1014I – Communication systems and cybersecurity (2025/26)

Wireless technologies for access networks

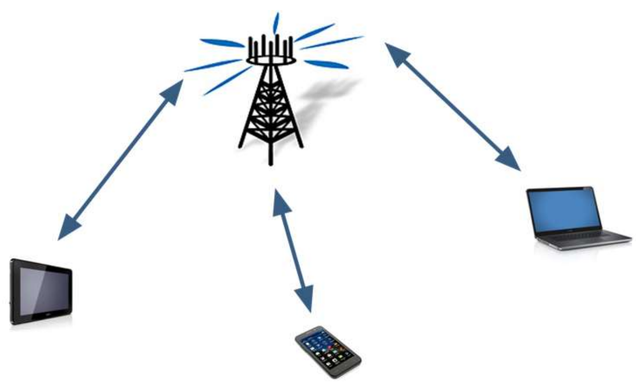
Giacomo Bacci
giacomo.bacci@unipi.it

Università di Pisa, Dip. Ingegneria dell'Informazione

Basic concepts of cellular communications

Wireless communication systems

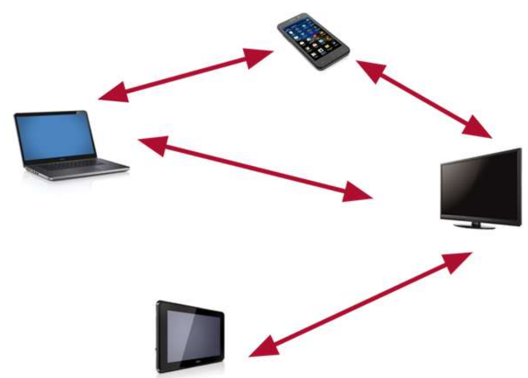
infrastructure networks



- higher rates
- lower latencies

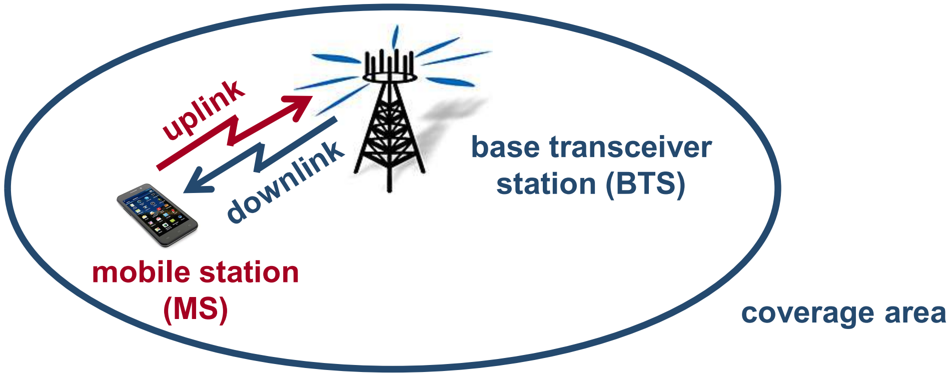
Examples:
- cellular networks
- WLANs
- paging systems

ad-hoc networks



- lower deployment costs
- useful in impaired environments

An elementary wireless system



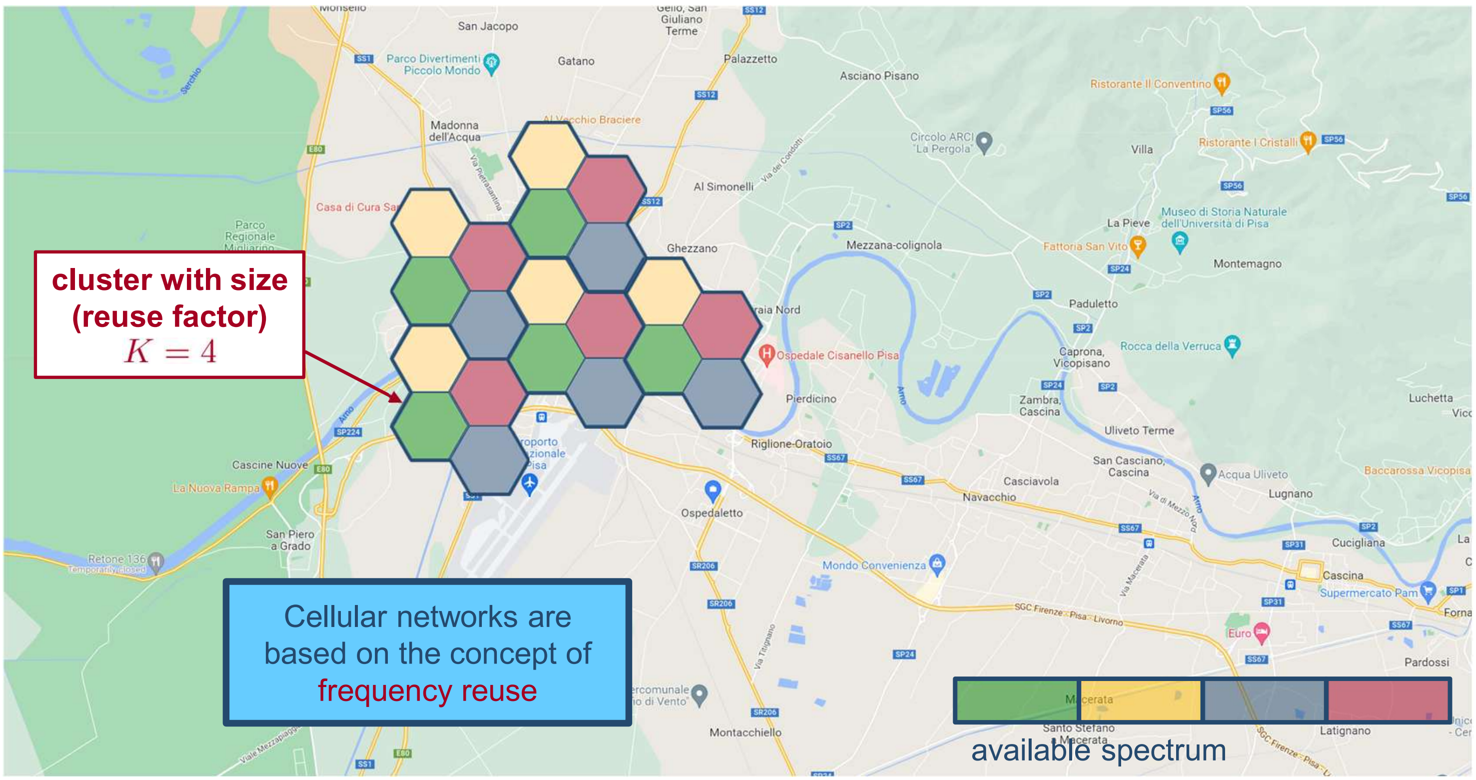
Note: This is not a cellular system, it can be labeled as a 0G system (1940s)

Constraints:
- limited frequency range (due to licensed spectrum)
- limited coverage area (due to power masks)

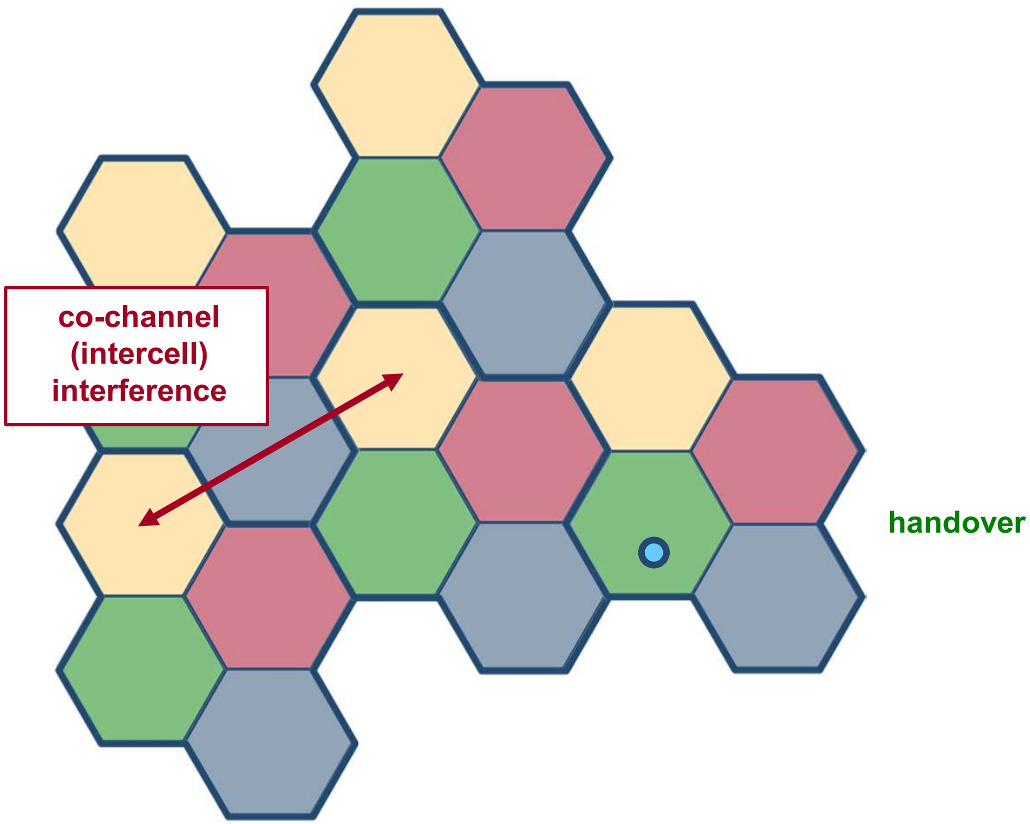
Features:
- low density of users (per unit of area)
- discontinued service when exiting the coverage area

The concept of a cellular network (1/4)

End of 1950s/beginning of 1960s: introducing cells to provide seamless coverage



The concept of a cellular network (2/4)



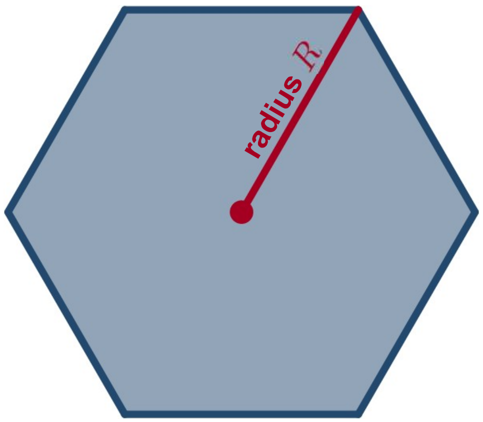
The concept of a cellular network (3/4)

The handover (or handoff) procedure can be managed:

- by the network only, based on measurements and information exchange across network nodes
- with the participation of the MS, which assists the network to properly choose the connection parameters to be modified

The concept of cellular network (4/4)

"Classical" shape (i.e., coverage area) of a cell:



$$A_{\text{cell}} = 6 \cdot \frac{\sqrt{3}}{4} R^2 = \frac{3\sqrt{3}}{2} R^2$$

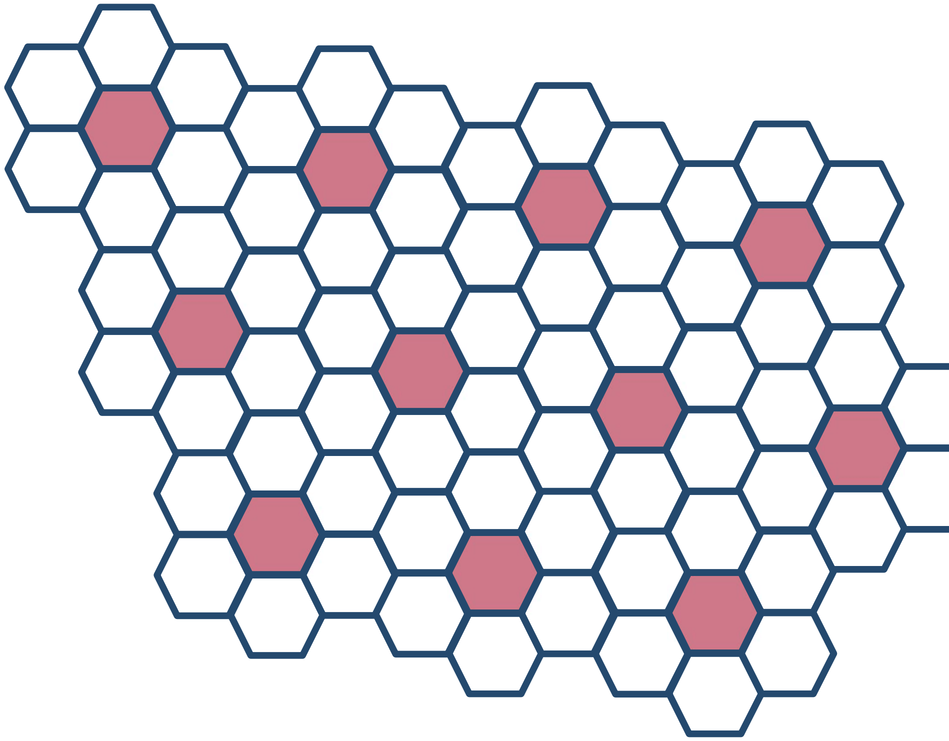
The hexagon is a good tradeoff between actual coverage of omni-directional antennas and simplicity of the shape (e.g., areas can be filled without holes and overlapping)

Planning of a cellular network

Introduction

Some key performance indicators (KPIs):

- spectral efficiency [b/s/Hz]
- energy efficiency [b/J]
- area spectral efficiency [b/s/Hz/m^2]
- handover frequency
- capital expenditure (CapEx) and operating expenditure (OpEx) costs
- …



Goal

As an exercise, let's try to design a cellular network:

Degrees of freedom:

- Reuse factor K
- Cell radius R

System KPIs:

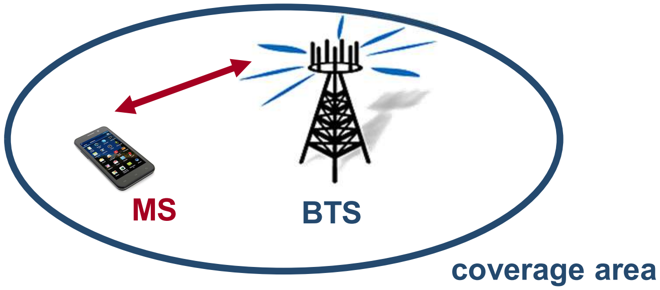
- Transmit power P_{T}
- Handoff rate μ_{H}
- User density u
- Minimum SIR $\underline{\xi}$

KPI	$R \uparrow$	$K \uparrow$
P_{T}	$\uparrow$ (✗)	$\leftrightarrow$
μ_{H}	$\downarrow$ (✓)	$\uparrow$ (✗)
u		
$\underline{\xi}$		

User density (1/4)

Goal: Host as many MSs as possible in the system, given a fixed set of resources (spectrum, transmit powers, MS and BS complexity, …)

Going back to the single-cell scenario, the trivial solution is to extend the coverage area



However, the drawbacks are greatly larger than the advantages: increased transmit power, increased bandwidth needed, …

User density (2/4)

To identify a key performance indicator (KPI) of the network, we can define the user geographical density as follows:

$$u = \frac{N}{A_{\text{cell}}}$$

where N is the maximum number of simultaneously active users in the network, and A_{cell} is the coverage area of the system

Note: increasing u is beneficial from both a network perspective (e.g., more subscriptions available) and a user perspective (e.g., better quality of experience)

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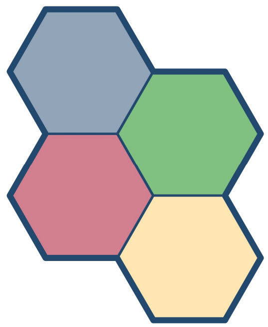
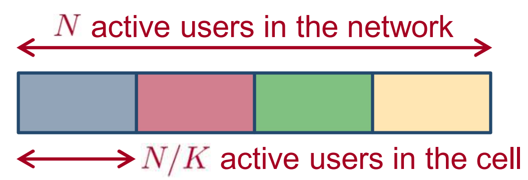
User density (3/4)

