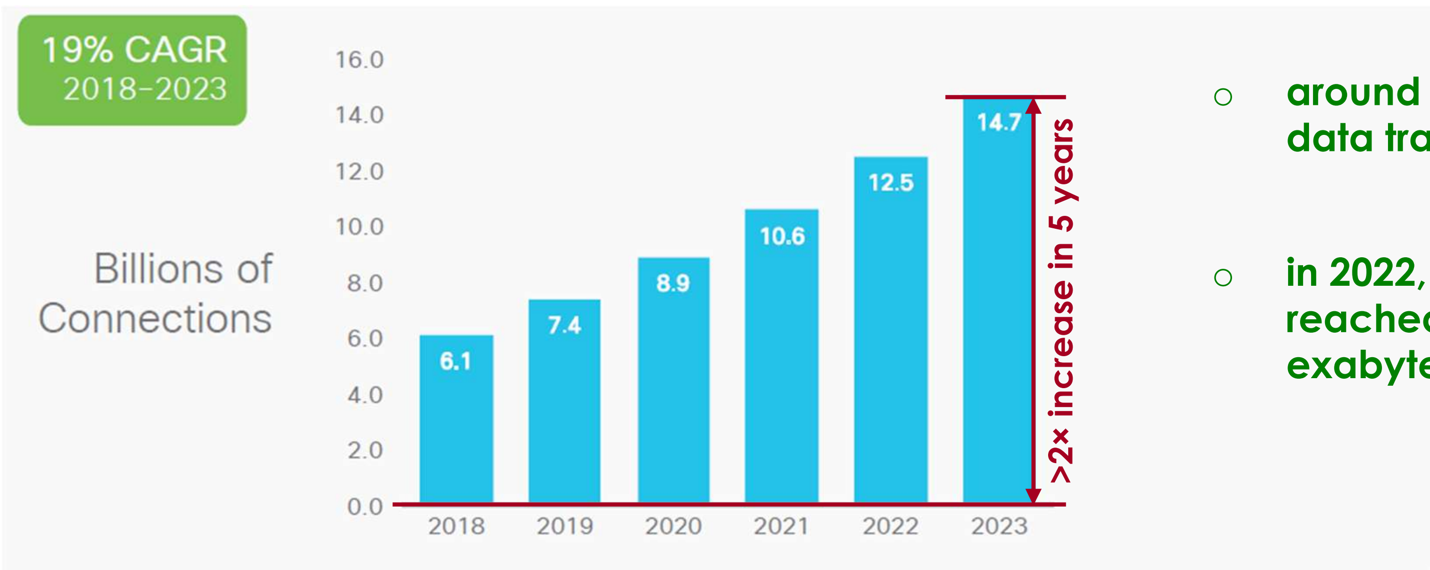
5G technologies

5G technologies (1/3)

Do we really need 5G?



Source: Cisco Annual Internet Report, 2018–2023

- around 20%/year growth in data traffic
- in 2022, global mobile traffic reached more than 77 exabytes per month

5G technologies (2/3)

According to Cisco, mobile data traffic will reach the following milestones within the **next three years**:

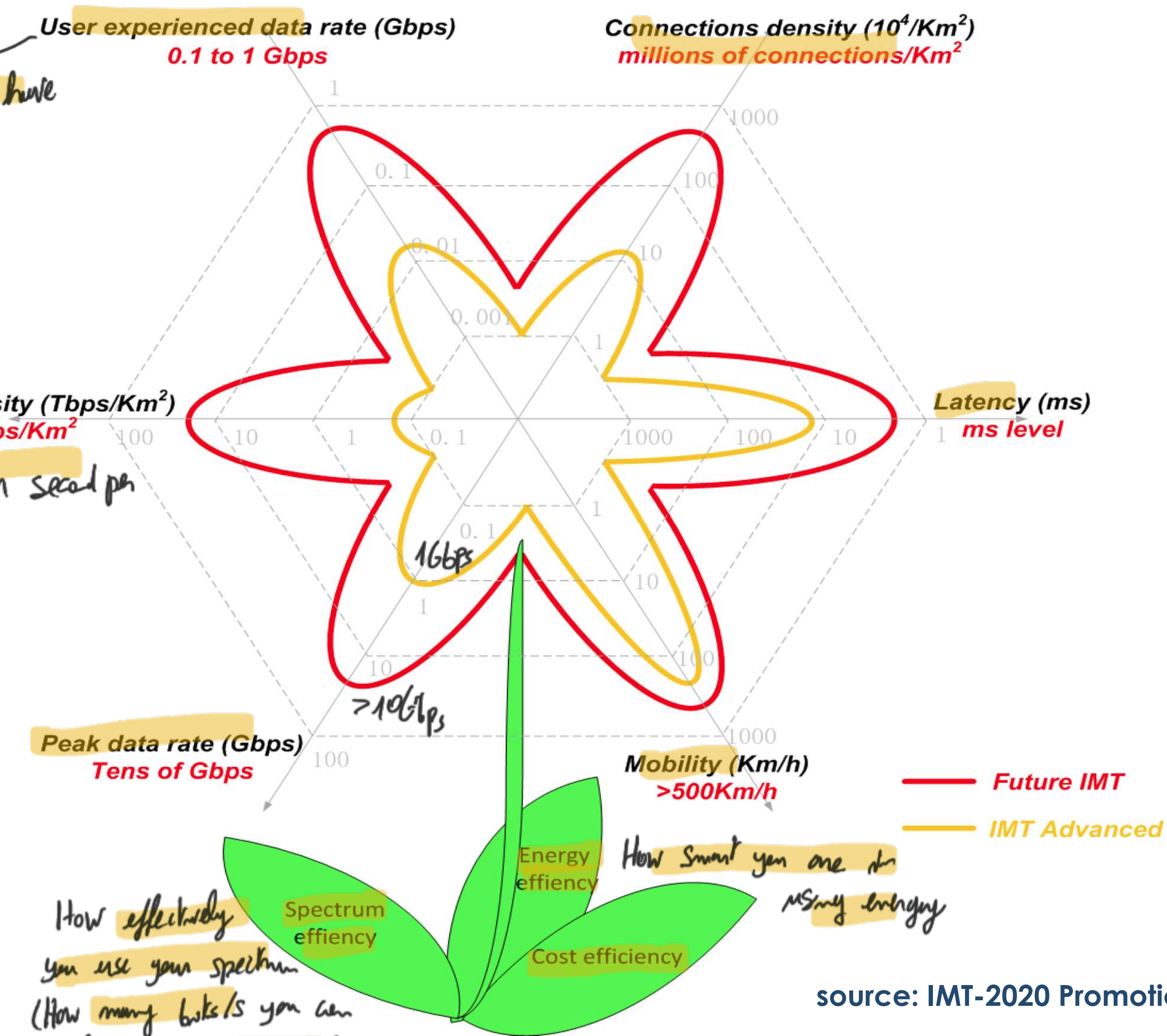
- over **70 percent** of the global population will have mobile connectivity by 2023

- mobile traffic will more than **triple** by 2023: the average mobile network connection speed was 13.2 Mb/s in 2018 and will be 43.9 Mb/s by 2023
- usage per month of the average top 1 percent of mobile users is steadily **decreasing** (i.e., the average traffic per user is **steadily increasing**)
- 5G speeds will be **13 times higher** than the average mobile connection by 2023: the average 5G connection speed will reach 575 Mb/s by 2023

5G technologies (3/3)

average data rate you can have wherever you are.

