Tutorial on 5G New Radio IFIP/IEEE PEMWN 2019

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Why 5G ?

Some potential 5G applications :

Multimedia

- Ultra HD video
- Immersive and interactive experiences (AR/VR, virtual presence, tactile internet)
- Network games
- Live/streaming/on demand
- Collaborative productions, social networks
- Mobile and adaptive contents
- On demand networking (for temporary events)

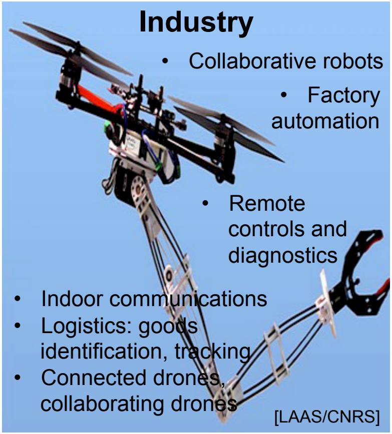
Health

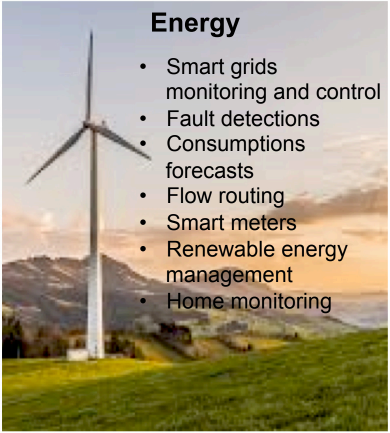
- Tele-surgery
- Bio-connectivity: monitoring, diagnosis, treatment

[Da Vinci]

- Wearable device communications
- Ambulance-hospital communications

Why 5G ?


Industry
• Collaborative robots
• Factory automation
• Remote controls and diagnostics
• Indoor communications
• Logistics: goods identification, tracking
• Connected drones, collaborating drones
[LAAS/CNRS]


Energy
• Smart grids monitoring and control
• Fault detections
• Consumptions forecasts
• Flow routing
• Smart meters
• Renewable energy management
• Home monitoring

Why 5G ?

Public services

- Public safety: operations of first responders in case of emergency or disaster; presence and localization of survivors; low network and terminal energy consumptions
- Public warning system
- Multimedia priority service for police, army, firemen
- Wide area sensor monitoring (forests, air and water quality)
- Private mobile radio (PMR)

Intelligent Transport Systems

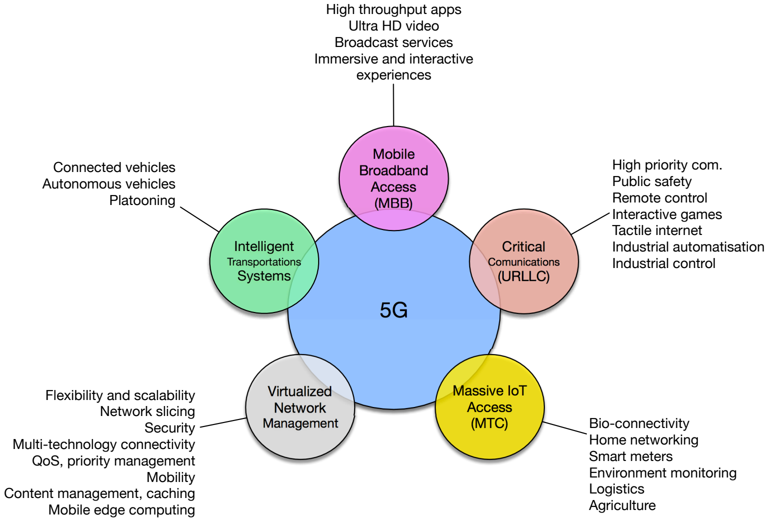
- Real-time control of vehicles
- Driver assistance
- Road traffic monitoring (floating car data)
- Accident prevention
- Remote vehicles diagnostics
- V2X communications
- Platooning
- Mobility support: high quality network access in buses, trains and airplanes

And many others that we don't even know today...
For more information and references : [3GPP 22.891, 2016]

Outlines

Outline

Use cases classification



Use cases classification

The three typical use cases envisioned for 5G :

- eMBB (Enhanced Mobile Broadband) : Low latency, higher spectral efficiency/throughput.
- mMTC (massive Machine Type Communications) : Improved link budget, low device complexity, long device battery life (low energy consumption), support high density device deployment.
- URLLC (Ultra Reliable Low Latency Communications) : High reliability (low packet error rate), low latency.

We can add :

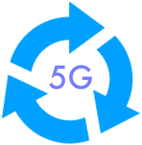
- eV2X (enhanced Vehicle to Everything) : High reliability, low latency, mobility.
- NETOP (network operation) : Flexibility, scalability, security, QoS, mobility.

Outline

Challenges

Mobile Broadband

Peak rate : 20 (DL)/10 (UL) Gbits/s
Peak spectral efficiency : 30/15 bits/s/Hz
5th percentile data rate : 100/50 Mbits/s
Average spectral efficiency : up to 9 bits/s/Hz/TRP
Capacity : 10 Mbits/s/m2
Mobility : up to 500 km/h



Massive Machine Type Communications

1 million connections/km2
(1 message/2hours/device)
Cost : <5€/chip
Energy : up to 10y battery lifetimes

Ultra Reliable and Low Latency Communications

Latency : 1-4 ms
Control plane latency : 10-20 ms
Reliability : 99,99999% success in 1 ms
for a 32 bytes layer 2 packet

[source: IMT-2020 ITU-R M2410]

See [ITU-R M.2410, 2017] for the complete list of requirements.

Outline

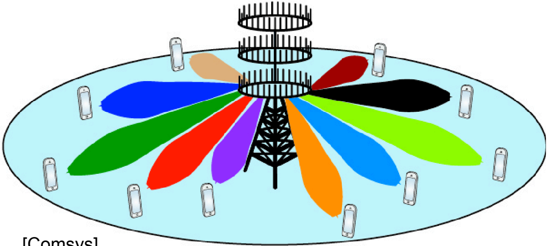
Achieving very high data rates

- Remember the Shannon formula : $C \approx n_{ant} W \log_2(1 + \frac{S}{I+N})$
- In practice however :
  - This is a not achieved upper bound
  - This function is bounded (by C_{max}) because we use finite modulations
  - Capacity should be shared by all active users in the cell
  - Some resources should be dedicated to signaling
- To increase data rates, we have few options :
  - Increase W... but issues with inter-symbol interference, power, spectrum
  - Decrease interference with lower frequency spatial reuse or other ICIC techniques... but less bandwidth per cell
  - Increase C_{max} by densifying the modulation... but the signal is more sensitive to noise and interference
  - Increase n_{ant}... but signal processing algorithm complexity may increases and large antenna form factors
  - Densify the network in order to decrease the number of users per cell... but more sites = more investments

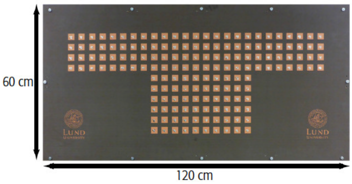
Massive MIMO

Massive MIMO = use >100 antennas to serve >10 users simultaneously on the same frequency. **Full Dimension MIMO** = beamform the signal in azimuth and elevation directions [Kammoun et al., 2019, Björnson et al., 2017, Marzetta, 2010].

- Advantages : high spectral and energy efficiency, simple linear precoding, the effects of noise and fading can be eliminated when the number of antennas is very large.
- Drawbacks/issues : antenna panel size, signalling for channel estimation, pilot contamination. Cell search, initial access and handovers requires a specific beam management.