Let us consider a cellular network with cluster size (and thus reuse factor) K





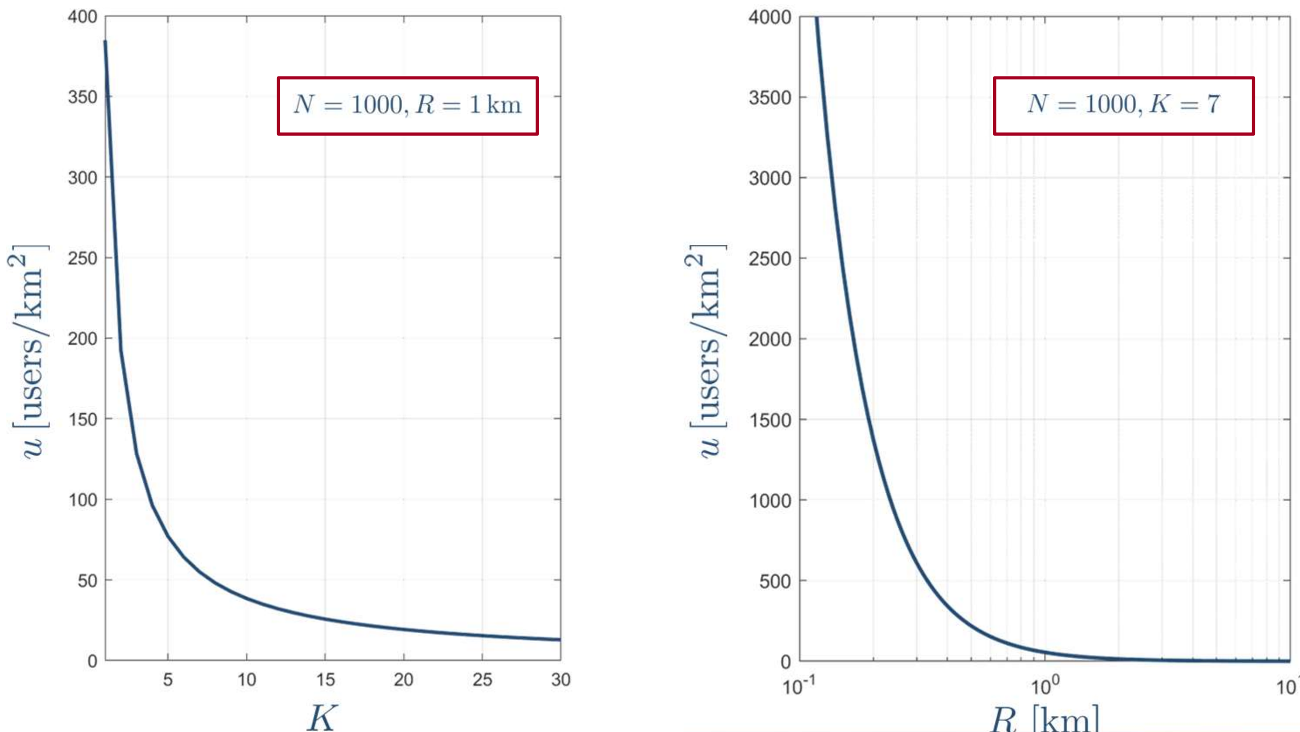
In this scenario, the user density becomes

$$u = \frac{N_{\text{cell}}}{A_{\text{cell}}}$$

$$= \frac{N/K}{3\sqrt{3}R^2/2} = \frac{2}{3\sqrt{3}R^2} \cdot \frac{N}{K}$$

User density (4/4)

$$u = \frac{N/K}{3\sqrt{3}R^2/2} = \frac{2}{3\sqrt{3}R^2} \cdot \frac{N}{K}$$



Goal revisited

As an exercise, let's try to design a cellular network:

Degrees of freedom:

- Reuse factor K
- Cell radius R

System KPIs:

- Transmit power P_{T}
- Handoff rate μ_{H}
- User density u
- Minimum SIR $\underline{\xi}$

KPI	$R \uparrow$	$K \uparrow$
P_{T}	$\uparrow$ (✗)	$\leftrightarrow$
μ_{H}	$\downarrow$ (✓)	$\uparrow$ (✗)
u	$\downarrow$ (✗)	$\downarrow$ (✗)
$\underline{\xi}$		

Signal-to-interference ratio (1/2)

The reuse distance is ancillary to evaluate another KPI of the network, the signal-to-interference ratio (SIR) ξ, defined as

$$\xi = \frac{C}{I}$$

where C is the received power associated to the desired user, and I is the (total) received power due to unintended users sharing the same resource taken by the desired user

Note: For simplicity, let us focus on strictly orthogonal multiple-access schemes, such as FDMA and TDMA, and let us neglect the impact of additive noise

Signal-to-interference ratio (2/2)

In general, the received power depends on the transmitter-receiver distance d according to

$$P_{\mathsf{Rx}}(d) = G_{\mathsf{Tx}} G_{\mathsf{Rx}} P_{\mathsf{Tx}} \left(\frac{\lambda}{4\pi d} \right)^n$$

where P_{Tx} is the transmit power, G_{Tx}(resp., G_{Rx}) is the transmit (resp., received) antenna gain, λ is the carrier wavelength, and n is the propagation path loss, that depends on the considered scenario

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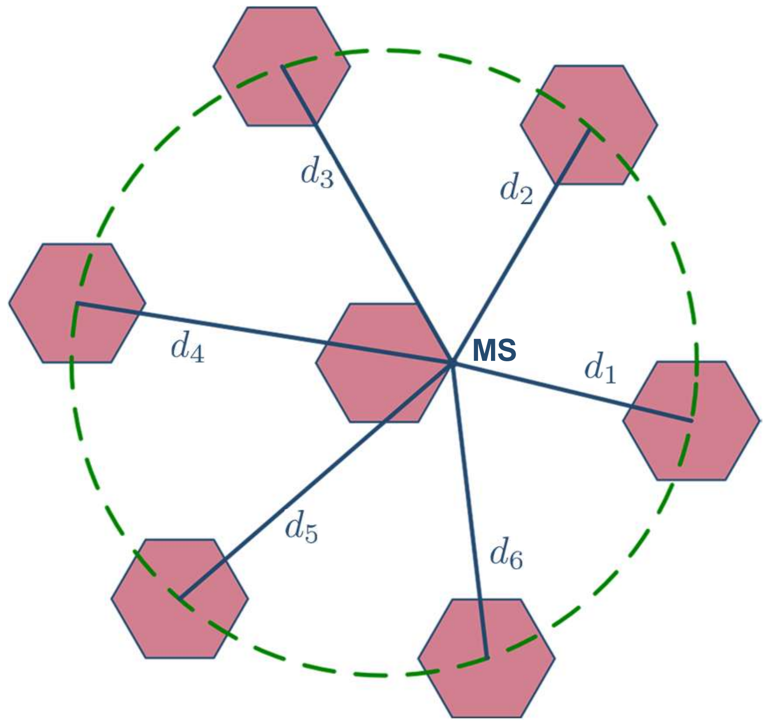
Downlink SIR (1/5)

Let us focus on the downlink segment, and let us consider the worst-case scenario:

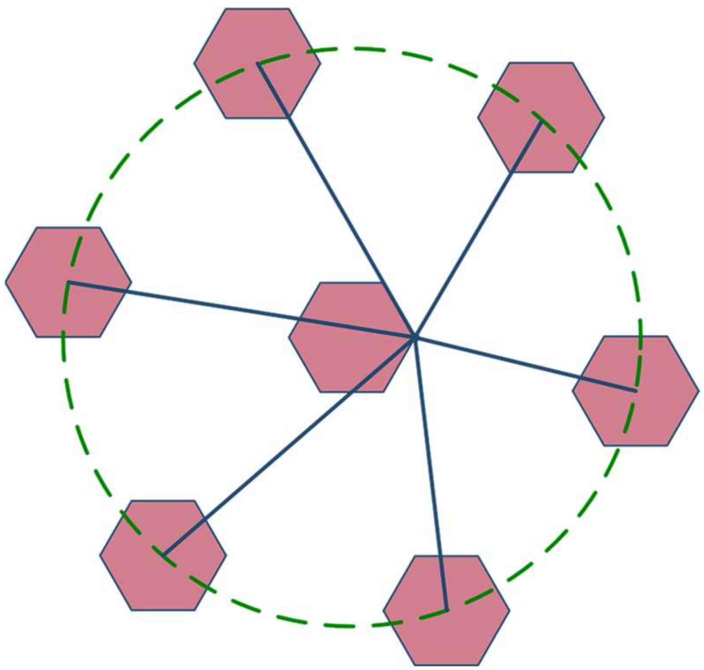


$d_k \approxeq D \quad \forall k$
when $K \gg 1$

Downlink SIR (2/5)

When computing ξ in the downlink, let us make the following simplifying assumptions:

- BTSs are located at the cell center
- Both the MS and the BTSs adopt omnidirectional antenna patterns
- Only the six first-tier co-channel interfering cells are considered
- Transmit powers are equal across all BTSs
- Propagation model is common across all nodes



Downlink SIR (3/5)

Under this hypothesis, the received power of the useful signal is

$$C = P_{\mathsf{Rx}}(R) = \frac{\chi}{R^n}$$

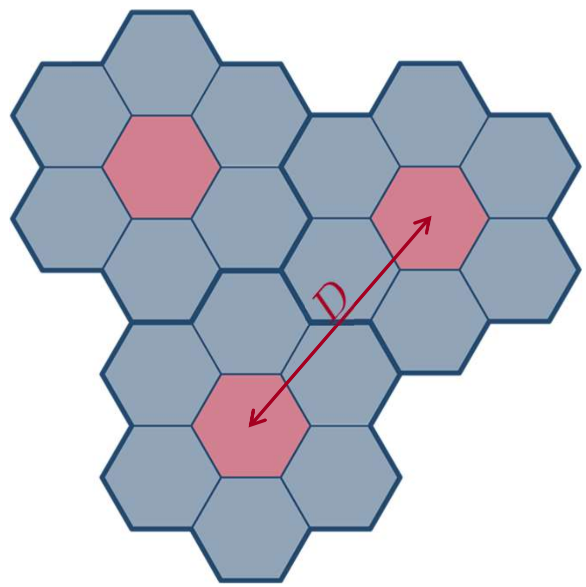
where $\chi = G_{\mathsf{Rx}} G_{\mathsf{Tx}} P_{\mathsf{Tx}} \lambda^n / (4\pi)^n$

Similarly, the interference from the *k*th BTS is

$$I_k = P_{\mathsf{Rx}}(d_k) \approx \frac{\chi}{D^n}$$

Reuse distance (1/4)

A fundamental parameter which impacts the performance of a cellular network is the **reuse distance** D:



Reuse distance (2/4)

In the attempt to calculate the reuse distance D, we need to better characterize the cluster size K

Experimentally, the only acceptable K's are those fulfilling

$$K = i^2 + j^2 + i \cdot j, \quad \text{with} \quad i, j \in \mathbb{N}, i + j \neq 0$$

i	0	0	0	1	1	1	1	2	2	2	3
j	1	2	3	1	2	3	4	2	3	4	3
K	1	4	9	3	7	13	21	12	19	28	27

≥3G (K = 1) — 2G (K = 9, 7) — 1G (K = 21, 19)

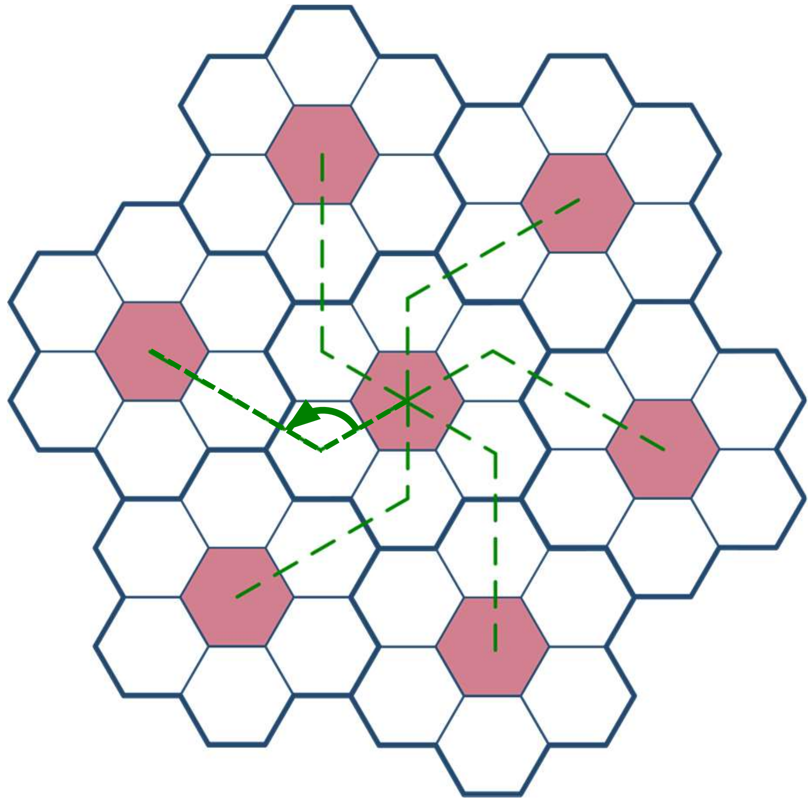
Reuse distance (3/4)

To find the first-tier co-channel interfering cell, we need to:

a) move i cells perpendicularly to one of the cell edges from the center

b) rotate $\alpha = 2\pi/3 = 120°$ (counter) clockwise

c) move j cells



$K(i = 1, j = 2) = 1^2 + 2^2 + 1 \cdot 2 = 7$

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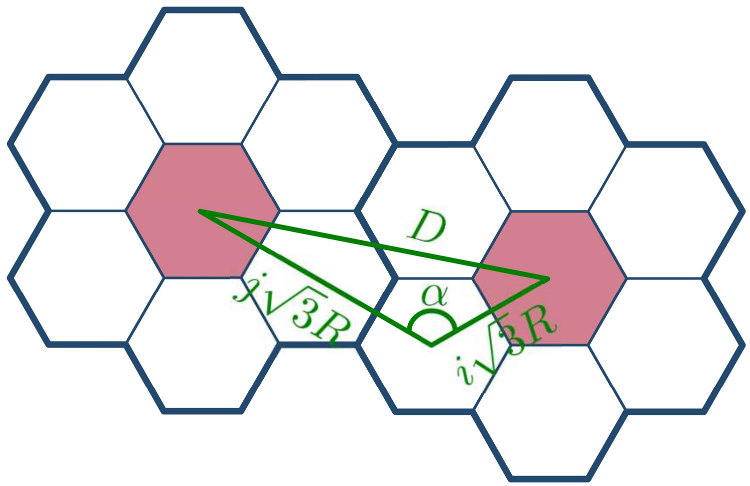
Reuse distance (4/4)



Using Carnot's theorem,

$$D = \sqrt{\left(i\sqrt{3}R\right)^2 + \left(j\sqrt{3}R\right)^2 - 2\left(i\sqrt{3}R\right)\left(j\sqrt{3}R\right)\cos\alpha}$$
$$= \sqrt{3\left(i^2 + j^2 + ij\right)}R = \sqrt{3K}R$$

Downlink SIR (4/5)

Since we are considering the worst-case scenario,

$$\xi \geq \frac{C}{\sum_{k=1}^{6} I_k} = \frac{(D/R)^n}{6}$$

Considering that $D = \sqrt{3K}R$

$$\xi \geq \xi_{\text{dl}} \triangleq \frac{(3K)^{n/2}}{6}$$

The larger the SIR, the better the performance: hence, increasing K is beneficial in terms of network performance in the downlink