Number of bits per second per square meter.



eful
[Mb/s]

How smart you are in using energy

How effectively you use your spectrum (How many bits/s you can fit in your spectrum).

source: IMT-2020 Promotion Group

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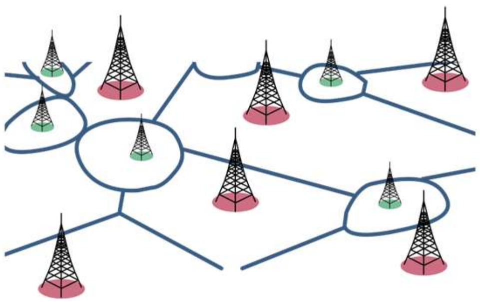
Technology drivers

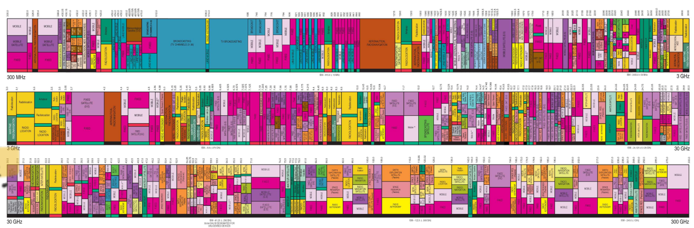
3 new technology



- network densitification

- massive MIMO

- millimeter
  mm-wave technology



↳ for 4G the maximum carrier frequency is up to 6GHz. We call it sub 6 GHz range.

With 5G up to 100GHz (millimeter wave) ⇒ $f_0 = 30\,GHz \rightarrow \lambda_0 = \frac{3 \cdot 10^8\ m/s}{30 \cdot 10^9\ Hz} = 1 \cdot 10^{-2}\ m \Rightarrow f_0 \in [30, 300]\ GHz \Rightarrow \lambda_0 \in [1, 10]\ mm$

and many more: spectrum sharing, advanced PHY and interference management, device-to-device (D2D) communications, etc.

In practice, when frequency is larger than 10 GHz we already talk about mm-Wave.

If you increase the carrier frequency①, you can increase the BW, and throughput.

Pairing this with network densification: use more small cells.

①, the Coherence time, $T_{coh} = \frac{1}{10 f_0}$; $f_0 = \frac{v}{c} \cdot f_0$ you need to estimate channel more frequently.

So you can decrease the speed to address it. If you have smaller cells you can imagine lower mobility.

