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
- Wearable device communications
- Ambulance-hospital communications

[Da Vinci]
Why 5G?

**Industry**
- Collaborative robots
- Factory automation
- Remote controls and diagnostics
- Indoor communications
- Logistics: goods identification, tracking
- Connected drones, collaborating drones

**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

1. Introduction
2. Use cases classification
3. Challenges
4. Key enablers
5. 5G NR radio interface
6. Some research topics
Outline

1 Introduction
2 Use cases classification
3 Challenges
4 Key enablers
5 5G NR radio interface
6 Some research topics
Use cases classification

High throughput apps
- Ultra HD video
- Broadcast services
- Immersive and interactive experiences

5G
- Critical Communications (URLLC)
- Massive IoT Access (MTC)
- Mobile Broadband Access (MBB)
- Intelligent Transportations Systems
- Virtualized Network Management

5G features:
- Flexibility and scalability
- Network slicing
- Security
- Multi-technology connectivity
- QoS, priority management
- Mobility
- Content management, caching
- Mobile edge computing

Use cases:
- Connected vehicles
- Autonomous vehicles
- Platooning

- High priority com.
- Public safety
- Remote control
- Interactive games
- Tactile internet
- Industrial automatisation
- Industrial control

- Bio-connectivity
- Home networking
- Smart meters
- Environment monitoring
- Logistics
- Agriculture

- Content management, caching
- Mobile edge computing
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.
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Challenges

Mobile Broadband

5G

Massive Machine Type Communications

- 1 million connections/km²
- (1 message/2 hours/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

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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.
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 1.2 GHz 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.

![Diagram showing frequency bands for sub-6 GHz and above-6 GHz](image-url)
mmWaves

Large spectrum bands are available and antenna sizes are small (proportional to the wave length)
In mm waves, very large bandwidths are possible and the number of antennas can increase drastically.

### Bandwidth (W)

<table>
<thead>
<tr>
<th>Generation</th>
<th>Bandwidth (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3G</td>
<td>5</td>
</tr>
<tr>
<td>4G</td>
<td>20</td>
</tr>
<tr>
<td>5G</td>
<td>400</td>
</tr>
</tbody>
</table>

### Number of antennas \( n_{\text{ant}} \)

<table>
<thead>
<tr>
<th>Generation</th>
<th>Antennas</th>
</tr>
</thead>
<tbody>
<tr>
<td>3G</td>
<td>2</td>
</tr>
<tr>
<td>4G</td>
<td>4</td>
</tr>
<tr>
<td>5G</td>
<td>64-256</td>
</tr>
</tbody>
</table>

[NB: first versions of the standard]
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.

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].
Key enablers

mmWaves

[Foliage depth = 5 m]

Foliage depth = 10 m

Foliage depth = 20 m

Foliage depth = 40 m

[Fri 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 (trunking 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 Assessment (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

**Heterogeneous 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

Service 1: e.g. eMBB  
Service 2: e.g. mMTC  
Service 3: e.g. URLLC
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>
<thead>
<tr>
<th></th>
<th>URLLC</th>
<th>eMBB</th>
<th>mMTC</th>
<th>mmW</th>
<th>Freq. &lt; 6GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large SCS</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Short SCS</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
Key enablers

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 resources.

**Very low latency**

<table>
<thead>
<tr>
<th>4G</th>
<th>5G</th>
</tr>
</thead>
<tbody>
<tr>
<td>data packet</td>
<td>data</td>
</tr>
<tr>
<td>1 ms</td>
<td>0.125 ms</td>
</tr>
<tr>
<td>0.25 ms</td>
<td>0.25 ms</td>
</tr>
</tbody>
</table>

**Ressource preemption**

<table>
<thead>
<tr>
<th>4G</th>
<th>5G</th>
</tr>
</thead>
<tbody>
<tr>
<td>non critical data</td>
<td>critical data</td>
</tr>
<tr>
<td>delay</td>
<td>interruption of non critical data</td>
</tr>
</tbody>
</table>
**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.

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.
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].

![Graphs showing power consumption over time and frequency](image-url)
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.
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Architecture

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


For more information: [3GPP 23.501, 2018]
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:

<table>
<thead>
<tr>
<th>Designation</th>
<th>FR</th>
<th>UL [MHz]</th>
<th>DL [MHz]</th>
<th>Duplex mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>n66</td>
<td>FR1</td>
<td>1710 – 1780</td>
<td>2110 – 2200</td>
<td>FDD</td>
</tr>
<tr>
<td>n78</td>
<td>FR1</td>
<td>3300 – 3800</td>
<td>3300 – 3800</td>
<td>TDD</td>
</tr>
<tr>
<td>n261</td>
<td>FR2</td>
<td>27500-28350</td>
<td></td>
<td>TDD</td>
</tr>
</tbody>
</table>

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

$\mu \in \{0, 1, 3, 4\}$ 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.
RB alignment across subcarrier spacings:

<table>
<thead>
<tr>
<th></th>
<th>RB3</th>
<th>RB2</th>
<th>RB1</th>
<th>RB0</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>120 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MC (Telecom Paris)
Physical Channels

**5G NR radio interface**

**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

**UL Physical Signals**
- Demodulation RS
- Phase-tracking RS
- Sounding RS

**MC (Telecom Paris)**

Tutorial on 5G NR – PEMWN 2019

28 Nov. 2019
Transport Channels

- BCH: Broadcast channel
- DL-SCH: Downlink shared channel
- PCH: Paging channel
- UL-SCH: Uplink shared channel
- RACH: Random access channel
Logical Channels

- **BCCH**: Broadcast control channel
- **PCCH**: Paging control channel
- **CCCH**: Common control channel
- **DCCH**: Dedicated control channel
- **DTCH**: Dedicated traffic channel
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

![Diagram of 5G NR radio interface](image)
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.

1. UE finds the best beam
2. UE performs random access on a RACH occasion mapped to this beam

Mapping between SSB indices and RACH occasions
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.

![Diagram](image)
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

![Diagram showing DMRS position relative to slot boundary and transmission start.]
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)

One slot = 14 OFDM symbols
**Some words on future releases**

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

- 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]
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1. Introduction
2. Use cases classification
3. Challenges
4. Key enablers
5. 5G NR radio interface
6. Some research topics
**Non-Orthogonal Multiple Access (NOMA)**

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.

### 4G: Orthogonal Multiple Access (OMA)

<table>
<thead>
<tr>
<th>User 1</th>
<th>U2</th>
<th>U3</th>
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<tbody>
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<td>Power</td>
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<td>Frequency</td>
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**Overload 100%**

### 5G: Non-Orthogonal Multiple Access (NOMA)

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<tr>
<th>U1</th>
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<th>U4</th>
<th>U5</th>
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**Overload 300%**
NOMA principle on the UL:

This technique is known to achieve the optimal rate region:
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.

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?
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