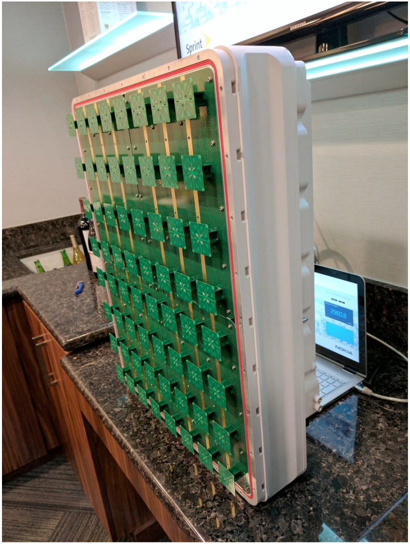


[Comsys]

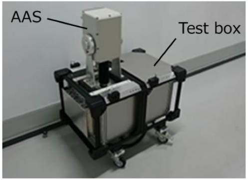


[Lund University: 160 antennes 3.5GHz]

Massive MIMO



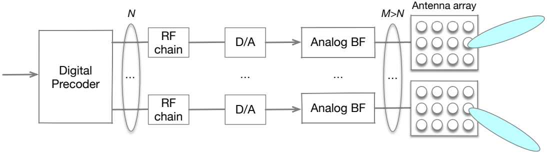
[Nokia: 128 antenna elements at 2.5GHz]

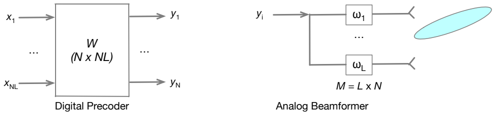


[NEC: 360 antenna elements at 28GHz, height=30cm]

Massive MIMO

Hybrid beamforming : It is still not practical to have fully digital precoder in mm waves because a dedicated RF chain is required per antenna element (space, cost issues).





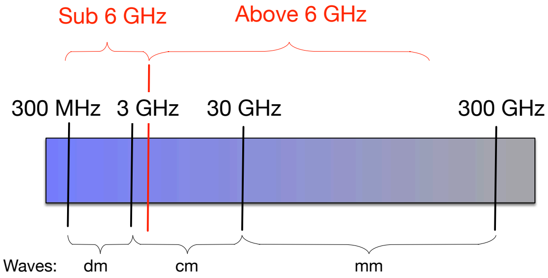
Typically :

- 3.5 GHz : 64 transceiver units, 128 antenna elements, mMIMO used for spatial multiplexing
- 28 GHz : 4 transceiver units, 512 or 1024 antenna elements, mMIMO used for beamforming

mmWaves

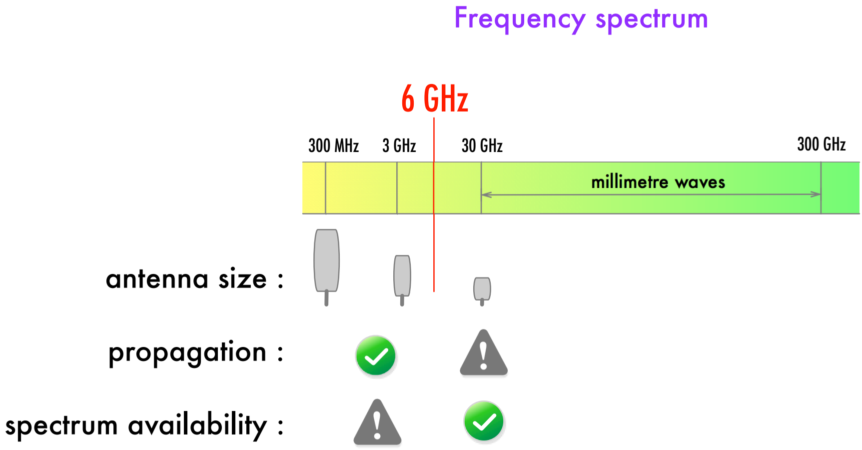
Millimeter Waves = use spectrum bands above 6 GHz.

- Advantages : above 6 GHz (26+41+66), around 11 GHz are available (vs 1.2GHz below), small antennas for massive MIMO, few co-channel interference, can provide both backhaul and access links.
- Drawbacks/issues : difficult propagation conditions (high attenuation, blockage, absorption), baseband and RF processing, modelling and performance.



mmWaves

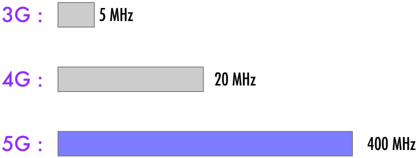
Large spectrum bands are available and antenna sizes are small (proportional to the wave length)



mmWaves

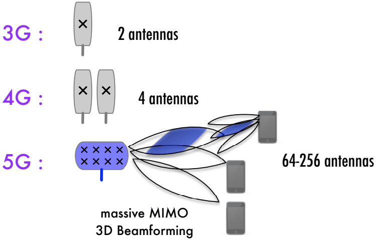
In mm waves, very large bandwidths are possible and the number of antennas can increase drastically

Bandwidth (W)



[NB: first versions of the standard]

Number of antennas (n_{ant})



mmWaves

Channel characteristics at 28 GHz for a cell range of 200 m [Pi and Khan, 2011, Rappaport et al., 2013, Akdeniz et al., 2014] :

- There is a 20-25 dB loss compared to traditional cellular frequencies.
- Rain attenuation and atmospheric absorption characteristics have little impact on the path-loss (less than 2 dB and 0.02 dB resp.).
- Outdoor materials like tinted glass or brick pillars have high penetration losses (30-40 dB), while indoor materials (clear glass and drywall) have moderate losses (4 to 7 dB).
- Outdoor, the average path-loss exponent is 2.55 in LOS and 5.76 in NLOS.
- In NLOS, there are several multipath components at different angles of arrivals (typically 2 to 4 clusters), which makes beam combining and spatial multiplexing feasible.
- Foliage may have a significant impact depending of its depth.

See also [ITU-R M.2376, 2017] for technical feasibility and [ITU-R M.2412, 2017] for channel modeling.

mmWaves

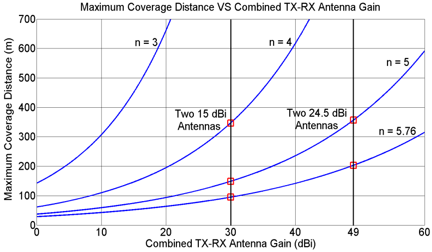


FIGURE 8. **Maximum coverage distance at 28 GHz with 119 dB maximum path loss dynamic range without antenna gains and 10 dB SNR, as a function of path loss exponent n.**

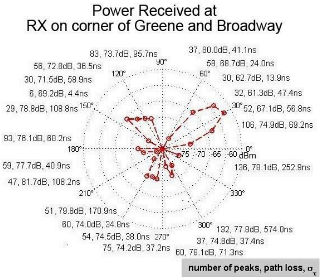
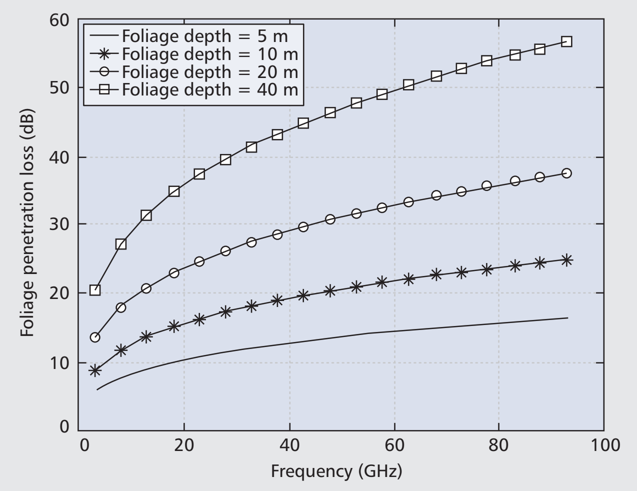