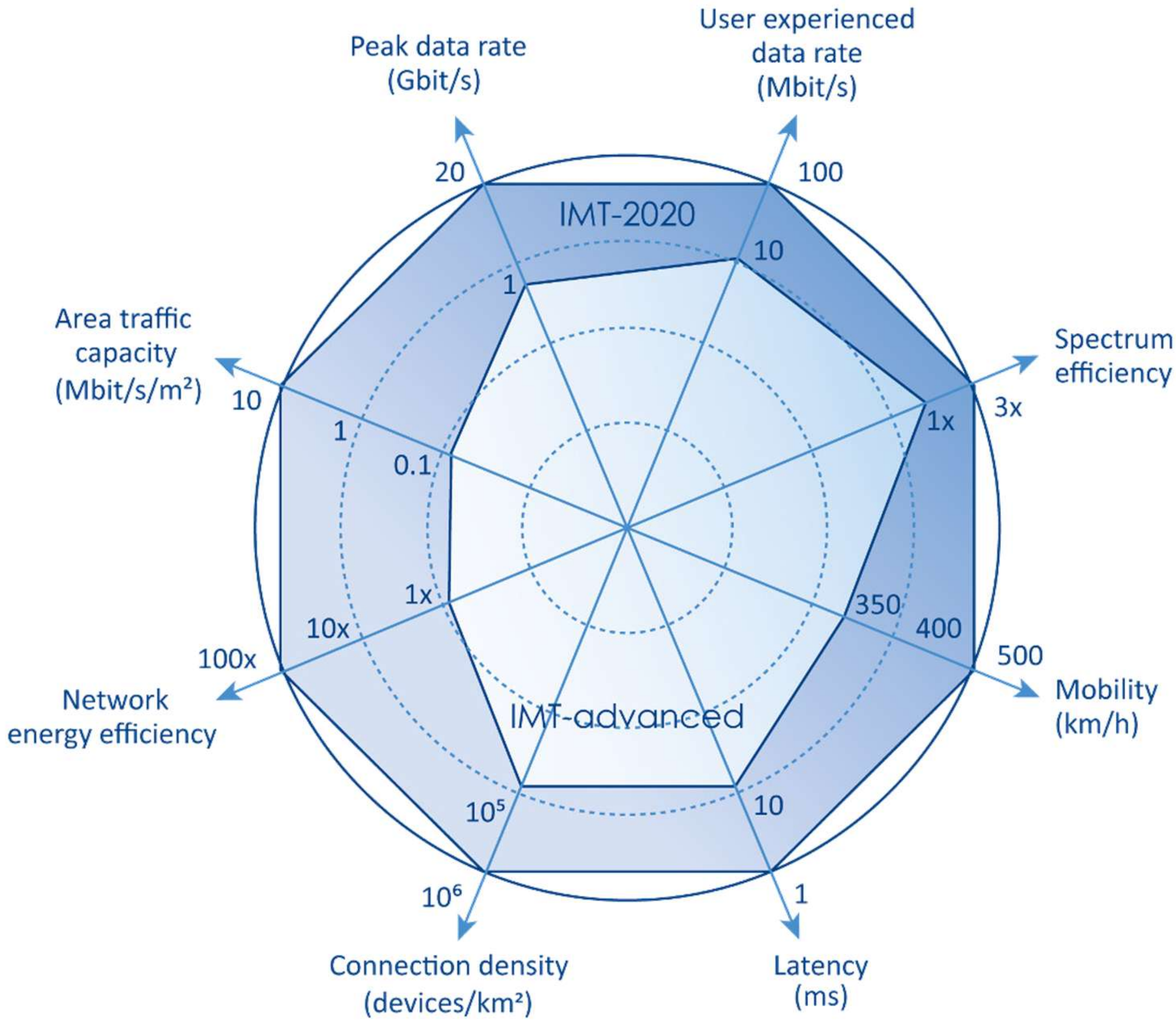
①, you cannot make isotropic antennas because of physical aspects. We have a higher path loss. But for this reason you could use massive mimo, because antenna size can also become smaller. More antennas in the same space.

All those three are benefitting to each other. Network densification for path loss too.

If you have high mobility, those users use sub-6GHz range and wider cells, so lower throughput.

The 5G NR standard

5G NR key capabilities



5G standard

Name for the standard

5G New Radio (NR) is a new radio access technology for the 5G mobile network

first version of 5G.

5G NR has been standardized by the 3GPP in Q2 2018, as **3GPP Release 15** (current stable version: Release 17; current working version: Release 18)

5G-Advanced. Current working version: Release 19

Uses ML techniques.

5G NR applications (1/3)

- **enhanced mobile broadband (eMBB):** it includes several use cases for a better communication experience from the human point of view, improving hotspots for higher user density and extending the coverage for higher mobility scenarios

- **ultra-reliable and low-latency communications (URLLC):** it mostly focuses on machine connectivity, commonly referred to as internet of things (IoT), with applications on safety, wireless control of industrial equipment, remote medical surgery

- **massive machine type communications (mMTC):** it targets scenarios with a very large number of transmissions of small data volumes, not particularly sensitive to delays, and low per-device costs

5G NR applications (2/3)

Key idea: distinguish 3 main use cases:

MED. RELIAB.