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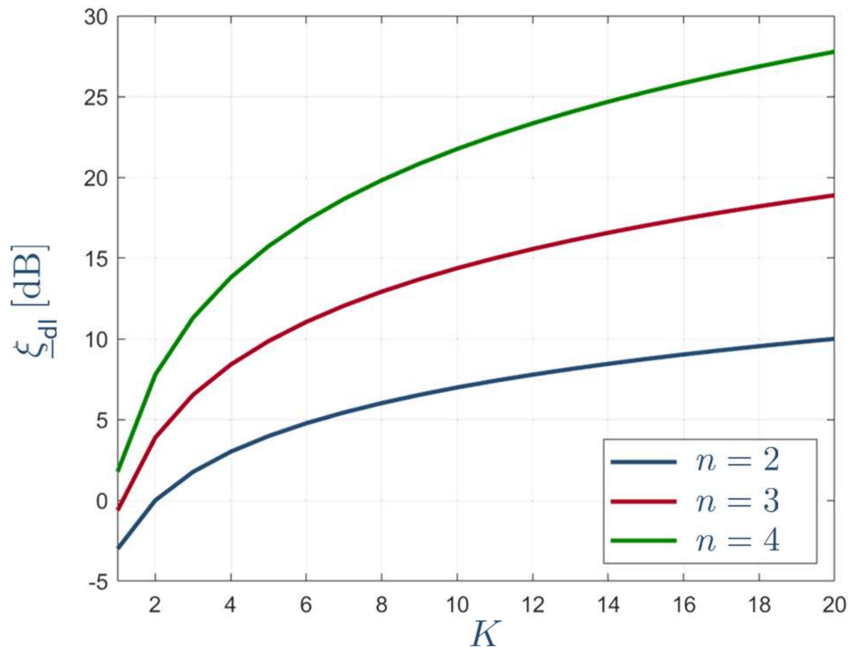
Downlink SIR (5/5)

$$\underline{\xi}_{\mathsf{dl}} \triangleq (3K)^{n/2}/6$$



Summary of the main tradeoffs

To sum up, designing a cellular network is a cumbersome task, even when we take the following simplifications:

Degrees of freedom:

- Reuse factor K
- Cell radius R

System KPIs:

- Transmit power P_T
- Handover rate μ_H
- User density u
- Minimum SIR $\underline{\xi}$

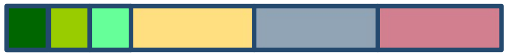
KPI	$R \uparrow$	$K \uparrow$
P_T	$\uparrow$ (✗)	$\leftrightarrow$
μ_H	$\downarrow$ (✓)	$\uparrow$ (✗)
u	$\downarrow$ (✗)	$\downarrow$ (✗)
$\underline{\xi}$	$\leftrightarrow$	$\uparrow$ (✓)

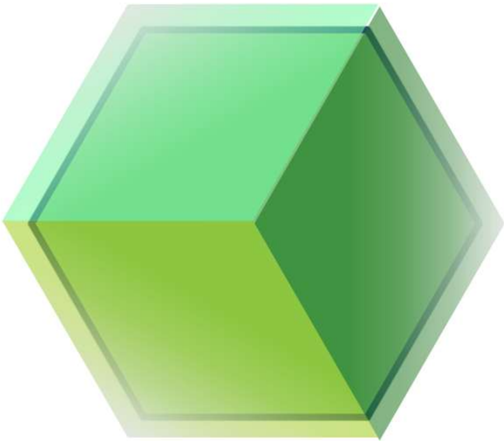
Improving the downlink SIR (1/3)

Many techniques exist to further mitigate the co-channel interference in the downlink

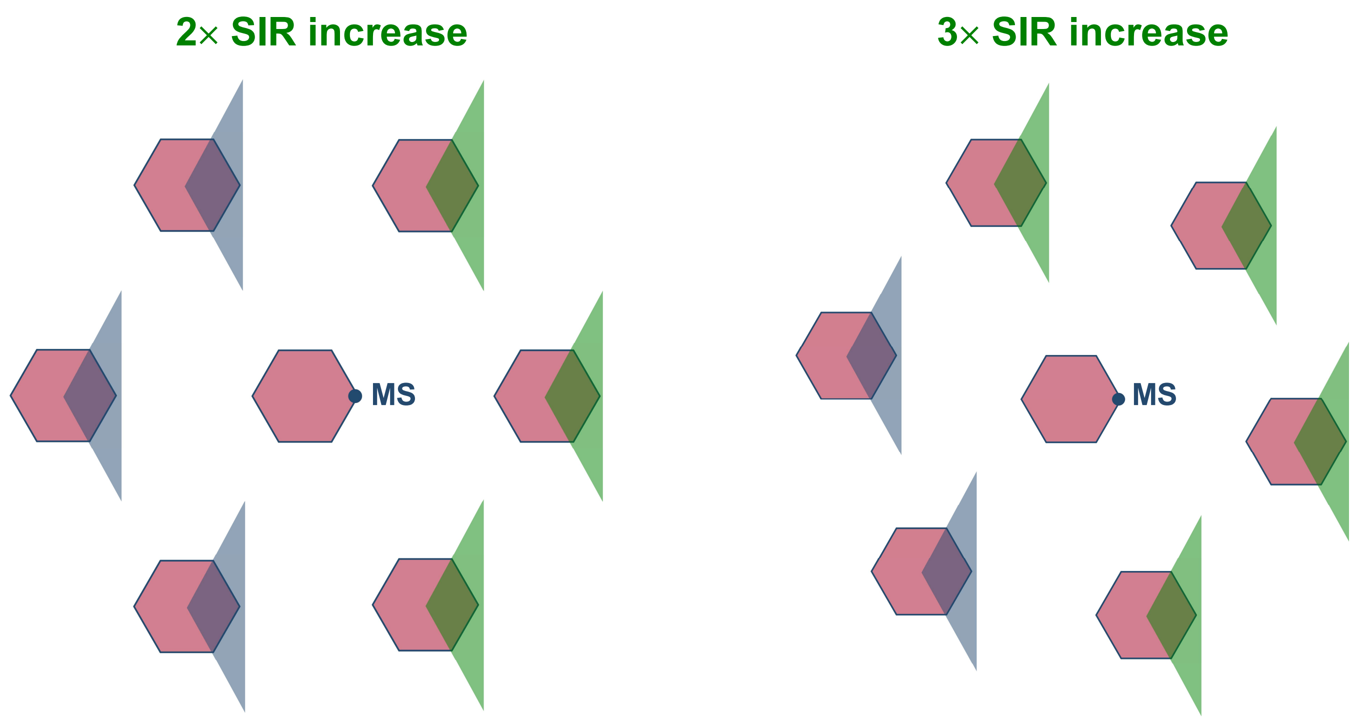
One of the simplest techniques is using cell sectoring at the BTS

Example: 120° antenna aperture





Improving the downlink SIR (2/3)



Drawbacks: increase in the number of antennas and handoffs

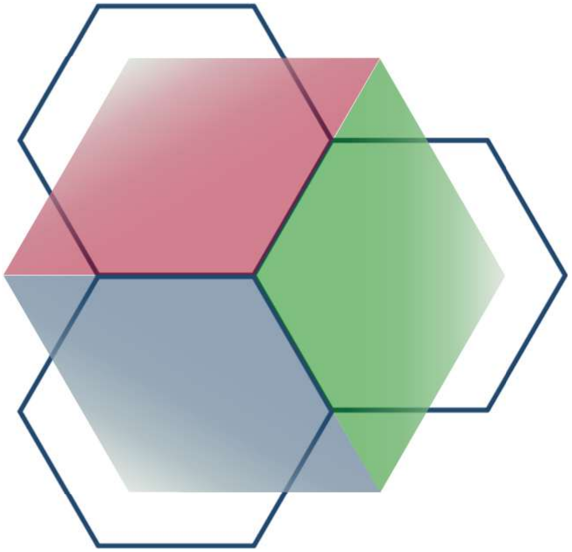
Improving the downlink SIR (3/3)

The rationale of cell sectoring can be extended to cover full cells: this leads to tri-cellular sites

Example:

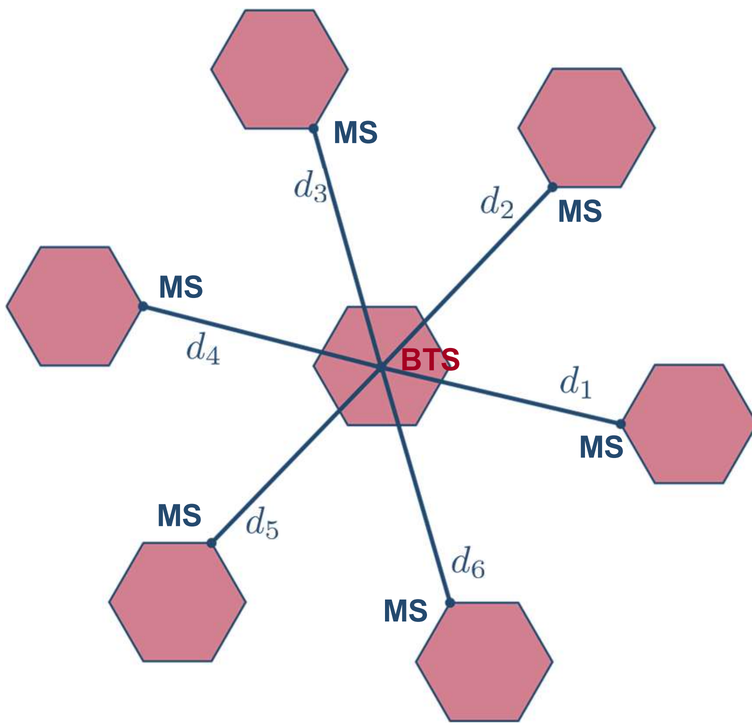
available channels

Advantage: decrease in the number of installation sites, while increasing the SIR



Uplink SIR (1/3)

Let us now focus on the uplink segment, in which the worst-case scenario is slightly different from the downlink one:



$$d_k \approxeq D - R \quad \forall k$$
when $K \gg 1$

Uplink SIR (2/3)

While the useful signal's received power remains the same, the interference from the *k*th MS is

$$I_k = P_{\mathrm{R}}(d_k) \approx \frac{\chi}{(D-R)^n}$$

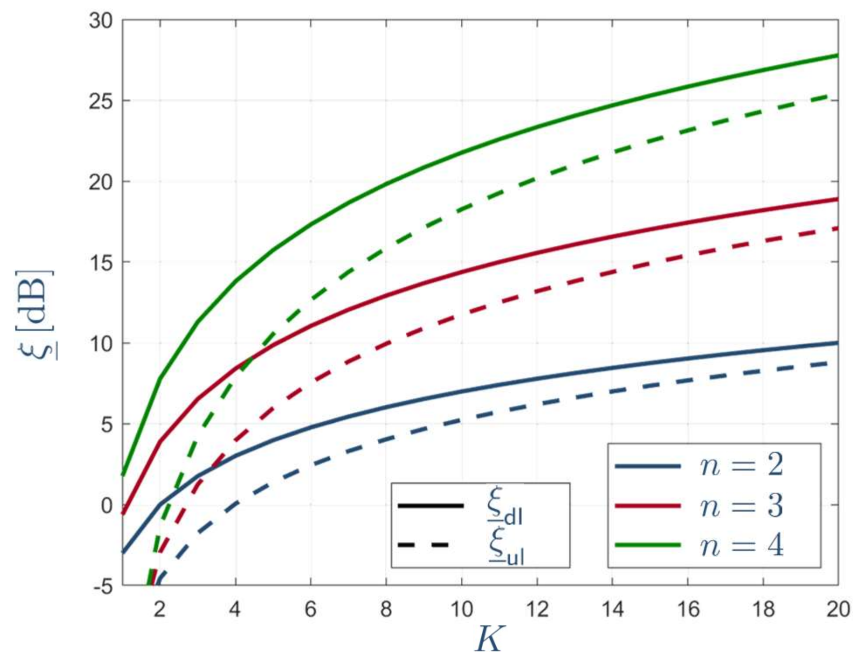
As a consequence,

$$\xi \geq \xi_{\mathrm{ul}} \triangleq \frac{C}{\sum_{k=1}^{6} I_k} = \frac{\left(\sqrt{3K}-1\right)^n}{6}$$

The SIR, albeit lower than in the downlink case, follows the same behavior: the larger the cluster size, the better the performance

Uplink SIR (3/3)

$$\underline{\xi}_{\text{ul}} \triangleq \left(\sqrt{3K}-1\right)^n/6$$



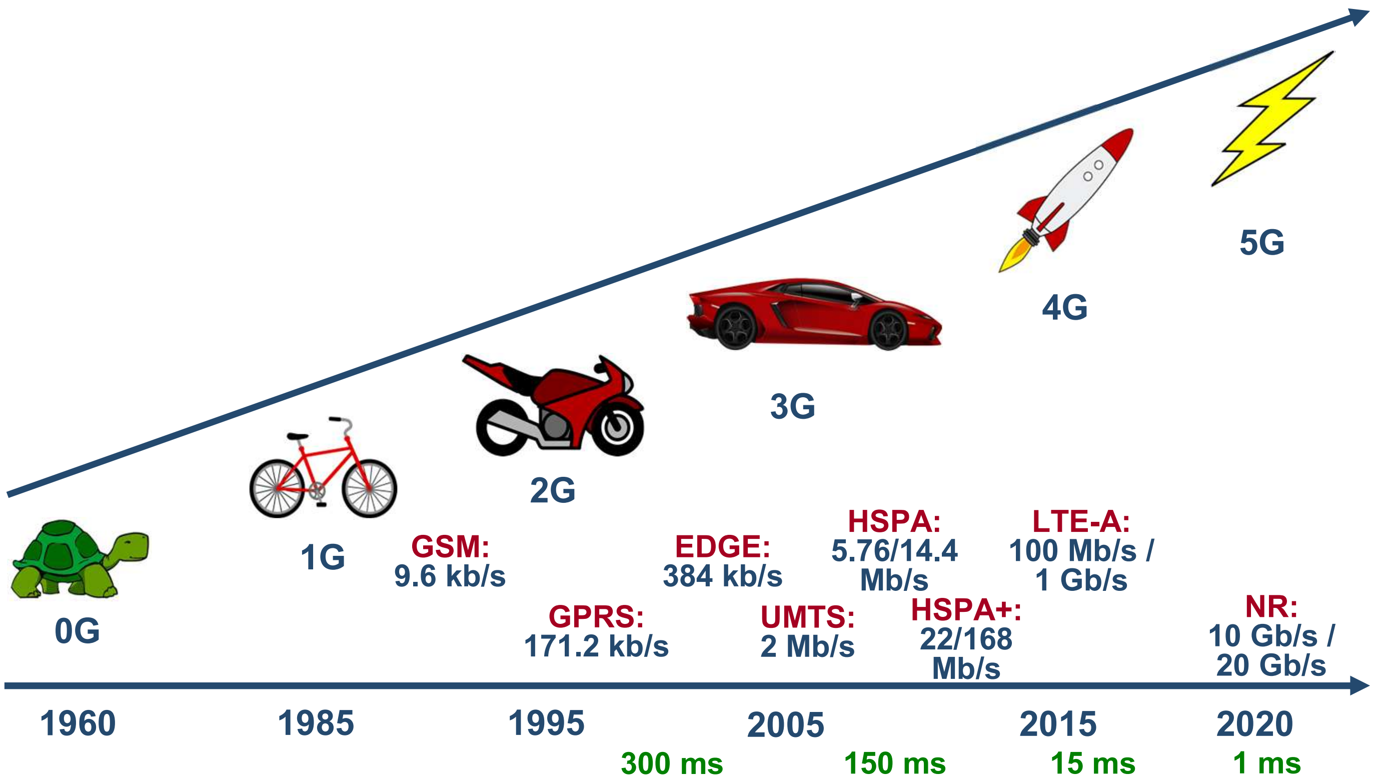
Improving the uplink SIR

Analogously to the techniques used in the downlink, there are many solutions taken to improve the performance in the uplink

An effective way to reduce co-channel and multiple-access interference is through the use of beamforming techniques, using multiple-input multiple-output (MIMO) architectures