FIGURE 9. **Polar plot showing the received power at a NLOS location. This plot shows an AOA measurement at the RX on Greene and Broadway from the TX on the five-story Kaufman building (78 m T-R separation). The polar plot shows the received power in dBm, the number of resolvable multipath components, the path loss in dB with respect to the 5 m free space reference, and RMS delay spread with varying RX azimuth angles [31].**

In an NLOS dense urban environment, a coverage range of 200 m is possible provided that the net antenna gain is 49 dBi [Rappaport et al., 2013].

mmWaves

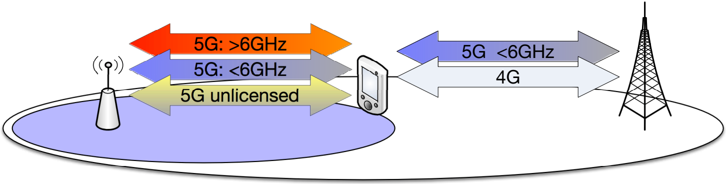


[Pi and Khan, 2011]

Spectrum aggregation and unlicensed bands

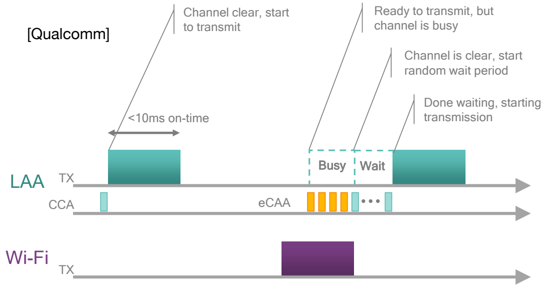
Spectrum aggregation = aggregate carriers and technologies from both licensed and unlicensed spectrum. **Multi-RAT dual connectivity** = connect to different technologies from different nodes. Variants : intraband (contiguous or not), inter-band, only DL or both links.

- Advantages : high data rates when channel conditions are bad and MIMO is not efficient ; smooth integration with existing technologies ; better use of fragmented spectrum (truncking gain) ; load balancing.
- Drawbacks/issues : complex signalling and protocol aspects, tight cooperation between cells (joint scheduling) ; coexistence with other technologies, no QoS guarantee, regulatory requirements in unlicensed bands.



Spectrum aggregation and unlicensed bands

Channel Clear Assesment (CCA) and Listen-Before-Talk (LBT) operation :



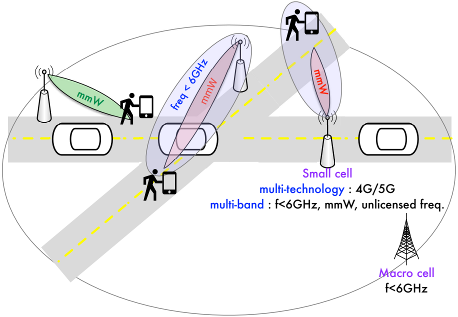
Remarks :

- LTE-U (R12) : only DL ; Licensed Assisted Access (LAA, R13) : only DL+LBT ; eLAA (R14) :UL+DL ; MulteFIRE : stand-alone LTE in unlicensed bands
- New Radio Unlicensed (NR-U) : foreseen for R16, priority on 5GHz and 60GHz bands, stand-alone operation

Heterogeneous networks

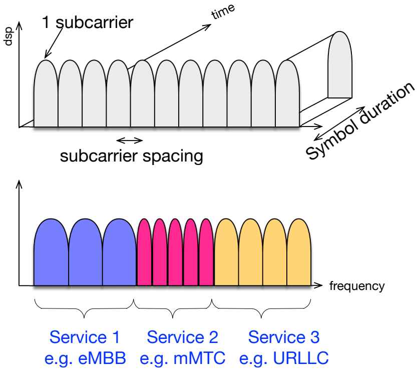
Heterogenous networks = small cells, femto cells, relays complement the macro cell layer. They use multiple bands (incl. unlicensed) and multiple technologies.

- Advantages : increase network capacity (network densification), good channel conditions and low user sharing for high data rates.
- Drawbacks/issues : increase of interference, load balancing ; site planning, sharing ; regulation rules (EM exposure) ; backhaul availability ; maintenance costs.



Flexible numerology

New waveform = CP-OFDM with flexible subcarrier spacing (SCS) and symbol duration.



4G: A single configuration

5G: A flexible numerology

Flexible numerology

- URLLC : requires short symbols for low latency $\Rightarrow$ large SCS
- eMBB : uses large bandwidths, requires not too large FFT $\Rightarrow$ large SCS
- mmW : uses large bandwidths, inter-carrier interference increases with frequency but decreases with SCS $\Rightarrow$ large SCS
- mMTC and sub-6GHz : smaller bandwidths and larger cells (more inter-symbol interference) $\Rightarrow$ short SCS

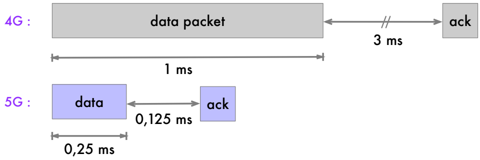
Table – Waveform design principles

	URLLC	eMBB	mMTC	mmW	Freq.<6GHz
Large SCS	✓	✓		✓	
Short SCS			✓		✓

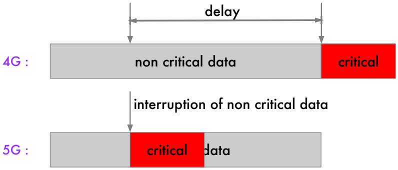
Mini-slots and dynamic TDD

Low latency = no fixed timing relations, dynamic TDD, self-contained slots, semi-persistent scheduling and grant free transmission, DL preemption of the ressources.

Very low latency



Ressource preemption



Mini-slots and dynamic TDD

Dynamic TDD = a transmission can start at any OFDM symbol (this is the notion of "mini-slot" transmission).

- Advantages : allows very flexible scheduling, very fast ACK/NACK feedback, very low latencies. The flexible starting time is useful when listen-before-talk is used in unlicensed bands.
- Drawbacks/issues : may require additional signalling, creates new co-channel inter-cell interference issues.

D	D	D	D	D	D	D	D	D	D	D	D	D	D
U	U	U	U	U	U	U	U	U	U	U	U	U	U
X	X	X	X	X	X	X	X	X	X	X	X	X	X
D	D	D	D	D	D	D	D	D	D	D	D	D	X
D	D	D	D	D	D	D	D	D	D	D	D	X	X

...

D	D	D	D	D	X	U	D	D	D	D	D	X	U

...

A slot is made of 14 OFDM symbols.

Mini-slots and dynamic TDD

Examples of slot formats (source :Ericsson) :

(a) Heavy downlink transmission with uplink feedback.

(b) Heavy uplink transmission with downlink feedback.

(c) Very short time critical downlink transmission with immediate uplink ack (no need to wait for a slot boundary) or transmission in unlicensed band (transmit asap the channel is free) or in mmWaves (few symbols may carry sufficient volume of data).

(d) Slot aggregation for heavy downlink transmission.