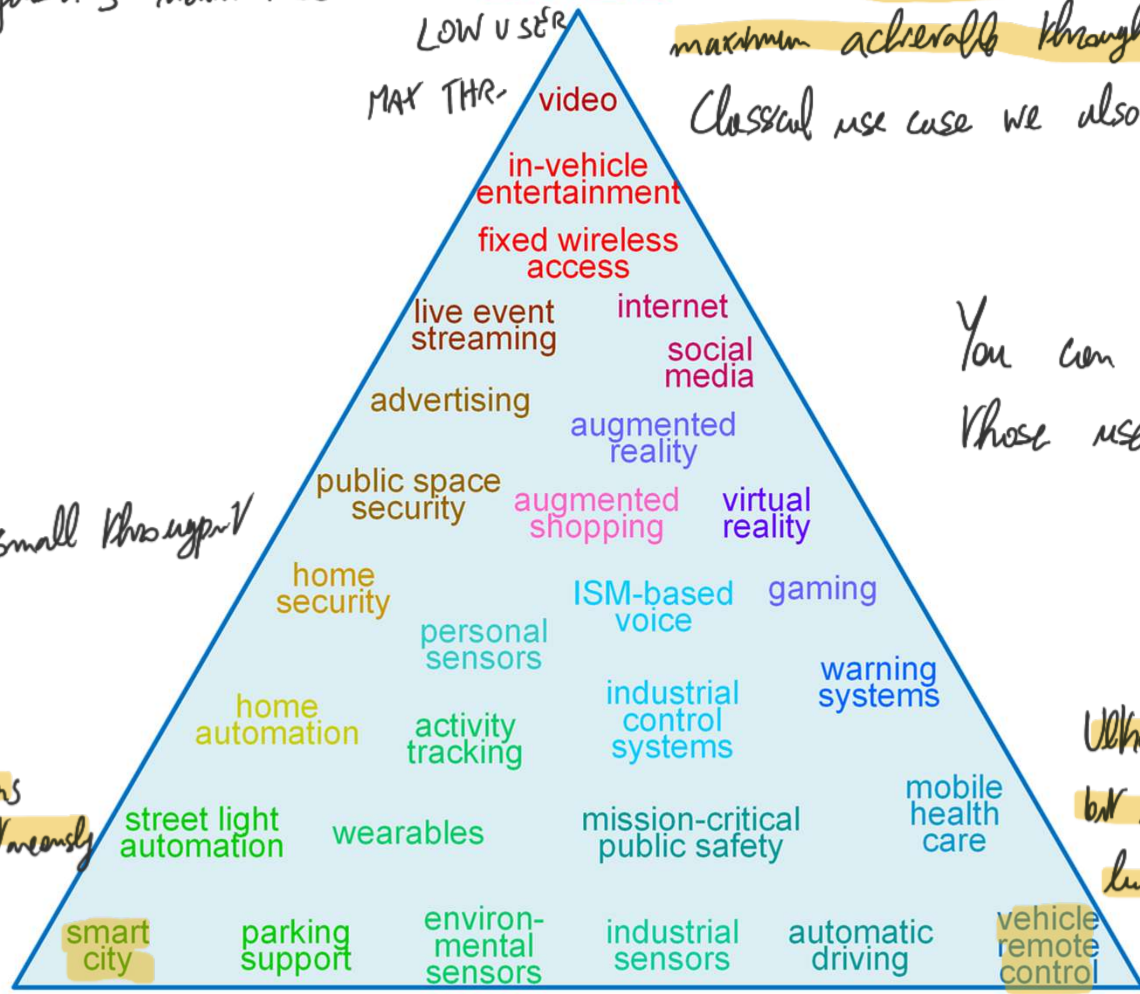
eMBB

LOW USER

MAX THR.

Enhanced Mobile BroadBand: service with the maximum achievable throughput.

Classical use case we also see in 4G.



You can build cells to support those use cases.

assign each sensor small throughput

Cover millions of sensors connected simultaneously

Massive Machine Type Communication

mMTC MAX USER

LOW REL,

LOW THROUGHPUT

Ultra reliable (requirement for bit error rate very low) low latency (very low!) communications

MED USER

URLLC MAX REL

MED. THROUGHPUT

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5G NR applications (3/3)

Reduce mobility: lower cell size, higher frequency, higher throughput

Overview of the 5G physical layer (1/2)

5G is just an extension of 4G. More choices for configuration.