History of cellular communication standards

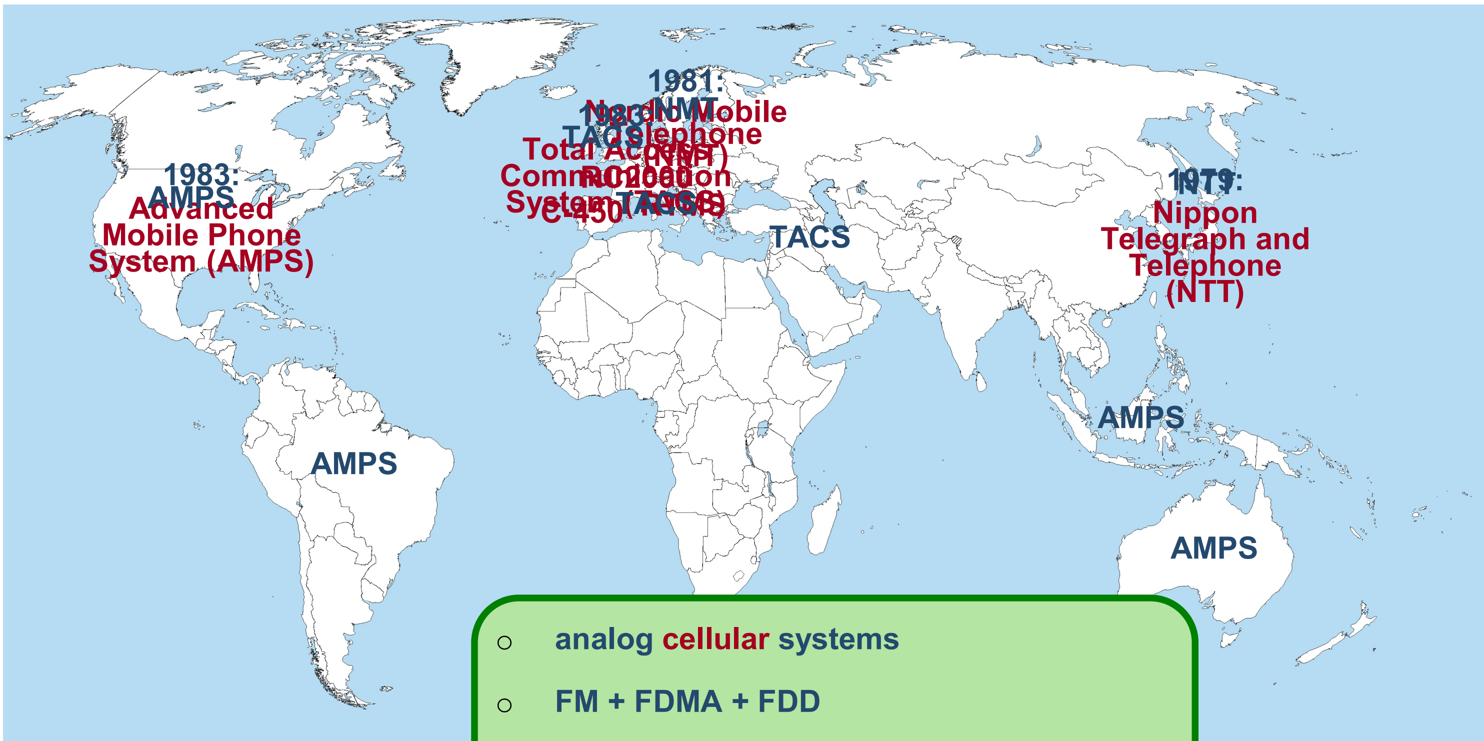
Cellular standards through time



0G systems

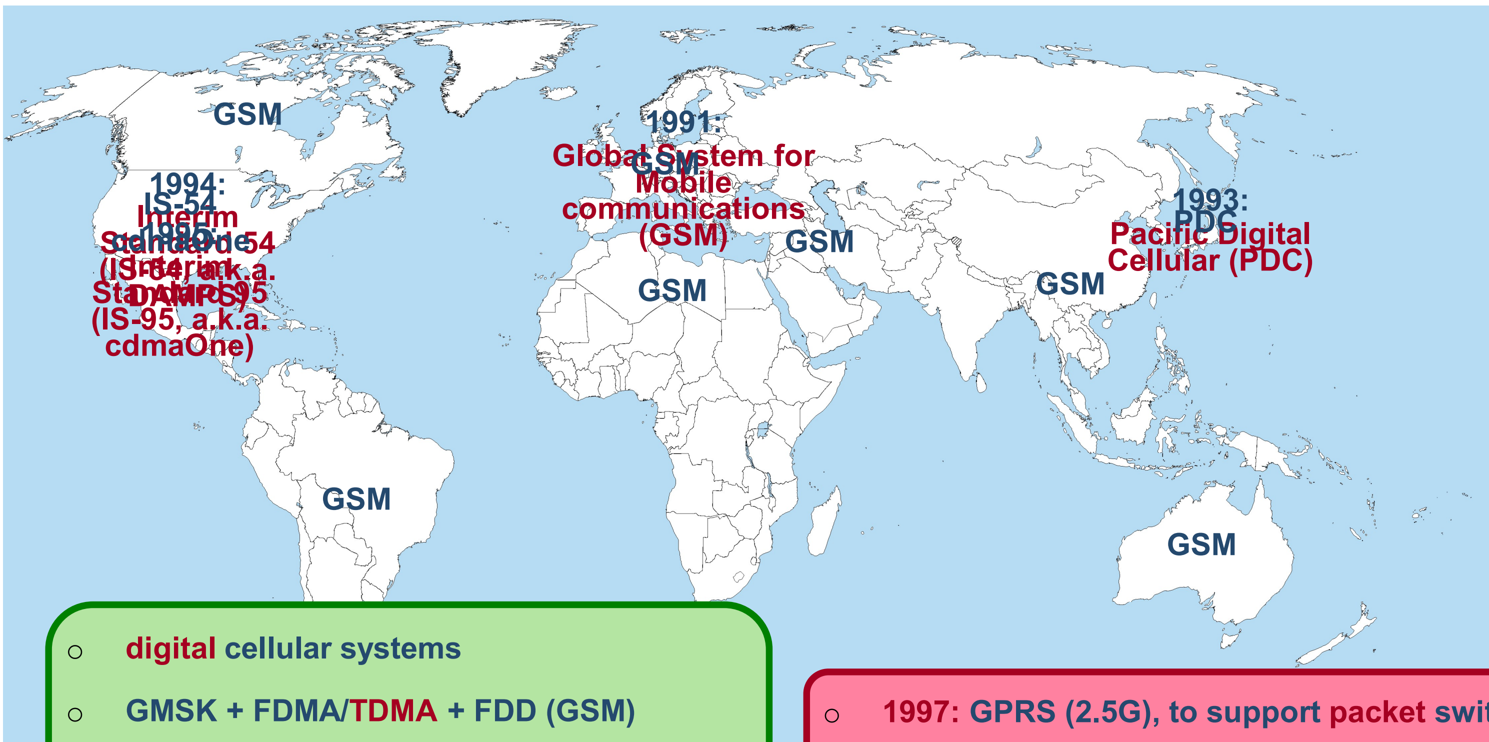
- analog single-cell systems
- frequency modulation (FM)
- FDMA
- FDD
- channel spacing:
  - 1940s: 120 kHz
  - 1960s: 60 kHz
  - 1970s: 25 kHz

1G systems



- analog cellular systems
- FM + FDMA + FDD
- carrier frequencies: 450 MHz, 900 MHz
- channel spacing: 12.5 ÷ 30 kHz

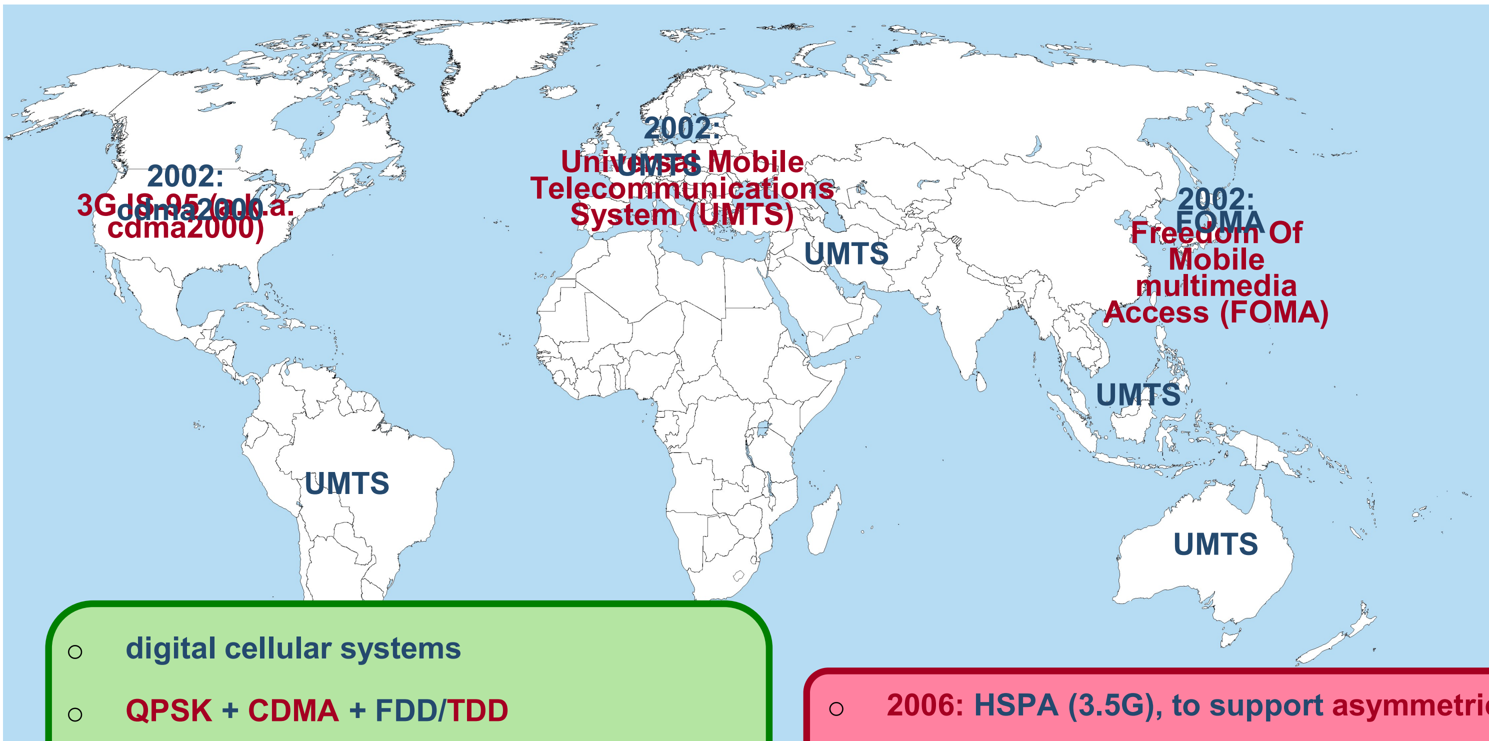
2G systems



- **digital cellular systems**
- **GMSK + FDMA/TDMA + FDD (GSM)**
- **carrier frequencies: 900 MHz, 1800 MHz**
- **channel spacing: 200 kHz (GSM)**

- **1997: GPRS (2.5G), to support packet switching**
- **2003: EDGE (2.75G), to support higher rates**

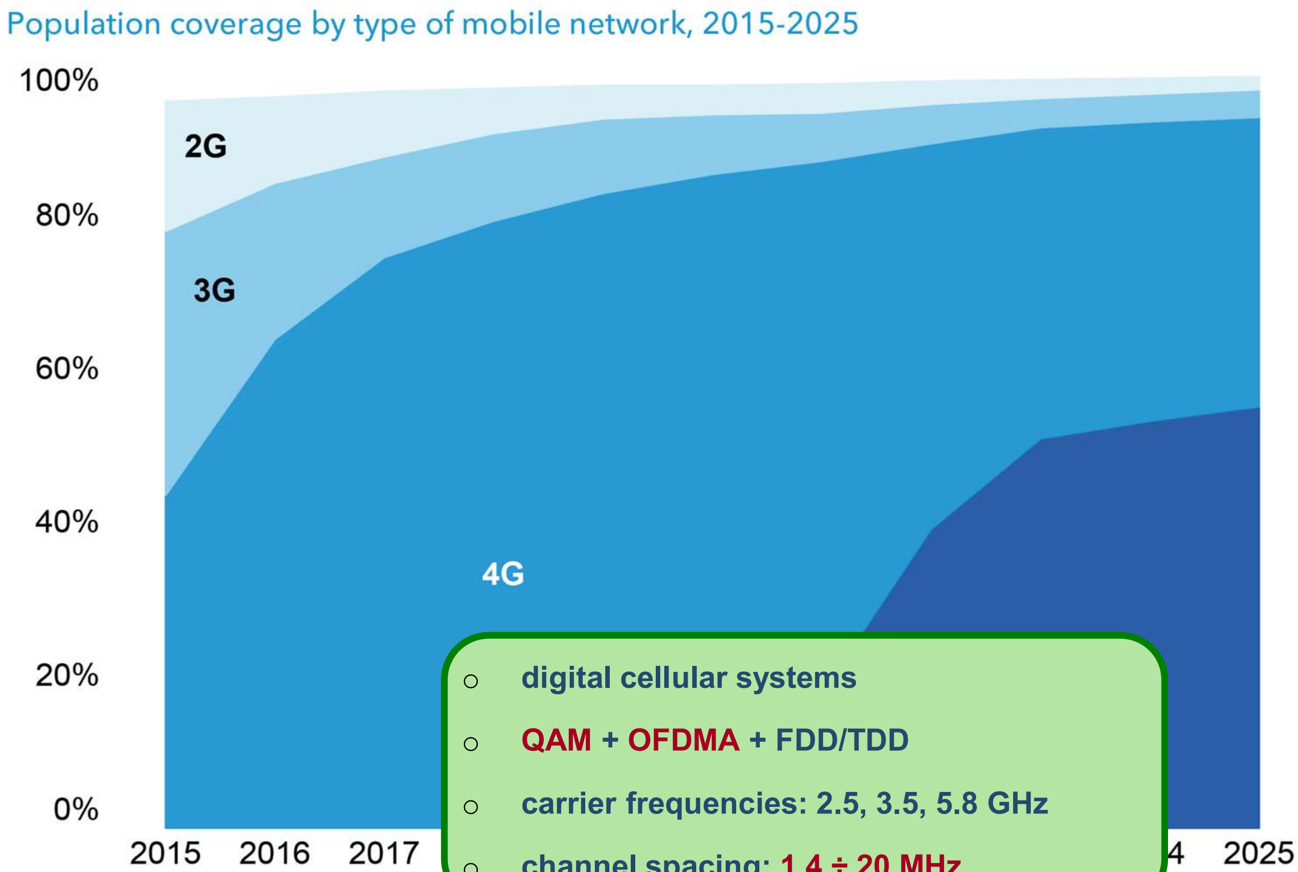
3G systems



- digital cellular systems
- QPSK + CDMA + FDD/TDD
- carrier frequencies: 2 GHz
- channel spacing: 5 MHz (UMTS/FOMA)

- 2006: HSPA (3.5G), to support asymmetric rates
- 2008: HSPA+ (3.75G), to support higher rates

4G systems

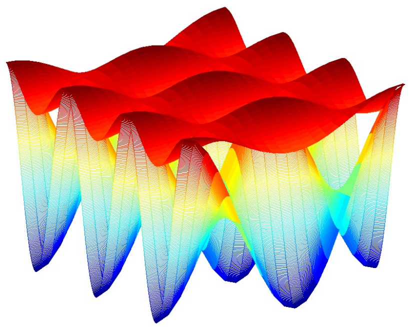


- digital cellular systems
- QAM + OFDMA + FDD/TDD
- carrier frequencies: 2.5, 3.5, 5.8 GHz
- channel spacing: 1.4 ÷ 20 MHz

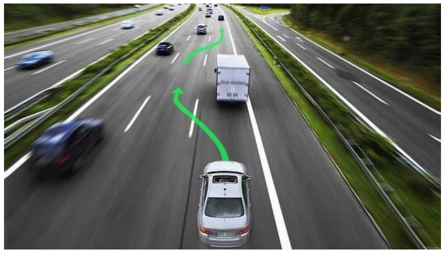
5G systems

The challenging requirements set by the IMT-2020 for 5G systems include:

- **data rates:**
  - **1000× aggregate data rate increase with respect to (wrt) 4G**
  - **100 Mb/s edge rate (100× wrt 4G)**



- **latency: 1 ms (10× wrt 4G)**



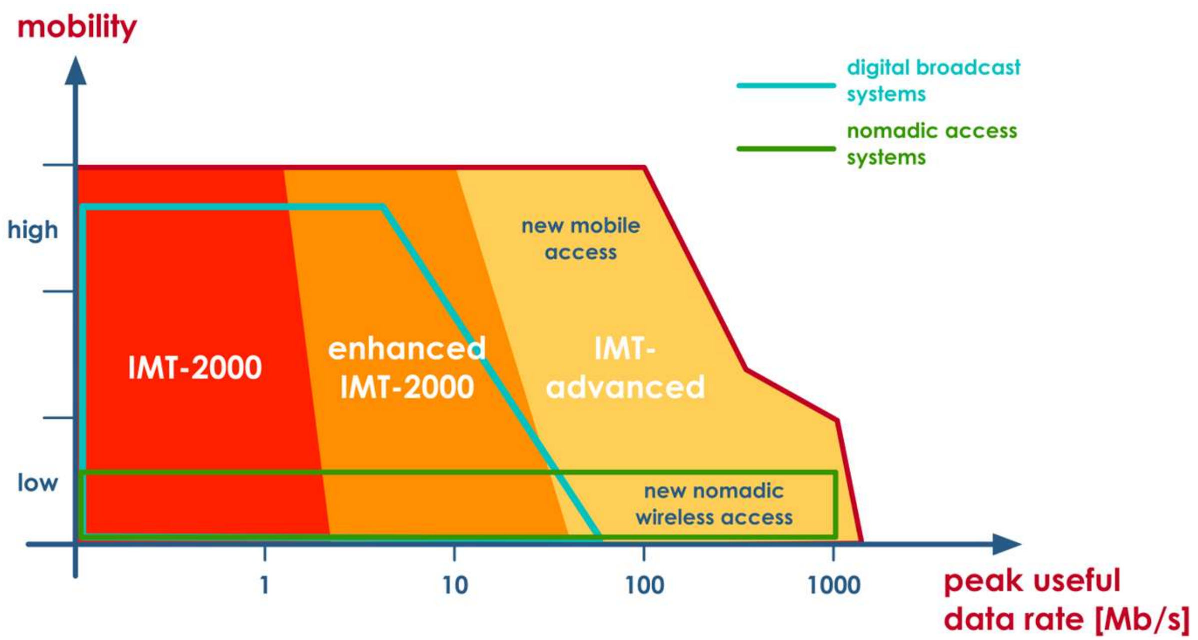
- **energy efficiency: 100× wrt 4G**

Generation shift highlights

- 0G ➔ 1G: cellular deployment
- 1G ➔ 2G: digital systems
- 2G ➔ 3G: wideband signals (using CDMA)
- 3G ➔ 4G: even wider bandwidths (using OFDMA)
- 4G ➔ 5G: network densification, mmWave, massive MIMO, spectrum sensing
- 5G ➔ 6G: THz and visible-light communications, full-duplex antennas, artificial intelligence, intelligent surfaces?

4G systems

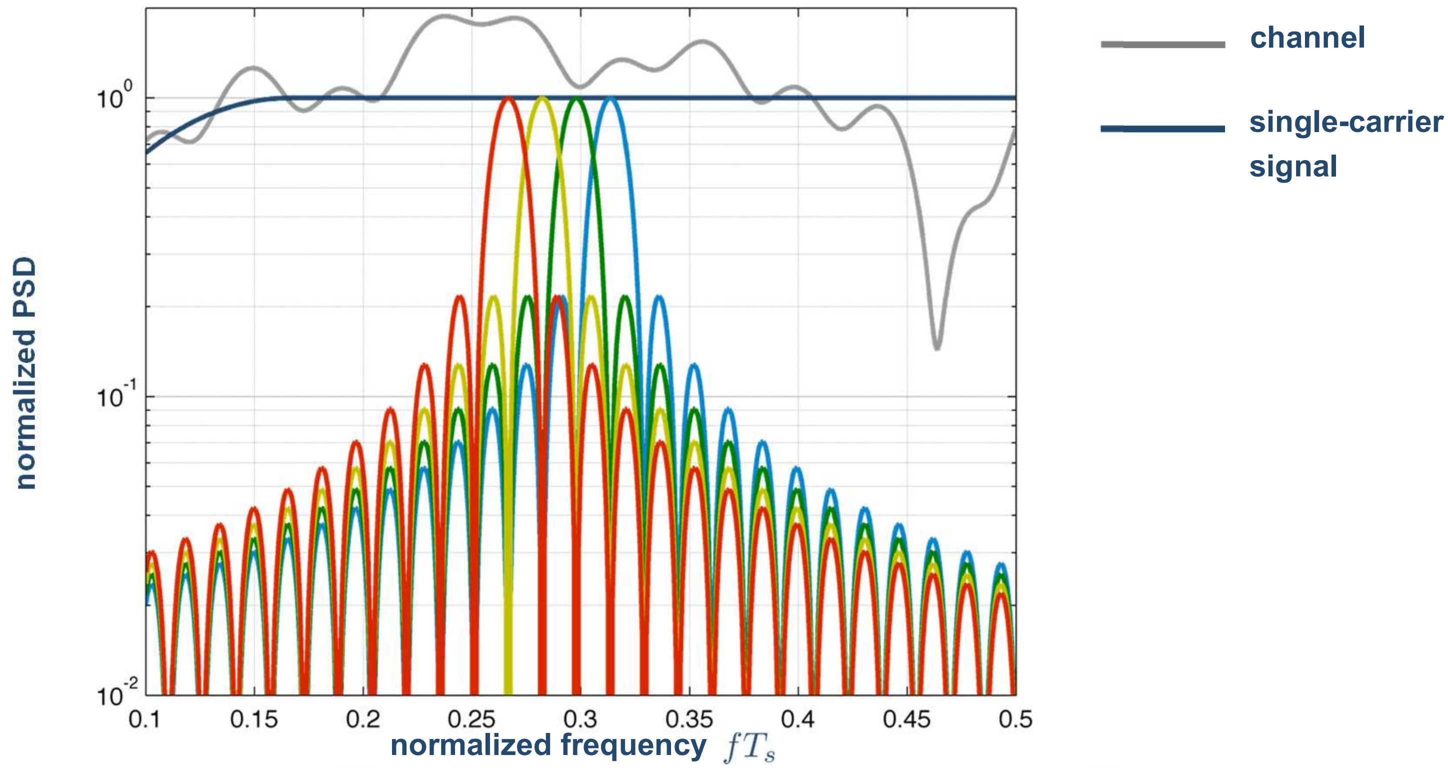
IMT-advanced requirements



- peak data rates of 100 Mb/s for high-mobility users, and 1 Gb/s for low-mobility users
- larger bandwidths (up to 40 MHz)
- lower latencies (< 15 ms)

Orthogonal frequency division multiplexing (OFDM)

The OFDM is an efficient solution to combat the selectivity of a wideband channel



Orthogonal frequency division multiplexing (OFDM)

How OFDM works (1/5)

In single-carrier modulations, the sequence $\mathbf{b}$ of input symbols is sent using

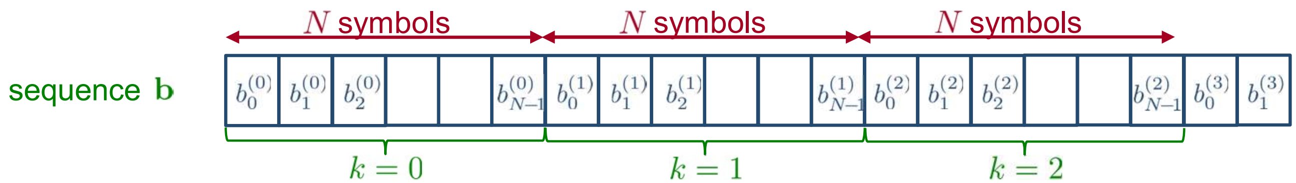
$$x(t) = \sum_{k=-\infty}^{+\infty} b_k g(t - kT_s)$$

shaping pulse

T_s: symbol interval

$$B \propto \frac{1}{T_s}$$

Let us suppose to group the sequence $\mathbf{b}$ into blocks of N symbols:



$$x(t) = \sum_{k=-\infty}^{+\infty} \sum_{n=0}^{N-1} b_n^{(k)} g_n(t - kT_s)$$

shaping pulse

(kN+n)-th source symbol, modulated on the n-th subcarrier

$T = NT_s$: OFDM symbol interval

$$B \propto \frac{N}{T} = \frac{1}{T_s}$$

$$\Delta f \propto \frac{1}{T} = \frac{B}{N}$$

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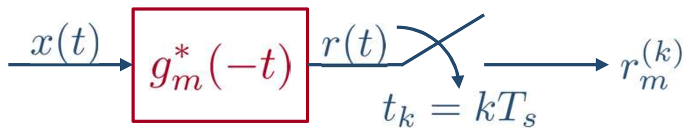
How OFDM works (2/5)

Pulse shaping: $$g_n(t) = \begin{cases} \frac{1}{\sqrt{T}} e^{j2\pi nt/T}, & 0 \le t \le T \\ 0, & \text{elsewhere} \end{cases}$$

What happens on an ideal channel?

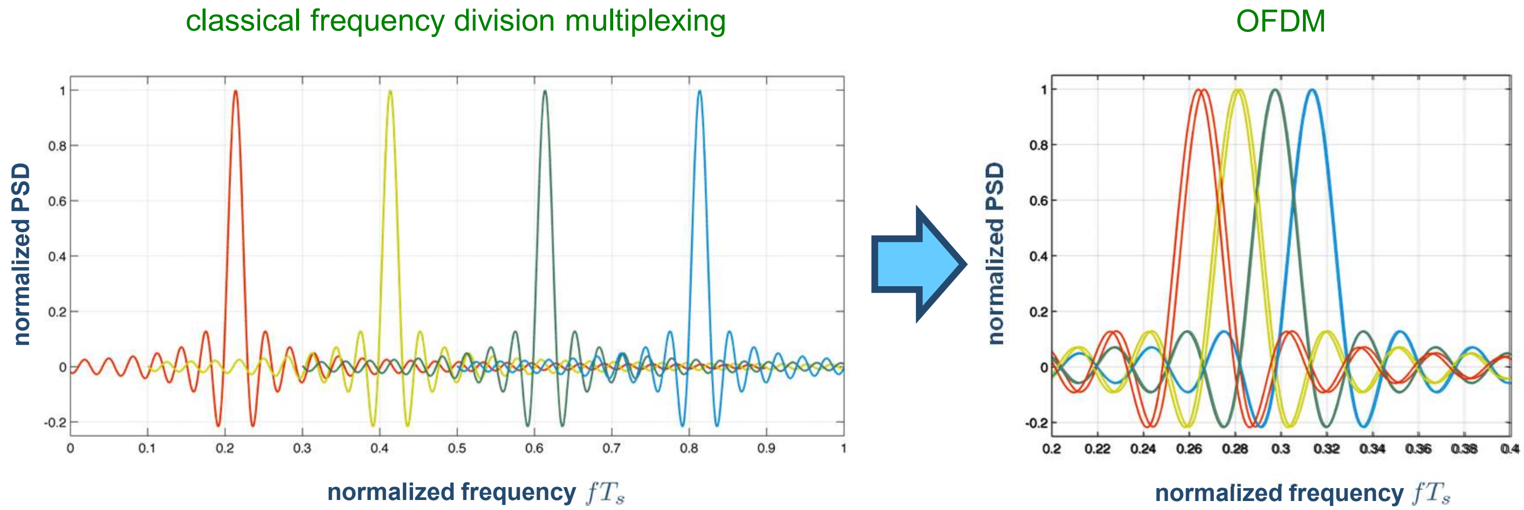


$$\begin{aligned} r_m^{(0)} &= r(t)|_{t=0} = x(t) \otimes g_m^*(-t)|_{t=0} \\ &= \int_0^T x(\varepsilon) g_m^*(t+\varepsilon) d\varepsilon|_{t=0} \\ &= \frac{1}{T} \sum_{n=0}^{N-1} b_n^{(0)} \int_0^T e^{j2\pi(n-m)\varepsilon/T} d\varepsilon \\ &= b_m^{(0)} \end{aligned}$$

$$\frac{1}{T} \int_0^T e^{j2\pi(n-m)\varepsilon/T} d\varepsilon = \begin{cases} 1, & n = m \\ 0, & n \ne m \end{cases}$$

How OFDM works (3/5)

To convey the stream of infomation symbols on multiple subcarriers, we use a set of orthogonal subcarriers:



This solution requires the minimum bandwidth occupancy

Note: high frequency accuracy is needed to avoid inter-carrier interference (ICI)

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How OFDM works (4/5)

How can we implement OFDM?

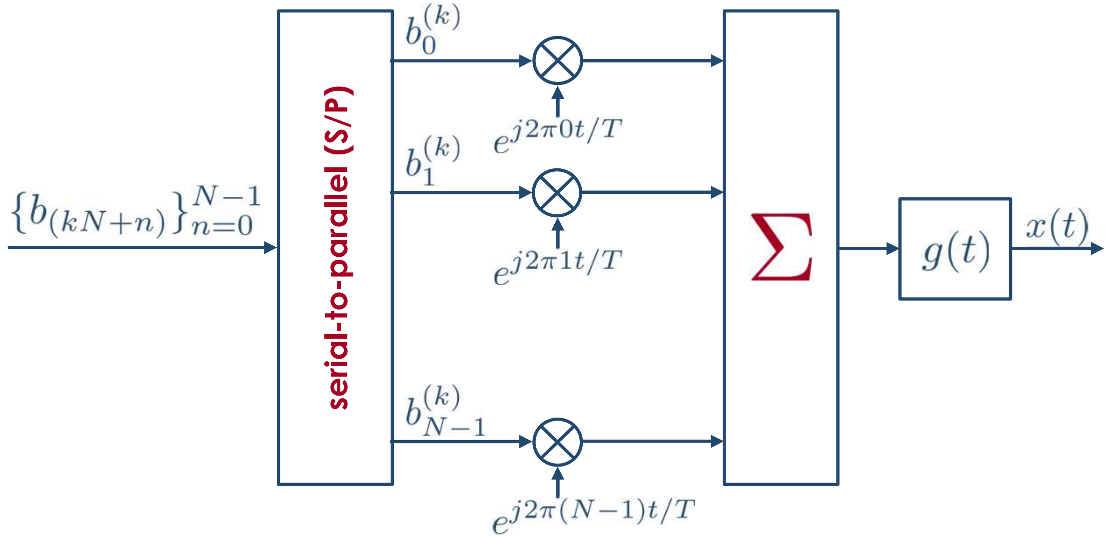
- Using *N* local oscillators to synthesize $\{e^{j2\pi nt/T}\}_{n=0}^{N-1}$ at the transmitter and the receiver is a highly inefficient architecture

- Let us try to sample our signal at intervals kT_s :

$$x_k = x(kT_s) = x\left(kT/N\right)$$
$$= \frac{1}{\sqrt{T}} \sum_{n=0}^{N-1} b_n^{(k)} e^{j2\pi nk/N}$$

inverse discrete Fourier transform (IDFT)

How OFDM works (5/5)



N: number of subcarriers

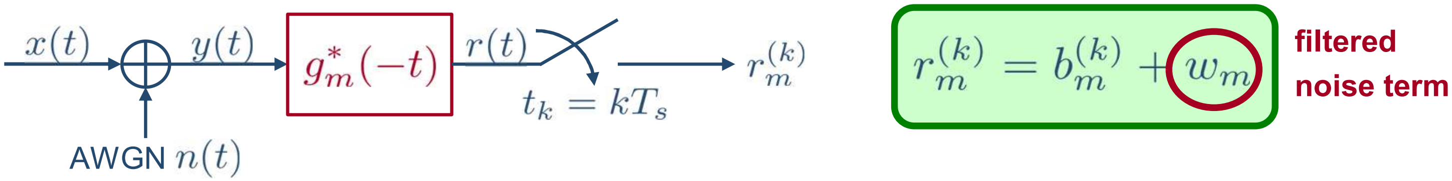
$1/T$: subcarrier spacing

This modulation scheme at the transmitter is very efficient, as it can exploit inverse fast Fourier transform (IFFT) schemes when $N = 2^D$ (e.g., $N = 1024$)

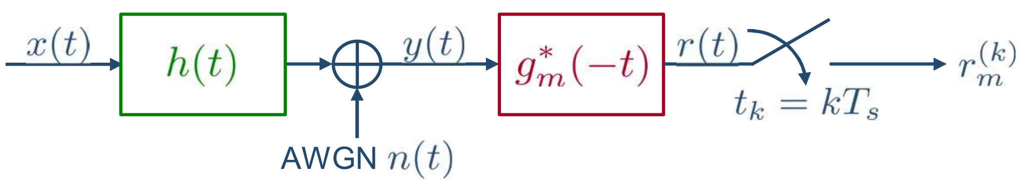
The same "trick" can be used at the receiver, using FFT

Channel equalization in OFDM (1/5)

What happens when introducing the additive white Gaussian noise (AWGN)?