(a)	D	D	D	D	D	D	D	D	D	D	D	D	X	U														
(b)	D	X	U	U	U	U	U	U	U	U	U	U	U	U														
(c)	X	X	X	X	D	D	X	U	X	X	X	X	X	X														
(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	D	X	U

Mini-slots and dynamic TDD

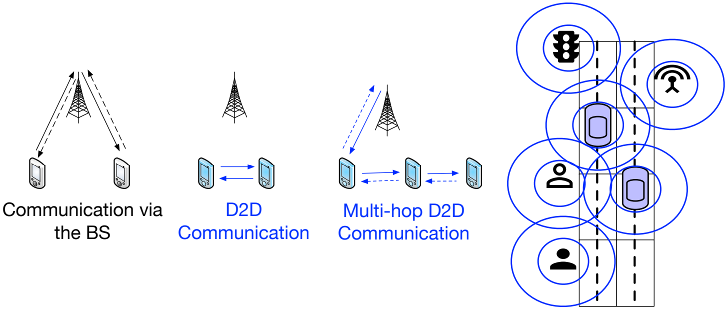
The slot format has an impact on several performance and planning aspects :

- DL/UL ratio : related to the amount of traffic in both directions.
- # of DL/UL switching points : more frequent switching points means lower latency, better channel estimation (positive impact, especially at high speed) and fast HARQ feedback. However, more guard periods are required and so more resources are lost.
- Coverage : large cells require long guard periods at every switching point.
- Coexistence : In France, the first deployment of 5G will be in the 3.5 GHz band. In order to avoid adjacent channel interference with LTE-TDD, slot format should be aligned between the two technologies.

Device-to-Device communications

Device to device = direct communications between terminals.

- Advantages : increase network capacity, low latency, good channel conditions for high data rates.
- Drawbacks/issues : increase of interference, resource management, signalling and synchronization.

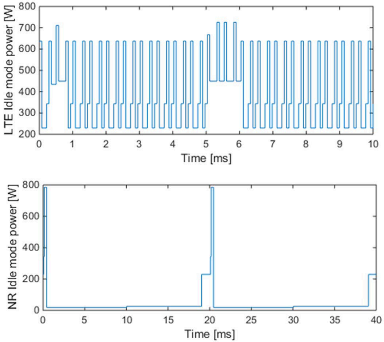


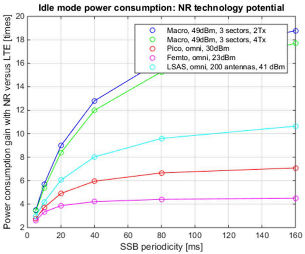
Lean design

Lean design = minimize "always on" transmission

- Advantages : forward compatibility, energy saving.
- Drawbacks/issues : delays, loss of synchronization.

In LTE, there are always on signals like reference signals, synchronization signals, broadcast of system information. In NR : reference signals are sent only when needed, longer periodicity, new sleep modes, improved dependence on load [Frenger and Tano, 2019].

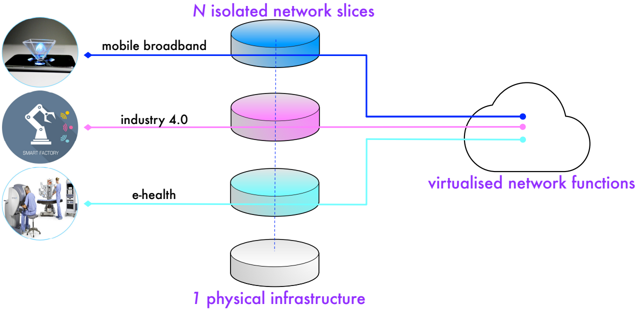




Virtualization

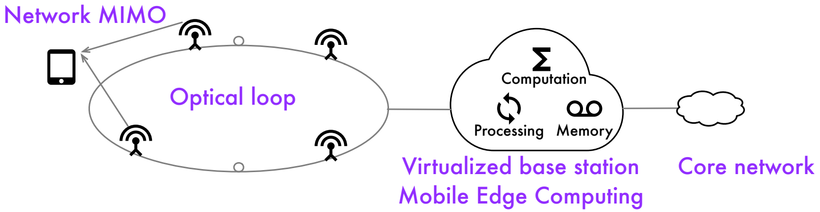
Virtualization = network functions are not anymore associated to a specific hardware, there are in programmable in software and located in a cloud made of generic hardware. Virtualization allows **network slicing** and **mobile edge computing**.
Network slice = a collection of network functions that support the communication requirements of particular uses case(s).

- Advantages : flexibility, scalability, isolation between slices.
- Drawbacks/issues : delays, security issues.



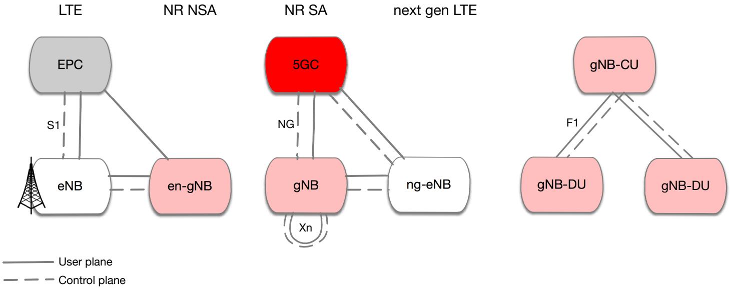
Virtualization

Mobile Edge Computing = signal processing, CPU and memory-intensive applications, caching is performed in an edge cloud ; radio signal is carried over fiber to simple radio heads ; coordination between antennas is made easier.



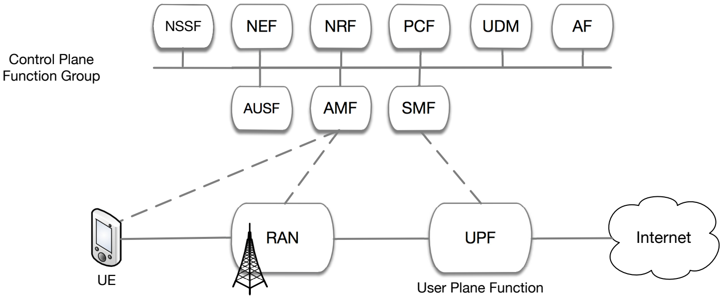
Outline

Architecture



- Non Stand Alone (NSA) : Initial deployments, dual connectivity with LTE
- Stand Alone (SA) : After R16
- For more information : [3GPP 38.401, 2018]

Architecture



- A service based architecture.
- AMF : Access and Mobility, SMF : Session Mgt, PCF : Policy Control, NEF : Network Exposure, NRF : Network Repository, UDM : Unified Data Mgt, AUSF : Authentication Server, AF : Application Function, NSSF : Network Slice Selection
- For more information : [3GPP 23.501, 2018]

Frequency bands and channel bandwidths

- Two *frequency ranges* are defined : FR1 (450 MHz - 6 GHz) and FR2 (24.25 GHz - 52.6 GHz)
- There is a list of possible *operating bands*. Each operating band is characterized by a frequency range (FR1 or FR2), a UL/DL band, a duplex mode, applicable SCS and BS/UE bandwidths.
- Examples of operating bands in FR1 :

Designation	FR	UL [MHz]	DL [MHz]	Duplex mode
n66	FR1	1710 – 1780	2110 – 2200	FDD
n78	FR1	3300 – 3800	3300 – 3800	TDD
n261	FR2	27500-28350		TDD

- Examples : In n66, subcarrier spacings 15, 30, and 60 kHz are applicable and BS/UE bandwidth are at most 40 MHz. In n78, same subcarrier spacings, BS/UE bandwidth up to 100 MHz. In n261, subcarrier spacing of 60 or 120 kHz, BS/UE bandwidth from 50 to 400 MHz.
- For more information : [3GPP 38.101, 2019, 3GPP 38.104, 2019]