5G NR adopts:

- DL: CP-OFDMA = OFDMA
- UL: CP-OFDMA for high-throughput scenarios (e.g., eMBB)
  discrete Fourier transform spread (DFT-s)-OFDMA = SC-FDMA for power-limited scenarios (e.g., mMTC)

- Carrier frequencies: from 700 MHz to 6 GHz to 100 GHz (from Release 17 on)
- Carrier spacing: from 15 kHz to 120 kHz *1 Not fixed anymore: you want to support users in smaller scenarios *2
- Maximum bandwidths: from 50 MHz to 400 MHz
- Constellations: $\underbrace{\text{QPSK, 16-QAM, 64-QAM, 256-QAM}}_{4G}$, π/2-BPSK ↑ for low throughput

*1 So you have lower delays, higher Bcoh.

*2 In this case you can use also OFDMA in uplink because PAPR not much of a problem.

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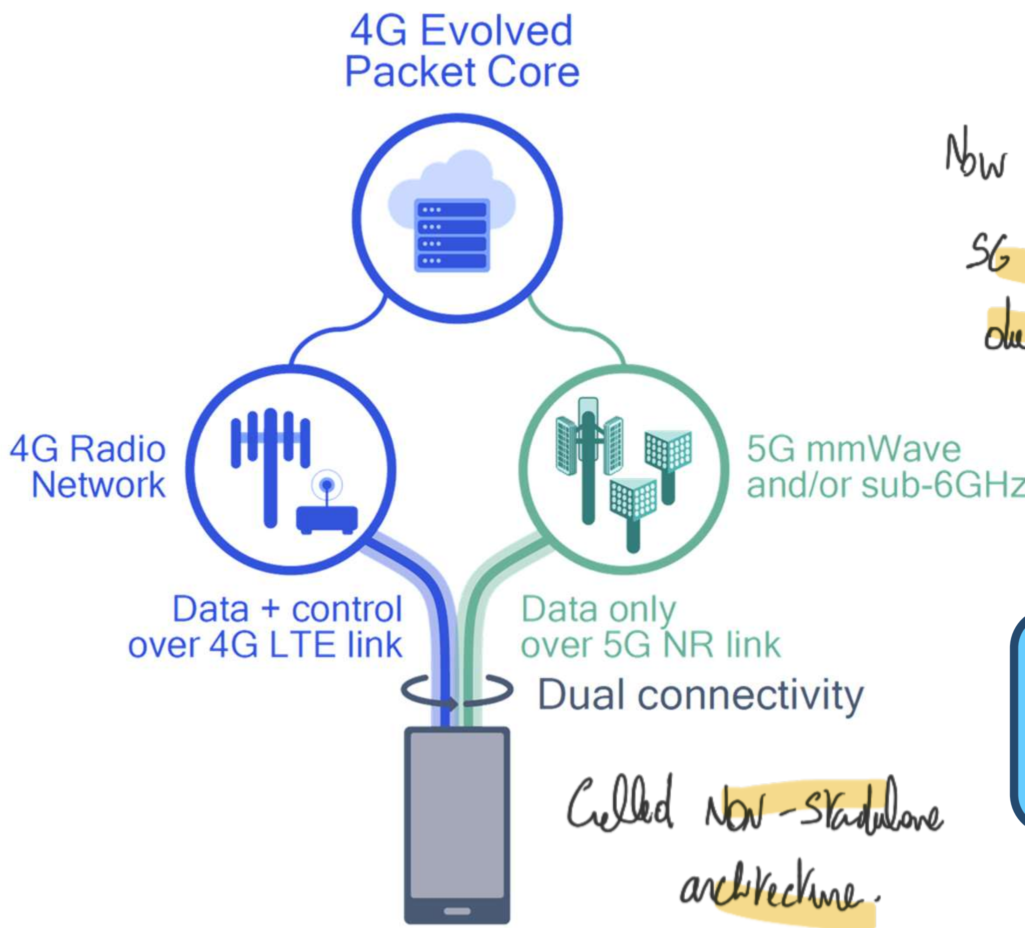
Overview of the 5G physical layer* (2/2)

Scalable **numerology** enables new scenarios:

Subcarrier spacing [kHz]	OFDM symbol duration [μs]	CP duration [μs]	OFDM+CP duration [μs]	OFDM symbols per subframe	Subframe duration [μs]
15	66.67	4.69	71.35	14	1000
30	33.33	2.34	35.68	14	500
60	16.67	1.17	17.84	12 or 14	250
120	8.33	0.59	8.92	14	125