Frequency bands and channel bandwidths

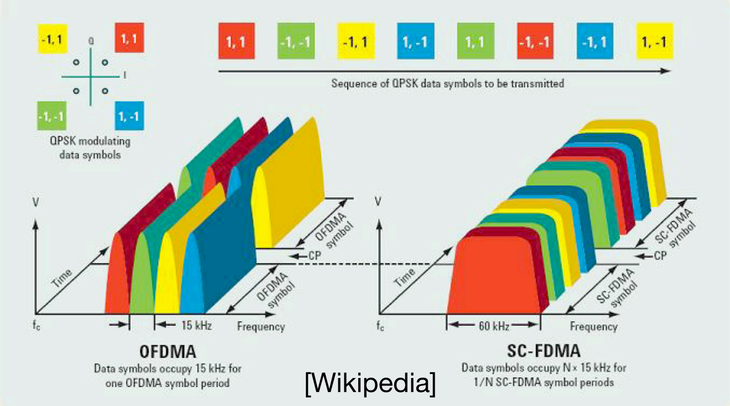
Although the standard defined a very wide range of possible bands, some are of particular interest (european perspective) :

- 700 MHz with maximum bandwidth of 20 MHz for coverage and/or machine-type communications.
- 1400 MHz only for downlink as a supplementary carrier for enhancing capacity.
- 3.4-3.8 GHz with maximum bandwidth of 100 MHz for capacity. The "core" band for 5G in early phases.
- 26 GHz with maximum bandwidth of 400 MHz for hot spots and small cells.
- Later : 42 GHz and 66-71 GHz.

Below 6 GHz, around 1.2 GHz may be available for mobile communications ; above 6 GHz (26+41+66), around 11 GHz are available.

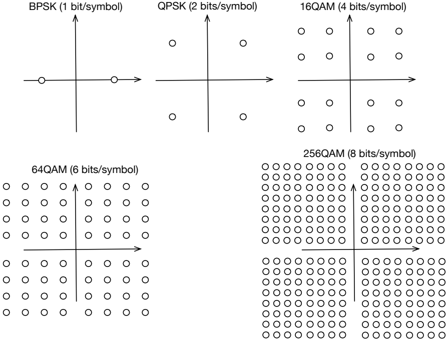
Duplexing and multiplexing

- **Duplexing** will be mainly FDD below 6 GHz and TDD above. Small/isolated cell can adopt dynamic TDD, while macro cells semi-static TDD or FDD.
- **Multiplexing** is OFDMA for DL and UL with SC-FDMA as an option for UL (for coverage limited scenarios).



Modulations

- **Modulations** : up to 256QAM (in both DL and UL) ; $\pi/2$-BPSK in UL for reduced PAPR and better amplifier efficiency at low data rates for IoT.



Coding

- Control channels : Reed-Muller block codes and CRC assisted polar codes [Arikan, 2009] (vs. tail-bitting convolutional codes in LTE).
- **Data channels** use rate compatible (for IR-HARQ) quasi-cyclic Low-Density Parity Check Codes (LDPC vs. Turbo codes in 3G, 4G).
- LDPC has been invented by Gallager in the 60's [Gallager, 1962], ignored for a long time and rediscovered in the 90's [MacKay and Neal, 1997].
- Already adopted in WiFi, DVB or ATSC.
- Compared to Turbo codes :
  - LDPC have usually similar performance but higher performance at high code rates
  - LDPC encoding and decoding is less complex
  - LDPC allow for a greater parallelism and thus lower decoding delay

[Richardson and Kudekar, 2018, Hui et al., 2018]

Coding

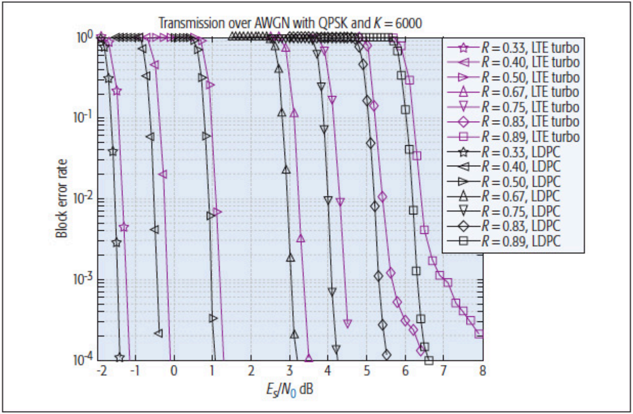
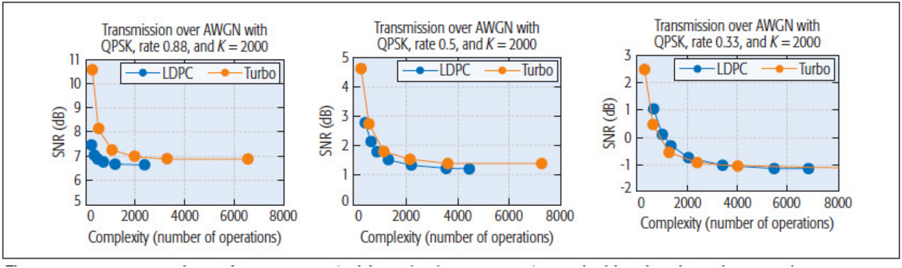


Figure 1. Performance comparison between LDPC with sum-product (SP) decoding and LTE turbo with log-MAP decoding. Both are decoded using their optimal decoders with sufficiently large number of iterations. The plot highlights the fundamental differences in the code structure itself.

from [Richardson and Kudekar, 2018]

Coding



from [Richardson and Kudekar, 2018]

Numerology

- NR supports different subcarrier spacings to support different kinds of services.
- Different numerologies are derived from a base by a scaling factor. They are time aligned and the number of OFDM symbols per subframe is constant.
- The cyclic prefix overhead is approximately constant (about 6%), except for an extended prefix configuration at 60 kHz subcarrier spacing.
- It may be possible to multiplex different numerologies on the same carrier.
- Configurations :
  - $f_c < 6$ GHz : $\mu \in \{0, 1, 2\}$ and bandwidth is from 5 MHz to 100 MHz
  - $f_c > 6$ GHz : $\mu \in \{2, 3\}$ and bandwidth is from 50 MHz to 400 MHz

Numerology

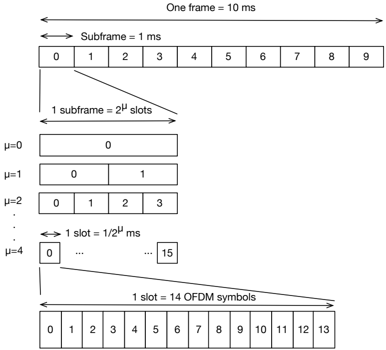
Table – Numerology

Subcarrier spacing config μ	0	1	2	3	4
Subcarrier spacing [kHz]	15	30	60	120	240
Symbol duration [μs]	66.7	33.3	16.6	8.33	4.17
Nominal cyclic prefix [μs]	4.7	2.41	1.205	0.6	0.3
Nominal max bandwidth [MHz]	49.5	99	188	396	397.4
Max FFT size	4096	4096	4096	4096	2048
Nb of symb/slot	14	14	14	14	14
Slot duration [ms]	1	0.5	0.25	0.125	0.0625

$\mu \in \{0, 1, 3, 4\}$ for PSS, SSS and PBCH, $\mu \in \{0, 1, 2, 3\}$ for other channels.
[3GPP 38.211, 2018]

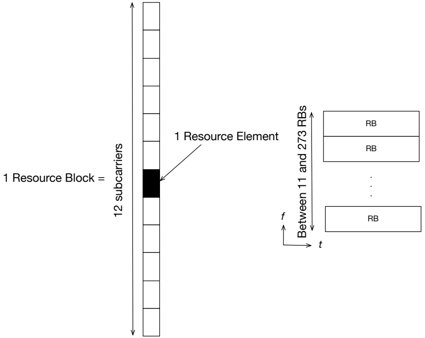
Frame Structure

- Regardless of the numerology, subframe and frame durations are constant (all numerologies align in time at subframe boundaries).
- The number of OFDM symbols per slot is always 14 for the normal prefix.



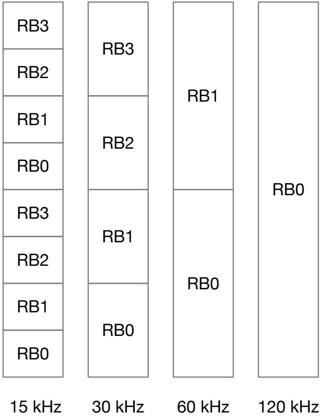
Resource Blocks and Resource Elements

- Resource Blocks are defined in the frequency domain as 12 consecutive subcarriers. There are bw 11 and 273 RBs (depending on the signal bandwidth).
- 1 RB during 1 OFDM symbol is called a Resource Element Group (REG).
- A Resource Element is defined as 1 subcarrier during 1 OFDM symbol on 1 antenna port for 1 subcarrier spacing configuration.

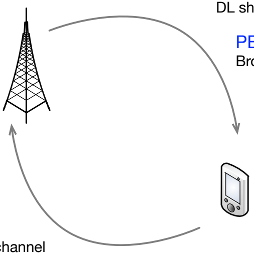


Resource Blocks and Resource Elements

RB alignment across subcarrier spacings :



Physical Channels



PDSCH
DL shared channel

PBCH
Broadcast channel

PDCCH
DL control channel

DL Physical Signals
Demodulation Reference Signals
Phase-tracking RS
Channel State Information RS
Primary Sync PSS
Secondary Sync SSS

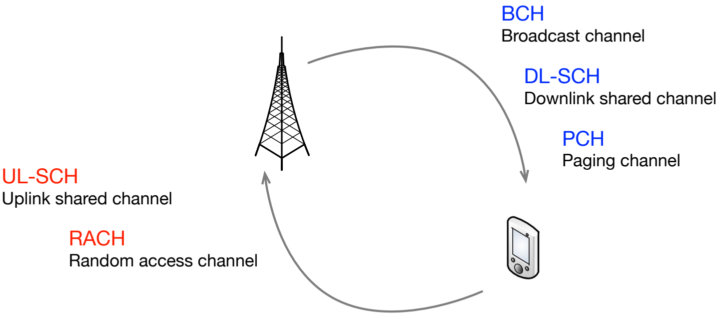
PUSCH
UL shared channel

PUCCH
UL control channel

PRACH
Random access channel

UL Physical Signals
Demodulation RS
Phase-tracking RS
Sounding RS

Transport Channels



Logical Channels

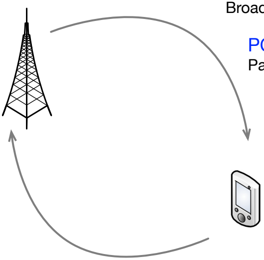
BCCH
Broadcast control channel

PCCH
Paging control channel

CCCH
Common control channel

DCCH
Dedicated control channel

DTCH
Dedicated traffic channel



CCCH
Common control channel

DCCH
Dedicated control channel

DTCH
Dedicated traffic channel

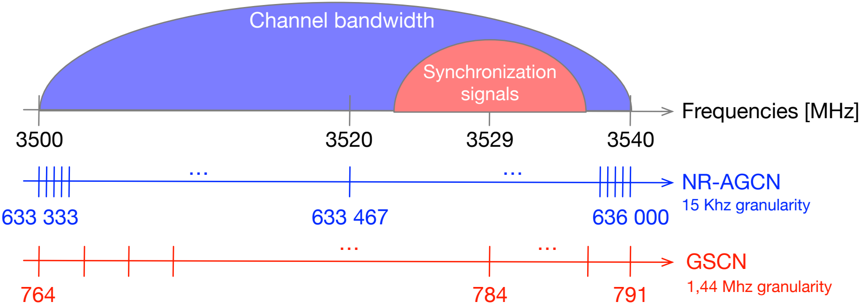
Cell search

Goal : acquiring time and frequency synchronisation, cell ID and system information

1. Find SSB in the synchronization raster
2. Get relative position of the SSB in the carrier bandwidth from PBCH
3. Get timing/beam index of the SSB from PBCH
4. Get initial CORESET from PBCH
5. Get SIB1 scheduling from CORESET

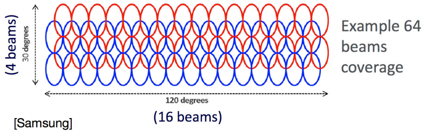
Cell search

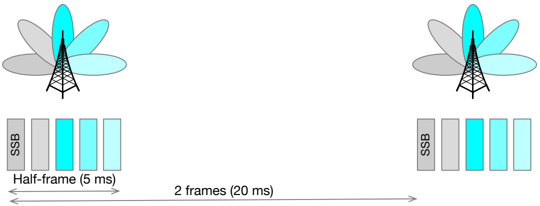
Example of channel and synchronization raster values around 3.5 GHz :

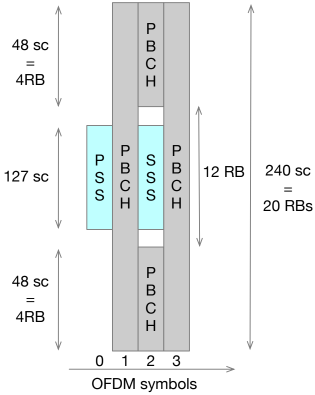


Cell search

Synchronization blocks :



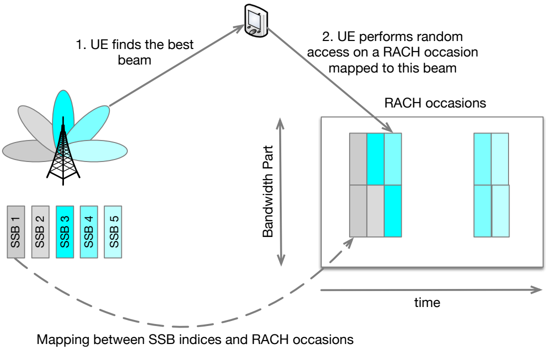




- PSS and SSS are used to determine slot boundaries and cell ID
- PBCH carries basic system information like control channel information, SSB/beam index

Random access

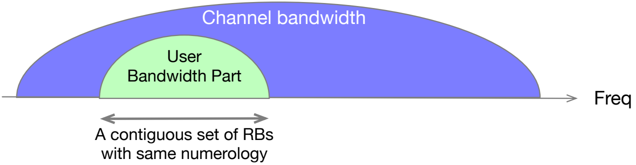
- The PRACH resources and the preamble format to be used are provided to the UE in the system information.
- Open loop power control and power ramping are applied.



Data transmission

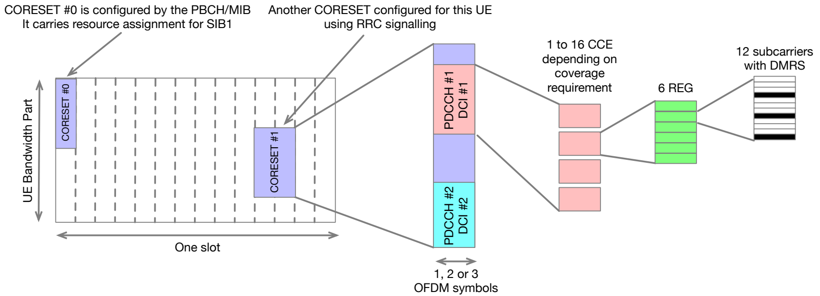
Bandwidth Parts (BWP) : "Stay in the box" !