5G architecture options* (1/2)

To speed up the deployment of 5G services and to leverage existing 4G investments, NR can be deployed in non-standalone (NSA) mode



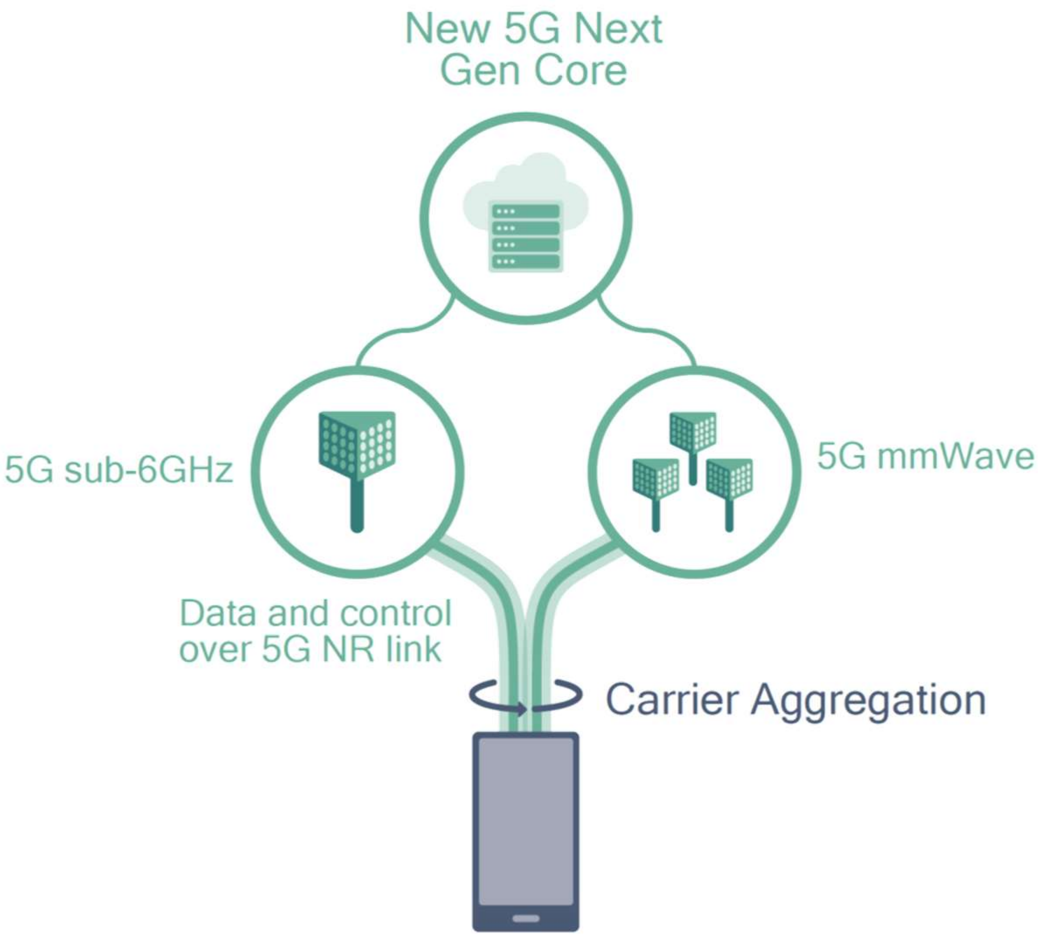
Called Non-Standalone architecture.

Now data plane and control plane are not fully 5G compliant. Now sometimes you use 5G for data plane. But most of the time its 4G.

- Smoother migration to 5G
- Improved data throughput

5G architecture options* (2/2)

To meet the ambitious IMT-2020 goals and to simplify the network architecture, the standalone (SA) mode is preferred



- **Lower costs**
- **Ideal for URLLC use cases**

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