- A UE can be active only on a narrow part of the NR carrier bandwidth (e.g. to reduce energy consumption or for low-end devices).
- With bandwidth adaptation, the receive and transmit bandwidth of a UE can be adjusted :
  - the width (e.g. the BWP can shrink in case of low activity to save power)
  - the location (to increase scheduling flexibility)
  - the subcarrier spacing (to adapt to different services)
- BWPs are configured at the UE. The network can inform the UE to dynamically change its active BWP.



Data transmission

Control Resource Sets (CORESETs) :

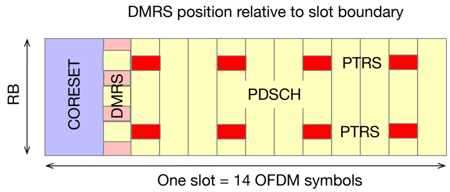


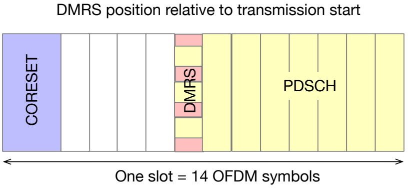
- A CORESET is a time-frequency resource where control channels PDCCH may be located. Contrary to LTE, it does not span the entire bandwidth.
- The location and the size of the CORESETs are semi-statically configured by RRC. Rather at the beginning of the slot but not necessary.
- Different code rates are available by aggregating CCEs.

Reference Signals

Demodulation Reference Signals (DRMS) for coherent demodulation.

- Support variable nb. of antenna ports, very short transmissions, high-speed scenarios
- Front-loaded : the receiver can decode on the fly for lower latency
- DMRS at the beginning of the slot : PDSCH occupies most of the slot
- DMRS at the beginning of the transmission : PDSCH short transmissions

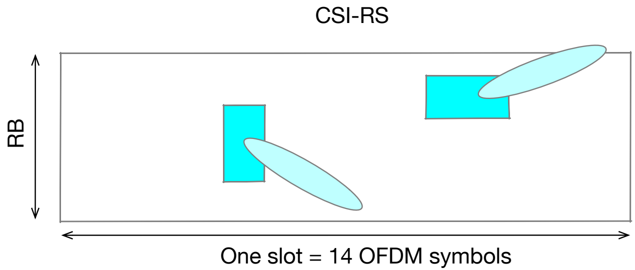




Reference Signals

Channel State Information Reference Signals (CSI-RS) for channel sounding on the DL

- Configured on a per-UE basis to avoid "always on" signals.
- Several UEs share the same set of CSI-RS.
- CSI-RS for different antenna ports are multiplexed in time, frequency or code
- Periodic, semi-persistent (may desactivated) or aperiodic (the UE is informed)



Some words on future releases

R16 expected for beg. of 2020 (R17 for end of 2021).

VERTICALS	SYSTEM IMPROVEMENTS
V2X Industrial IoT URLLC	Unlicensed bands Enhancements for eMBB

- V2X : platooning, extended sensors, automated driving, remote driving.
- IIoT and URLLC : for factory automation with the goal of replacing wired Ethernet
- Unlicensed bands : LAA and standalone operation
- eMBB enhancements : positioning, MIMO, power consumption, dual connectivity, SON, interference mitigation, mobility, etc.

[3GPP 21.916, 2019, Balazs Bertenyi, 2019]

Some words on future releases

R17 expected for end of 2021. Some potential work areas (decisions in Dec 2019) :

- NR light for mid-tier devices
- NR above 52.6GHz with decision on waveform
- Multi-SIM operation
- NR multicast and broadcast mainly for V2X and public safety
- NR for non terrestrial networks
- Data collection to enable AI and SON
- Enhancements in small data transfer, D2D, coverage, IoT, URLLC, MIMO, integrated access and backhaul.

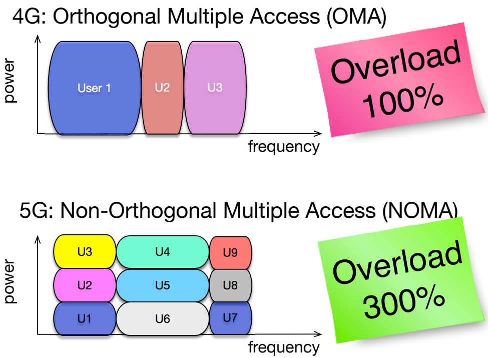
[Balazs Bertenyi, 2019]

Outline

NOMA

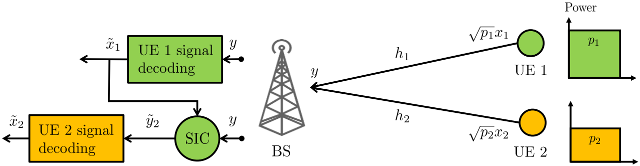
Non-Orthogonal Multiple Access = several users share the same resource, based on Successive Interference Cancellation (SIC).

- Advantages : capacity achieving scheme, more simultaneous connections (goal is 10x the number of connections in 4G).
- Drawbacks/issues : residual interference, resource allocation, complex receivers.

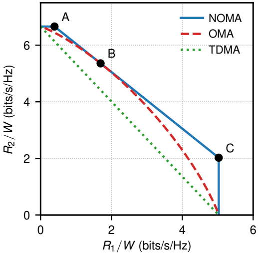


NOMA

NOMA principle on the UL :

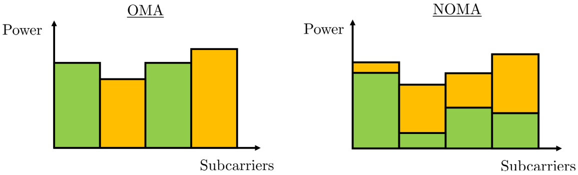


This technique is known to achieve the optimal rate region :



NOMA

NOMA resource allocation consists in assigning subcarriers and powers to users in order to maximize e.g. a weighted sum rate under power constraints (global or per subcarrier) and a maximum number of users per subcarrier.

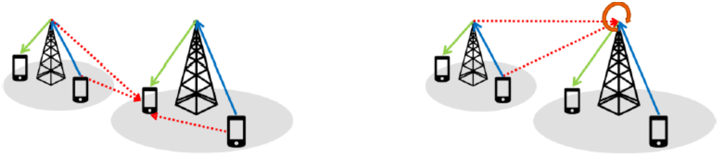


- There are approximation algorithms in the literature for single cell, see e.g. [Lei et al., 2016, Salaün et al., 2019].
- The problem is open in multi-cell scenarios, incl. with cell cooperation (e.g. CoMP+NOMA) [Ali et al., 2018, Kudathanthirige and Baduge, 2019] or with overlapping of subcarriers [Al-Eryani and Hossain, 2019, Kim et al., 2019].
- Imperfect SIC, connection density maximization, uplink grant-free NOMA are other topics of interest.

Full Duplex

Full Duplex = the possibility to transmit and receive on the same frequency channel at the same time, based on self interference cancellation.

- Advantages : potentially double the spectral efficiency for a point-to-point communication.
- Drawbacks/issues : there is residual interference, new interference scenarios arise in a multi-cell scenario that limit the gains in practice.



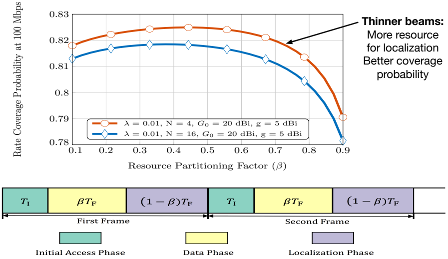
(a) Downlink in FD (b) Uplink in FD

The DL is improved, the cell spectral efficiency is increased but the UL is degraded [Arrano-Scharager et al., 2018]. Difficult to envision for macro cells even with perfect self-IC.

Localization with mmWaves

mmWaves allows accurate **localization** (<1m, incl. orientation of the user) thanks to large bandwidths and antenna arrays with single anchor in both LOS and NLOS [Abu-Shaban et al., 2018]. A trade-off arises between localization and data rate :

- Allocating more resources to the communication phase increases the data rate.
- Lower localization accuracy leads to beam selection and beam alignment errors and thus lower data rate.



[Destino and Wymeersch, 2017, Ghatak et al., 2018]

Towards 6G ?

Some possible hot topics to imagine 6G :

- THz communications
- Visible light communications
- Cell-less architectures
- Intelligent meta-surfaces
- Zero-battery devices and wireless transfer
- ML physical layer design
- ML based resource allocation
- AI based network optimization

6G for what ? Telepresence ? What about energy consumption ?

References I

[3GPP 21.916, 2019] 3GPP 21.916 (2019).
3GPP TS 21.916 : Release 16 Description ; Summary of Rel-16 Work Items .

[3GPP 22.891, 2016] 3GPP 22.891 (2016).
3GPP TS 22.891 : Feasibility Study on New Services and Markets Technology Enablers.

[3GPP 23.501, 2018] 3GPP 23.501 (2018).
3GPP TS 23.501 : System Architecture for the 5G System.

[3GPP 38.101, 2019] 3GPP 38.101 (2019).
3GPP TS 38.101 : User Equipment (UE) radio transmission and reception.

[3GPP 38.104, 2019] 3GPP 38.104 (2019).
3GPP TS 38.104 : Base Station (BS) radio transmission and reception.

[3GPP 38.211, 2018] 3GPP 38.211 (2018).
3GPP TS 38.211 : Physical channels and modulation.

References II

[3GPP 38.401, 2018] 3GPP 38.401 (2018).
3GPP TS 38.401 : NG-RAN ; Architecture Description.

[Abu-Shaban et al., 2018] Abu-Shaban, Z., Zhou, X., Abhayapala, T., Seco-Granados, G., and Wymeersch, H. (2018).
Error bounds for uplink and downlink 3d localization in 5g millimeter wave systems.
IEEE Transactions on Wireless Communications, 17(8) :4939–4954.

[Akdeniz et al., 2014] Akdeniz, M. R., Liu, Y., Samimi, M. K., Sun, S., Rangan, S., Rappaport, T. S., and Erkip, E. (2014).
Millimeter wave channel modeling and cellular capacity evaluation.
IEEE journal on selected areas in communications, 32(6) :1164–1179.

[Al-Eryani and Hossain, 2019] Al-Eryani, Y. and Hossain, E. (2019).
The d-oma method for massive multiple access in 6g : Performance, security, and challenges.
IEEE Vehicular Technology Magazine, 14(3) :92–99.

References III

[Ali et al., 2018] Ali, M. S., Hossain, E., Al-Dweik, A., and Kim, D. I. (2018).
Downlink power allocation for comp-noma in multi-cell networks.
IEEE Transactions on Communications, 66(9) :3982–3998.

[Arikan, 2009] Arikan, E. (2009).
Channel polarization : A method for constructing capacity-achieving codes for symmetric binary-input memoryless channels.
IEEE Transactions on information Theory, 55(7) :3051–3073.

[Arrano-Scharager et al., 2018] Arrano-Scharager, H.-F., Coupechoux, M., and Kelif, J.-M. (2018).
Full and half duplex-switching policy for cellular networks under uplink degradation constraint.
In *2018 IEEE International Conference on Communications (ICC)*, pages 1–7. IEEE.

[Balazs Bertenyi, 2019] Balazs Bertenyi (2019).
RAN Rel-16 progress and Rel-17 potential work areas.

References IV

[Björnson et al., 2017] Björnson, E., Hoydis, J., Sanguinetti, L., et al. (2017).
Massive mimo networks : Spectral, energy, and hardware efficiency.
Foundations and Trends® in Signal Processing, 11(3-4) :154–655.

[Destino and Wymeersch, 2017] Destino, G. and Wymeersch, H. (2017).
On the trade-off between positioning and data rate for mm-wave communication.
In *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*, pages 797–802. IEEE.

[Frenger and Tano, 2019] Frenger, P. and Tano, R. (2019).
More capacity and less power : How 5g nr can reduce network energy consumption.
In *2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring)*, pages 1–5. IEEE.

[Gallager, 1962] Gallager, R. (1962).
Low-density parity-check codes.
IRE Transactions on information theory, 8(1) :21–28.

References V

[Ghatak et al., 2018] Ghatak, G., Koirala, R., De Domenico, A., Denis, B., Dardari, D., and Uguen, B. (2018).
Positioning data-rate trade-off in mm-wave small cells and service differentiation for 5g networks.
In *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, pages 1–5. IEEE.

[Hui et al., 2018] Hui, D., Sandberg, S., Blankenship, Y., Andersson, M., and Grosjean, L. (2018).
Channel coding in 5g new radio : A tutorial overview and performance comparison with 4g lte.
ieee vehicular technology magazine, 13(4) :60–69.

[ITU-R M.2376, 2017] ITU-R M.2376 (2017).
ITU-R M.2376 : Technical feasibility of IMT in bands above 6 GHz.

[ITU-R M.2410, 2017] ITU-R M.2410 (2017).
ITU-R M.2410 : Minimum requirements related to technical performance for IMT-2020 radio interface(s).

References VI

[ITU-R M.2412, 2017] ITU-R M.2412 (2017).
ITU-R M.2412 : Guidelines for evaluation of radio interface technologies for IMT-2020.

[Kammoun et al., 2019] Kammoun, A., Alouini, M.-S., et al. (2019).
Elevation beamforming with full dimension mimo architectures in 5g systems : A tutorial.
IEEE Communications Surveys & Tutorials.

[Kim et al., 2019] Kim, B., Park, Y., and Hong, D. (2019).
Partial non-orthogonal multiple access (p-noma).
IEEE Wireless Communications Letters.

[Kudathanthirige and Baduge, 2019] Kudathanthirige, D. and Baduge, G. A. A. (2019).
Noma-aided multicell downlink massive mimo.
IEEE Journal of Selected Topics in Signal Processing, 13(3) :612–627.

References VII

[Lei et al., 2016] Lei, L., Yuan, D., Ho, C. K., and Sun, S. (2016).
Power and channel allocation for non-orthogonal multiple access in 5g systems : Tractability and computation.
IEEE Transactions on Wireless Communications, 15(12) :8580–8594.

[MacKay and Neal, 1997] MacKay, D. J. and Neal, R. M. (1997).
Near shannon limit performance of low density parity check codes.
Electronics letters, 33(6) :457–458.

[Marzetta, 2010] Marzetta, T. L. (2010).
Noncooperative cellular wireless with unlimited numbers of base station antennas.
IEEE transactions on wireless communications, 9(11) :3590–3600.

[Pi and Khan, 2011] Pi, Z. and Khan, F. (2011).
An introduction to millimeter-wave mobile broadband systems.
IEEE communications magazine, 49(6) :101–107.

References VIII

[Rappaport et al., 2013] Rappaport, T. S., Sun, S., Mayzus, R., Zhao, H., Azar, Y., Wang, K., Wong, G. N., Schulz, J. K., Samimi, M., and Gutierrez, F. (2013).
Millimeter wave mobile communications for 5g cellular : It will work !
IEEE access, 1 :335–349.

[Richardson and Kudekar, 2018] Richardson, T. and Kudekar, S. (2018).
Design of low-density parity check codes for 5g new radio.
IEEE Communications Magazine, 56(3) :28–34.

[Salaün et al., 2019] Salaün, L., Coupechoux, M., and Chen, C. S. (2019).
Weighted sum-rate maximization in multi-carrier noma with cellular power constraint.
In *IEEE INFOCOM 2019-IEEE Conference on Computer Communications*, pages 451–459. IEEE.