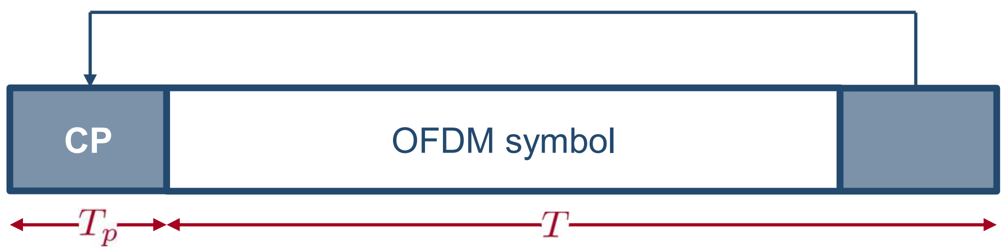
And when also the channel selectivity is considered?



In this case, although $\sigma_\tau \ll T$, multipath propagation can lead to inter-block interference (IBI), thus affecting the demodulation performance

Channel equalization in OFDM (2/5)

To mitigate the IBI, we can add a special guard interval, called the cyclic prefix (CP), with length $T_p > \sigma_\tau$:



$$x(t) = \sum_{k=-\infty}^{+\infty} \sum_{n=0}^{N-1} b_n^{(k)} \tilde{g}_n(t-kT), \text{ with } \tilde{g}_n(t) = \begin{cases} \frac{1}{\sqrt{T}} e^{j2\pi nt/T}, & -T_p \le t \le T \\ 0, & \text{elsewhere} \end{cases}$$

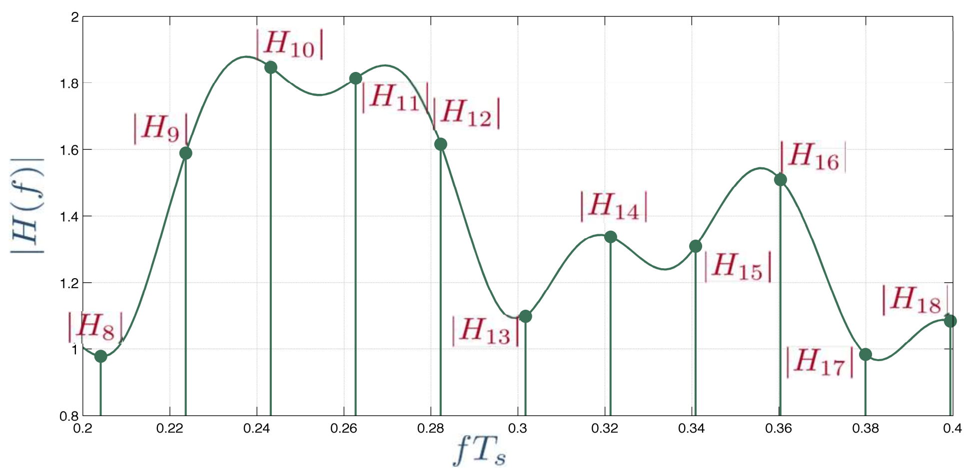
Using the CP, we have "artificially" introduced a cyclic IBI, that can now be controlled

Channel equalization in OFDM (3/5)

Adopting the same receiver technique,

$$
\begin{aligned}
r_m^{(k)} &= y(t) \otimes g_m^*(-t)|_{t=kT_s} \\
&= H\left(\frac{m}{T}\right) b_m^{(k)} + w_m \triangleq H_m b_m^{(k)} + w_m
\end{aligned}
$$

In this case, channel equalization is extremely simple:



Channel equalization in OFDM (4/5)

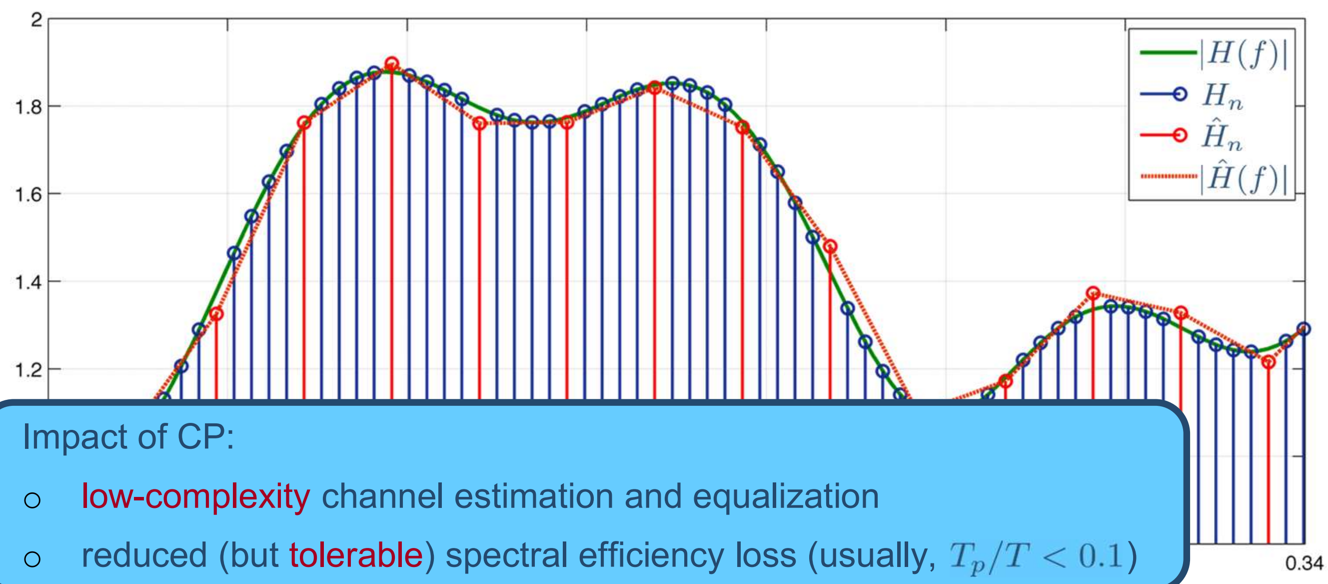
OFDM channel equalization techniques:

- zero forcing (ZF): $G_m = \frac{1}{\hat{H}_m}$
- maximal-ratio combining (MRC): $G_m = \hat{H}_m^*$
- equal-gain combining (EGC): $G_m = \frac{\hat{H}_m^*}{|\hat{H}_m|}$
- minimum mean-square error (MMSE): $G_m = \frac{\hat{H}_m^*}{|\hat{H}_m|^2 + \hat{\sigma}^2}$

Channel equalization in OFDM (5/5)

How can the receiver estimate the coefficients $\{\hat{H}_n\}_{n=0}^{N-1}$ in practice?

OFDM symbols contain sparse pilot subcarriers, with known symbols, to let the receiver get an accurate estimation of the channel response:



Impact of CP:

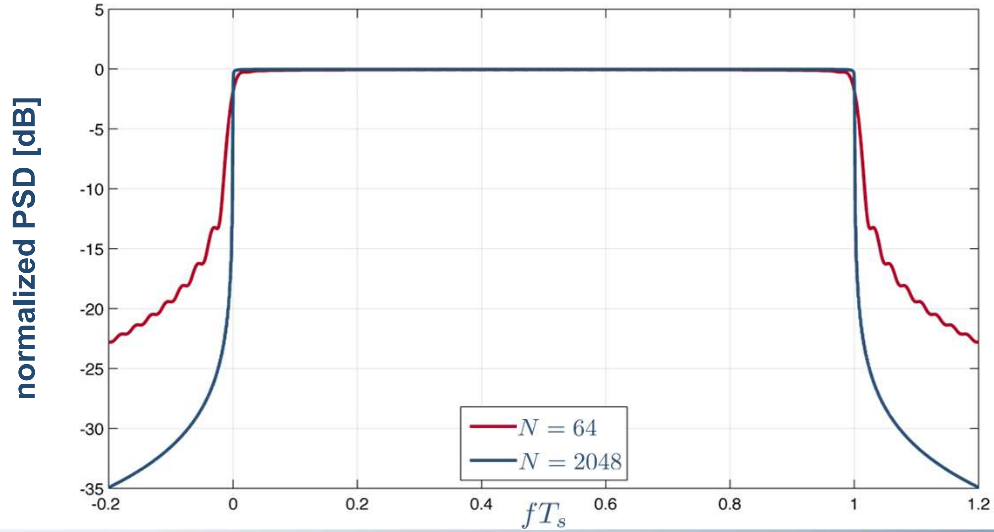
- low-complexity channel estimation and equalization
- reduced (but tolerable) spectral efficiency loss (usually, $T_p/T < 0.1$)

PSD of an OFDM signal (1/2)

To compute the spectral properties of OFDM signals, let's compute the PSD:

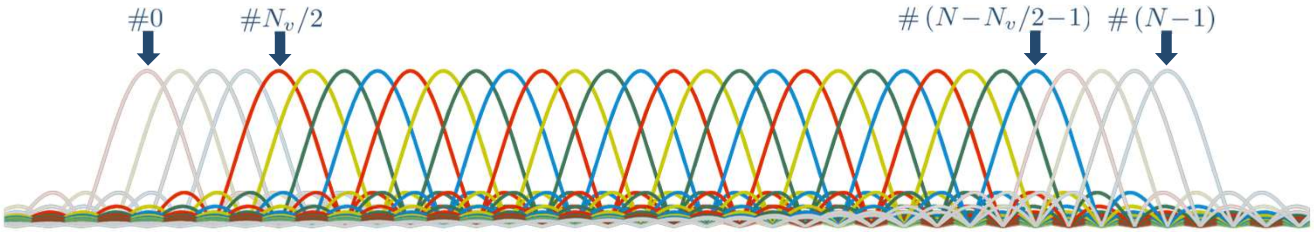
$$\mathcal{P}_x(f) = \sum_{n=0}^{N-1} \mathcal{P}(f - n/T)$$

where $\mathcal{P}(f) = T \cdot \mathrm{sinc}^2(fT) = \dfrac{\sin^2(\pi f T)}{\pi^2 f^2 T}$

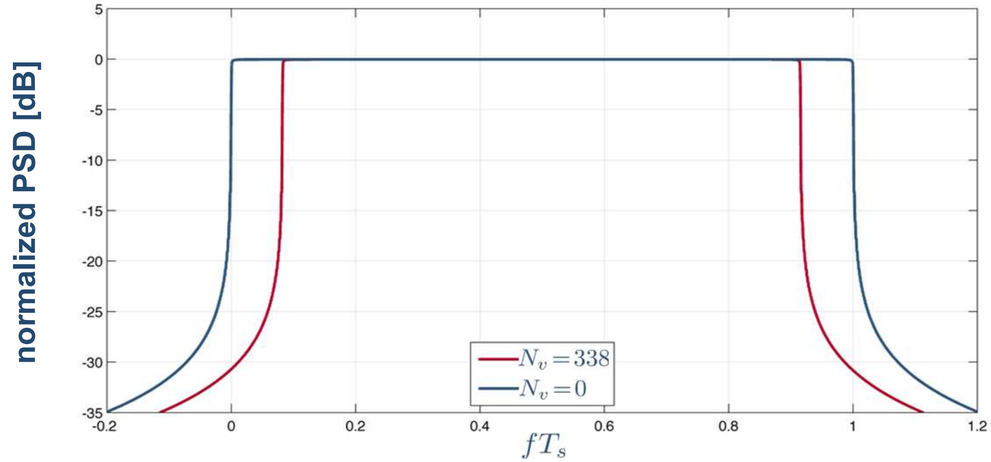


PSD of an OFDM signal (2/2)

To reduce out-of-band (OOB) emisssions, we can introduce N_v virtual subcarriers

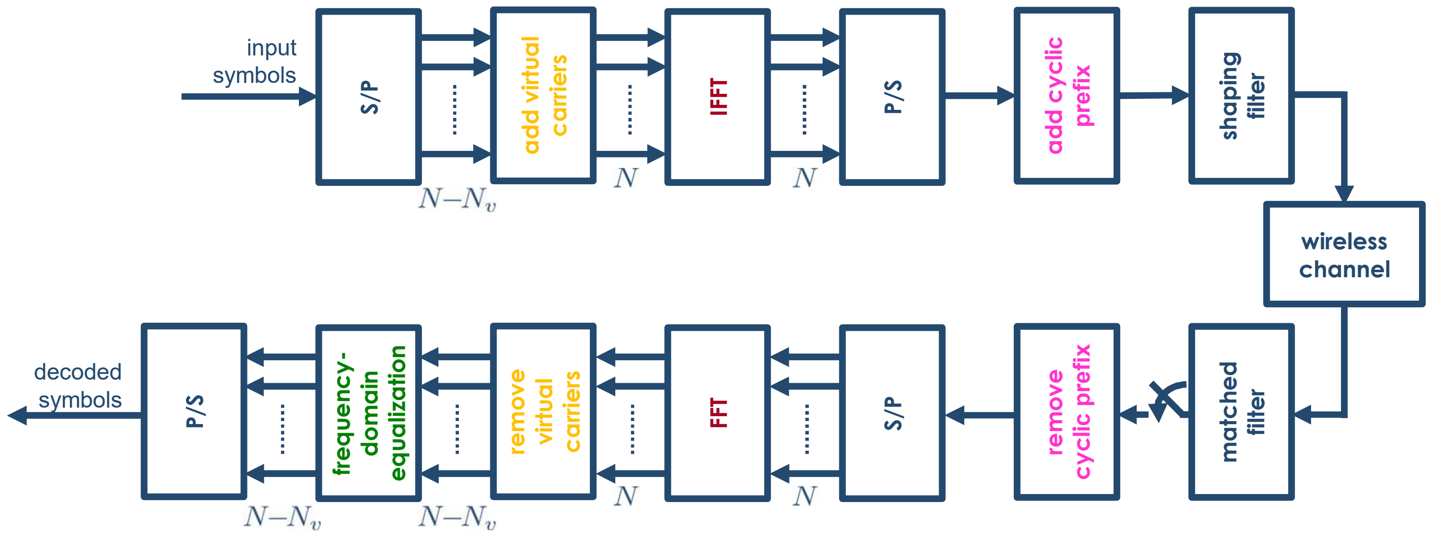


The PSD of the signal can be squeezed:



OFDM-based multiple access schemes

OFDM architecture



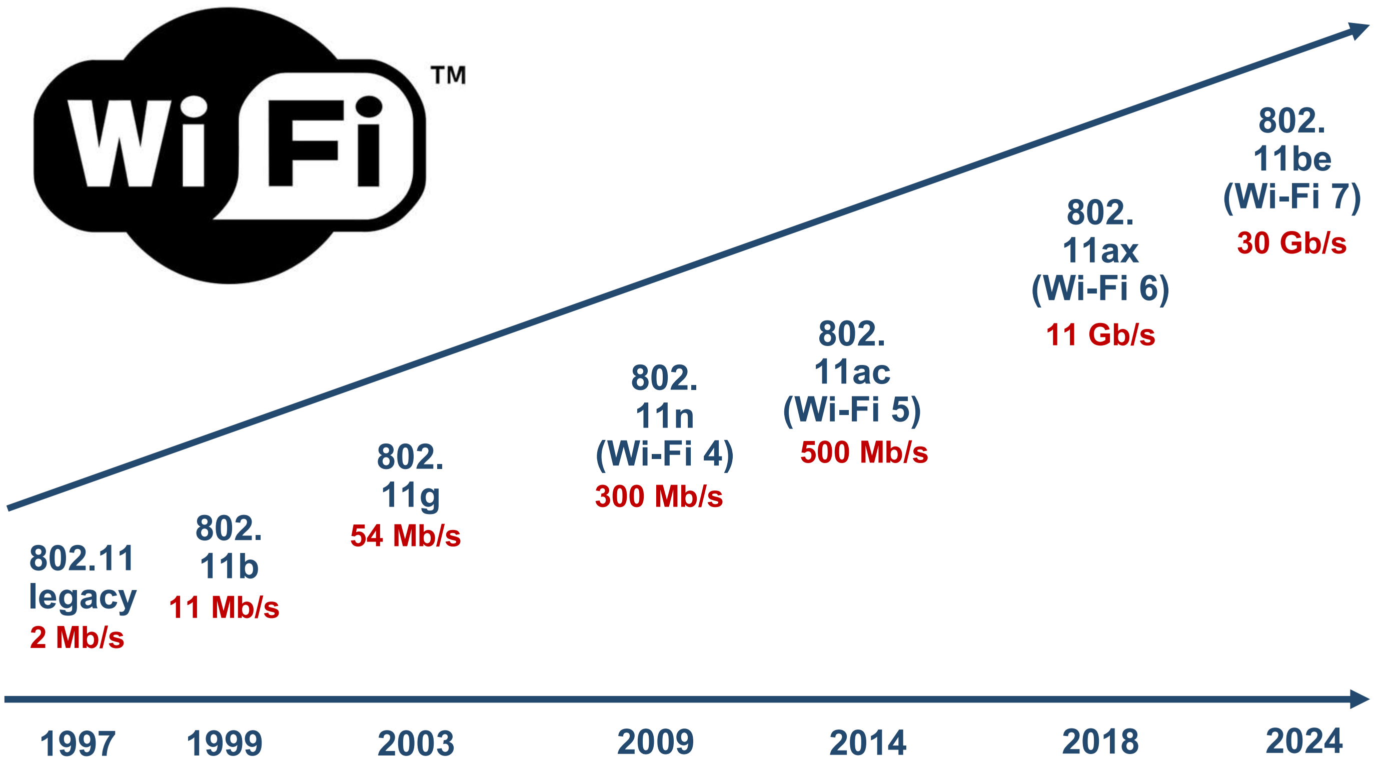
Features:

- optimal implementation via (I)FFT
- no ICI due to carrier orthogonality
- controlled OOB emissions thanks to the virtual carriers
- frequency-domain equalization thanks to the CP

An example of OFDM-based systems: WLAN standards (1/2)

Standard	Freq. range [GHz]	Throughput [Mb/s]	MA scheme	Max mod. order
802.11 legacy	2.4	2	DSSS/FHSS	BPSK
802.11b	2.4	11	DSSS	DQPSK
802.11g	2.4	54	DSSS	64-QAM
802.11n	2.4 / 5	300	OFDM	64-QAM
802.11ac	2.4 / 5	500	OFDM+ MIMO	256-QAM
802.11ax	2.4 / 5	11,000	OFDM+ MU-MIMO	1024-QAM
802.11be	2.4 / 5 / 6	30,000	OFDM+ CMU-MIMO	1024-QAM

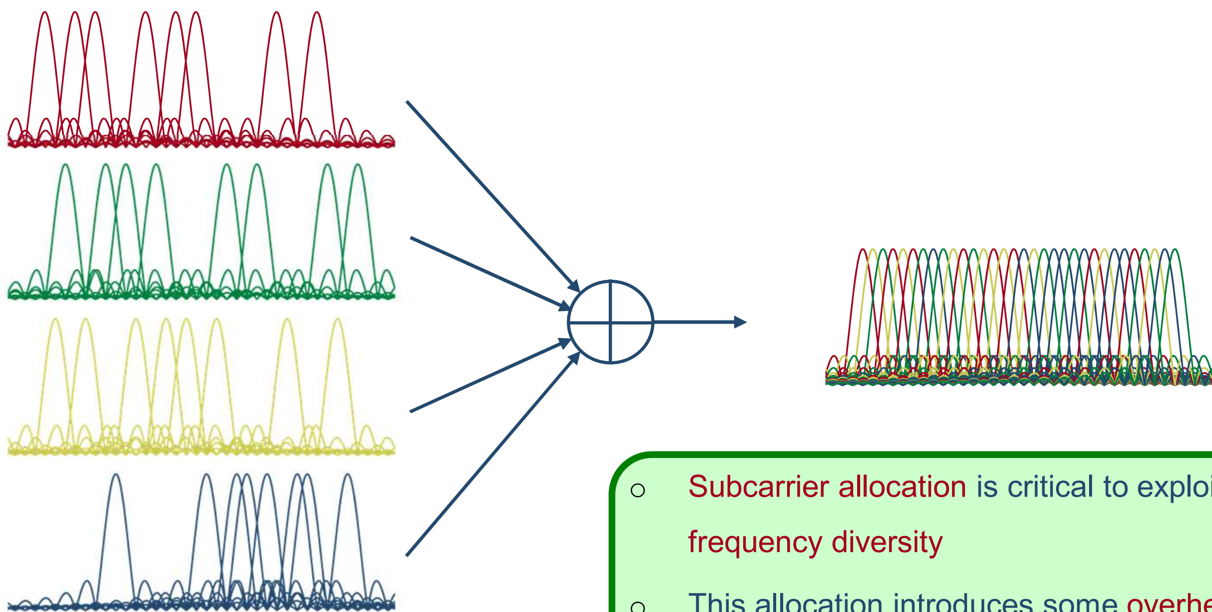
An example of OFDM-based systems: WLAN standards (2/2)



Orthogonal frequency division multiple access (OFDMA)

How can we adapt the OFDM technology to the multiuser case?

Each user can be assigned a subset of subcarriers, by zeroing the inactive subcarriers



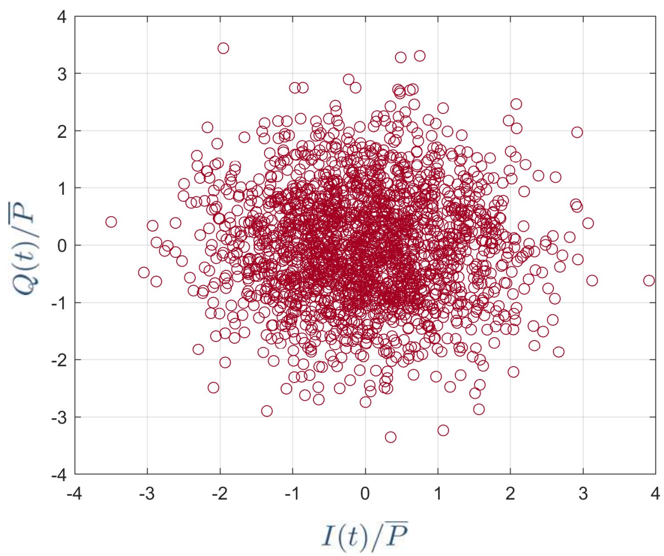
- Subcarrier allocation is critical to exploit the frequency diversity
- This allocation introduces some overhead in the network

Limits of OFDM(A)

- sensitivity to synchronization errors:
  - single-carrier systems: the residual frequency offset ν must be $\nu \ll \frac{1}{T_s}$
  - multicarrier systems: $\nu \ll \frac{1}{T} = \frac{1}{NT_s}$
- high peak-to-average power ratio (PAPR):
  - the superposition of N sinusoidal signals yields a large PAPR, thus calling for linear radio-frequency (RF) amplifiers
  - to improve the efficiency of the RF stage at the MSs, the uplink can adopt a modified version of OFDMA, called single-carrier FDMA (SC-FDMA)

High PAPR in OFDMA (1/3)

Looking at the I/Q diagram of an OFDMA-based signal with average power $\overline{P}$, we can appreciate the impact on PAPR:



The amplitude $A(t) = \sqrt{I^2(t) + Q^2(t)}$ is Rayleigh-distributed:

$$f_A(a) = \frac{a}{\overline{P}} e^{-a^2/(2\overline{P})} \mathrm{u}(a)$$

The power $p(t) = A^2(t)/2$ is exponentially distributed:

$$f_P(p) = \frac{1}{\overline{P}} e^{-p/\overline{P}} \mathrm{u}(p)$$

High PAPR in OFDMA (2/3)

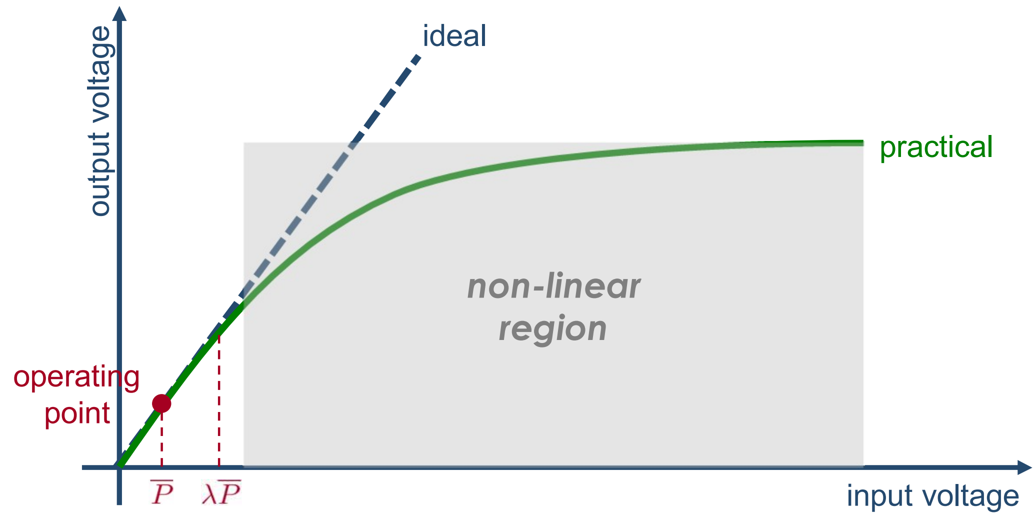
A practical method to compute the PAPR λ is to identify a working value of the peak power, by defining a sufficiently low theoretical probability of exceeding it (e.g., 10^{-5}):

$$\lambda \quad \text{s.t.} \quad \int_{\lambda \overline{P}}^{+\infty} f_P(p)dp = 10^{-5}$$

$$\int_{\lambda \overline{P}}^{+\infty} f_P(p)dp = \int_{\lambda \overline{P}}^{+\infty} \frac{1}{\overline{P}} e^{-p/\overline{P}} dp = - \left. e^{-p/\overline{P}} \right|_{\lambda \overline{P}}^{+\infty} = e^{-\lambda}$$

$$\lambda = 5 \ln 10 = 11.5 = 10.6 \, \text{dB}$$

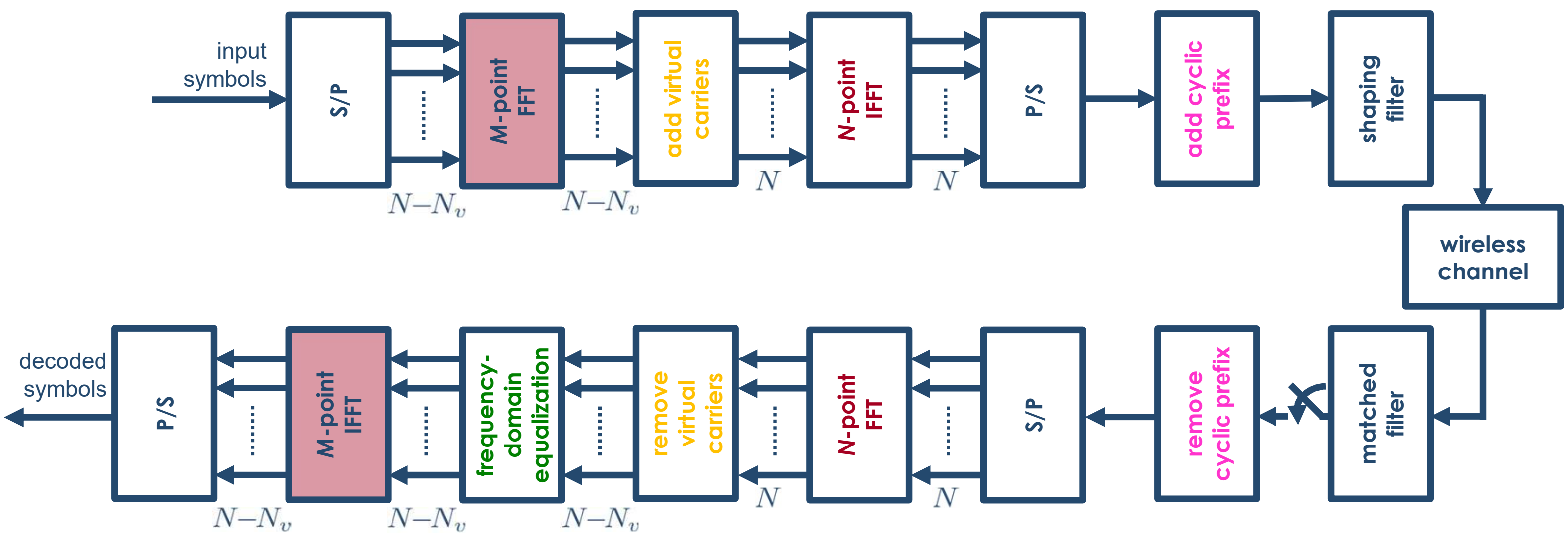
High PAPR in OFDMA (3/3)



We then need either to transmit at a lower power (hence, reduced coverage) or to use linear yet inefficient high-power amplifiers (hence, reduced battery life)

Single-carrier FDMA (SC-FDMA) (1/2)

To significantly reduce the PAPR, we can modify the OFDMA scheme as follows, by implementing the so called single-carrier FDMA (SC-FDMA):



Single-carrier FDMA (SC-FDMA) (2/2)

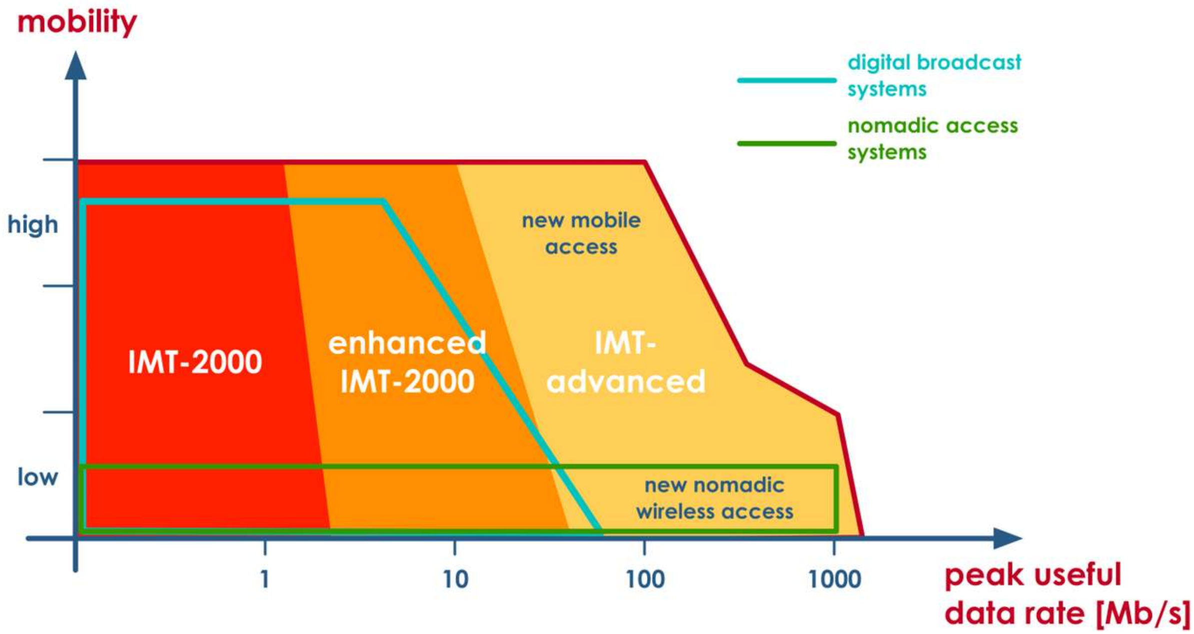
Together with a valuable PAPR reduction, the SC-FDMA also shows the following features:

- the IFFT at the transmitter operates on the Fourier coefficients rather than on information symbols (as in OFDMA) (hence, computationally efficient implementation)

- the distinctive feature with respect to a traditional FDMA is the presence of the CP, that allows for frequency-domain equalization

4G standards

IMT-advanced requirements



- peak data rates of 100 Mb/s for high-mobility users, and 1 Gb/s for low-mobility users
- larger bandwidths (up to 40 MHz)
- lower latencies (< 15 ms)

4G standards

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

- LTE-advanced (LTE-A), standardized by the 3rd generation partnership project (3GPP)
- IEEE 802.16m, standardized by the Institute of Electrical and Electronic Engineers (IEEE)

LTE-advanced (LTE-A) standard

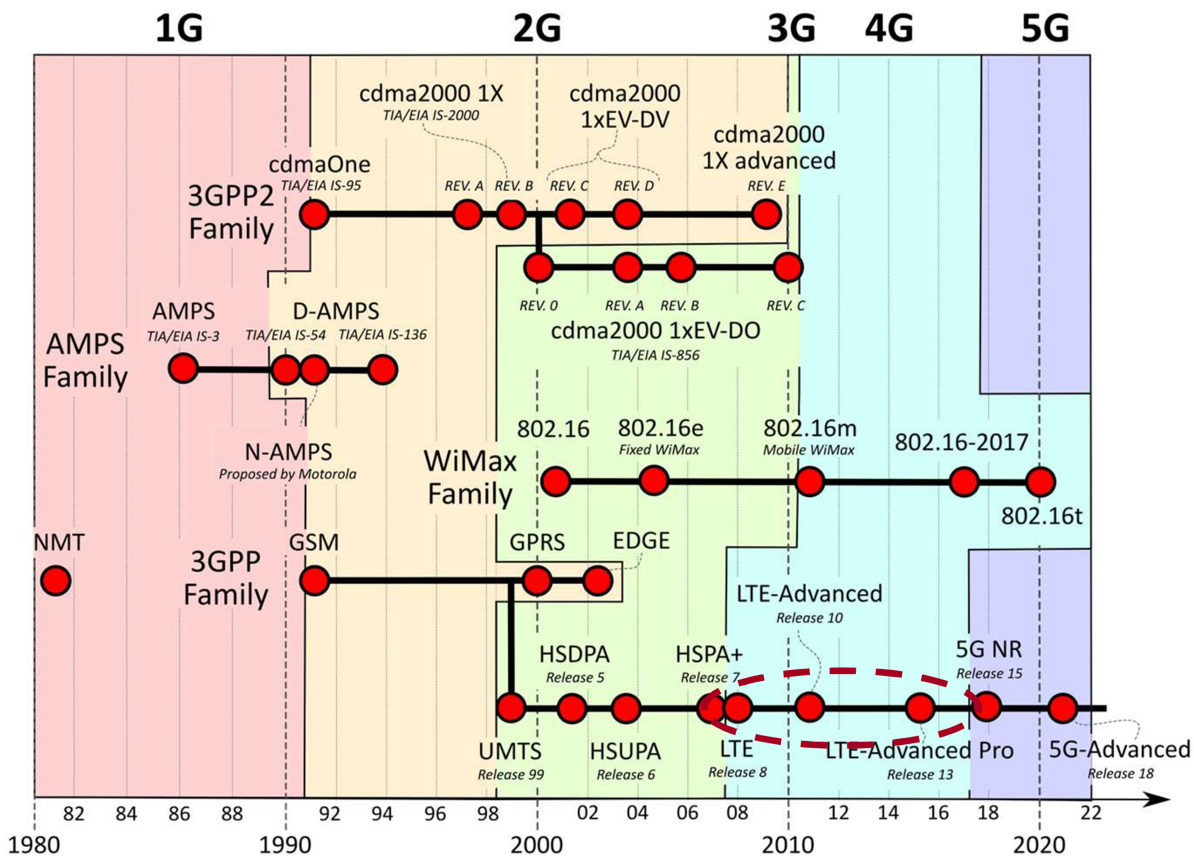
LTE-advanced

- 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)

- 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
- Bandwidths: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz
- Constellations: QPSK, 16-QAM, 64-QAM

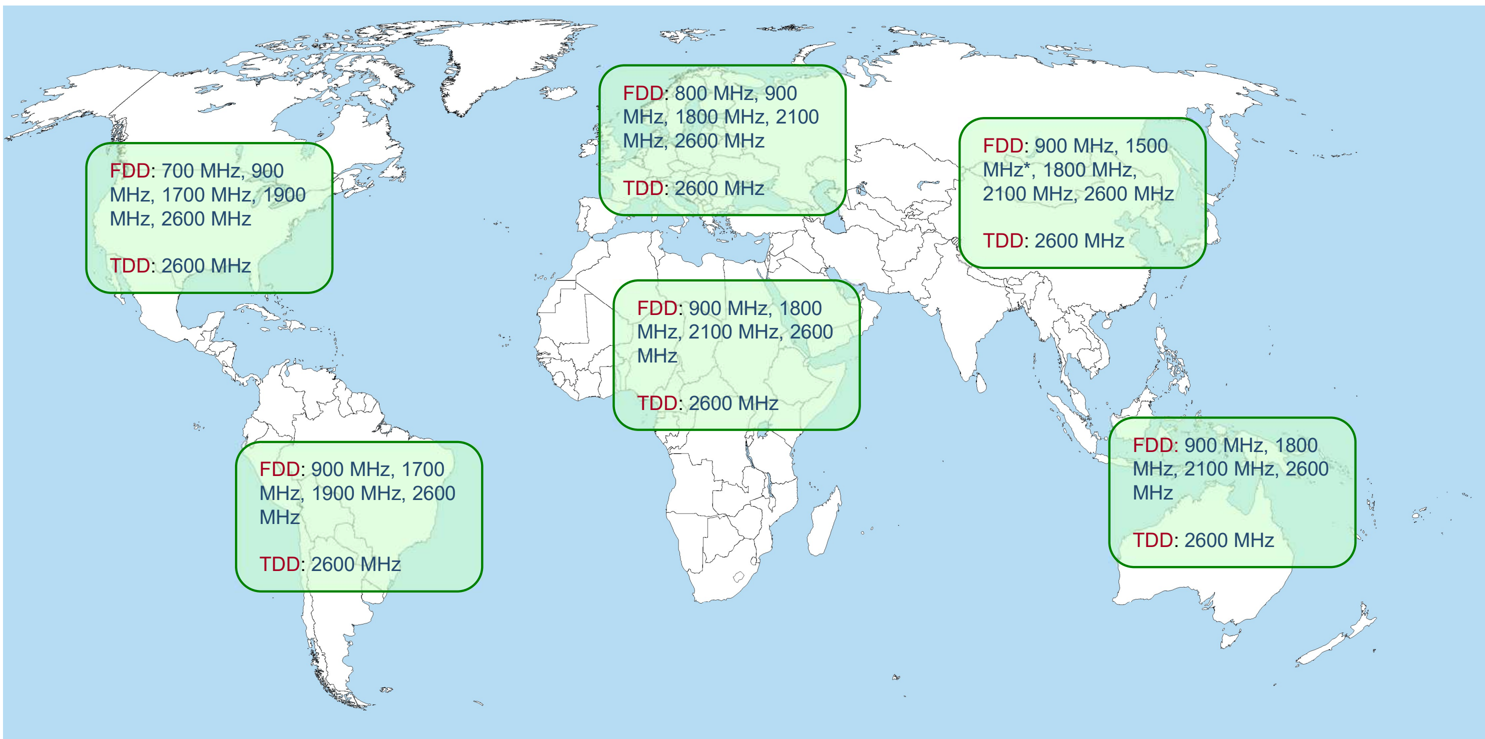
History of LTE releases



Dip. Ingegneria dell'Informazione
University of Pisa, Pisa, Italy

Communication systems (25/26) M.Sc. Communications Eng.

Spectrum allocation



Supported QoS classes (1/2)

- Guaranted-bitrate (GBR) class, which preserves time relation between information entities of the stream:
  - Conversational voice
  - Real time video and games
  - Buffered videos
- Non-guaranteed-bitrate (NGBR) class, which preserves payload content:
  - IP multimedia subsystem (IMS) signalling
  - Web browsing
  - Email and file transfer protocol (FTP)

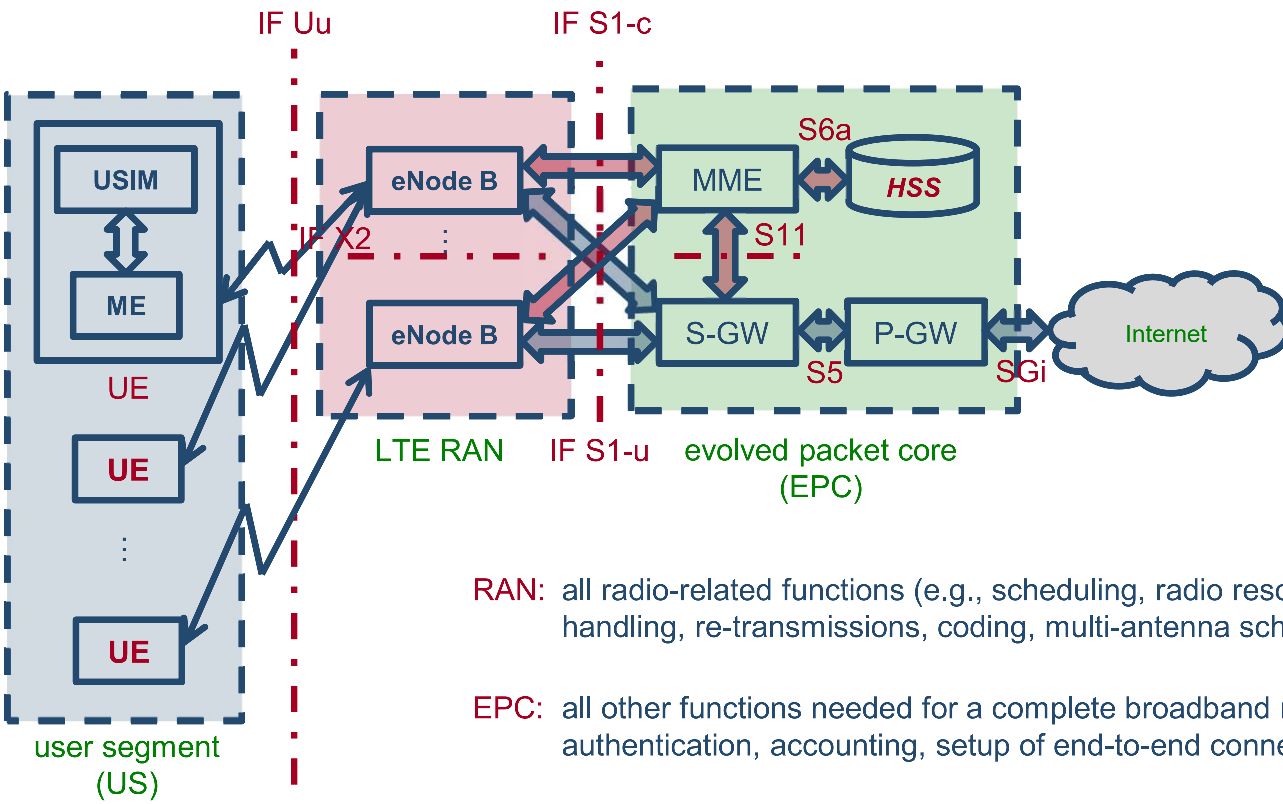
Communication systems (25/26) M.Sc. Communications Eng.

Supported QoS classes (2/2)

QoS class	Delay latency	Delay jitter	Reliability
Conversational voice	low	low	low
Real time video	medium	low	medium
Real time games	very low	low	medium
Buffered video	high	low	high
IMS signalling	low	high	high
Web, email, FTP	high	high	high

The most important parameter used by LTE-A to identify the QoS is the 8-bit QoS class identifier (QCI)

System architecture evolution (SAE) (1/2)



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)

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**

Mapping across channels

In LTE-A, channels are classified according to:

- Logical channels (control vs. data/traffic channels)
- Transport channels (data+signalling, random access requests, paging messages)
- Physical channels (actual radio-frequency bearers, using the air interface Uu to apply OFDMA/SC-FDMA and MIMO techniques)

Note 1: Thanks to these multiple-access techniques, all transport channels are shared

Note 2: Only data-oriented shared channels can adapt their coding rate and make use of (hybrid) ARQ in addition to FEC

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:

$$f_{\mathsf{D}} \ll \Delta f \ll B_{\mathsf{coh}}$$

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

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

Subcarrier spacing (2/2)

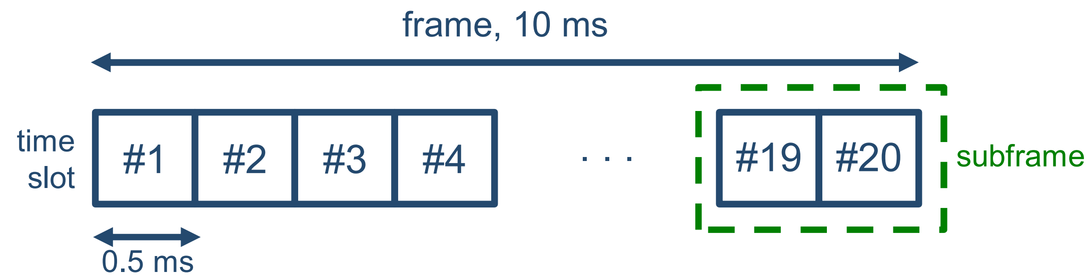
Frequency selectivity: LTE-A systems normally work with a maximum delay spread $\sigma_\tau = 4.7\,\mu\text{s}$

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

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

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

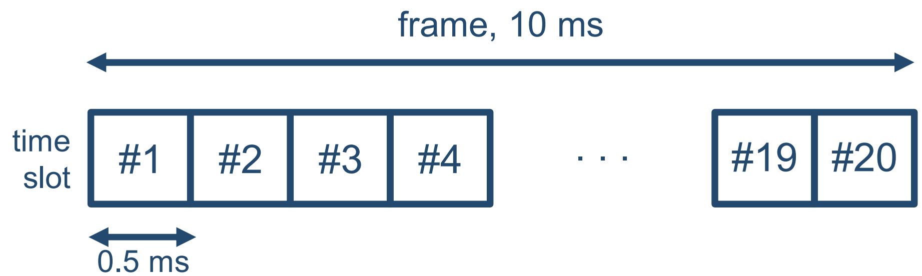
Frame structure in FDD (1/2)



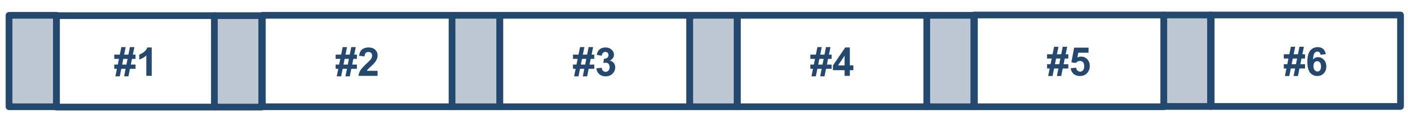
Normal configuration: One slot (0.5 ms) is composed by 7 OFDM symbols, with "net" duration $T = 1/\Delta f = 66.7\,\mu\mathrm{s}$

The cyclic prefix has a duration $T_p = 4.7\,\mu\mathrm{s}$, which is suitable for mostly used cell sizes (radius ≤ 1 km)

Frame structure in FDD (2/2)

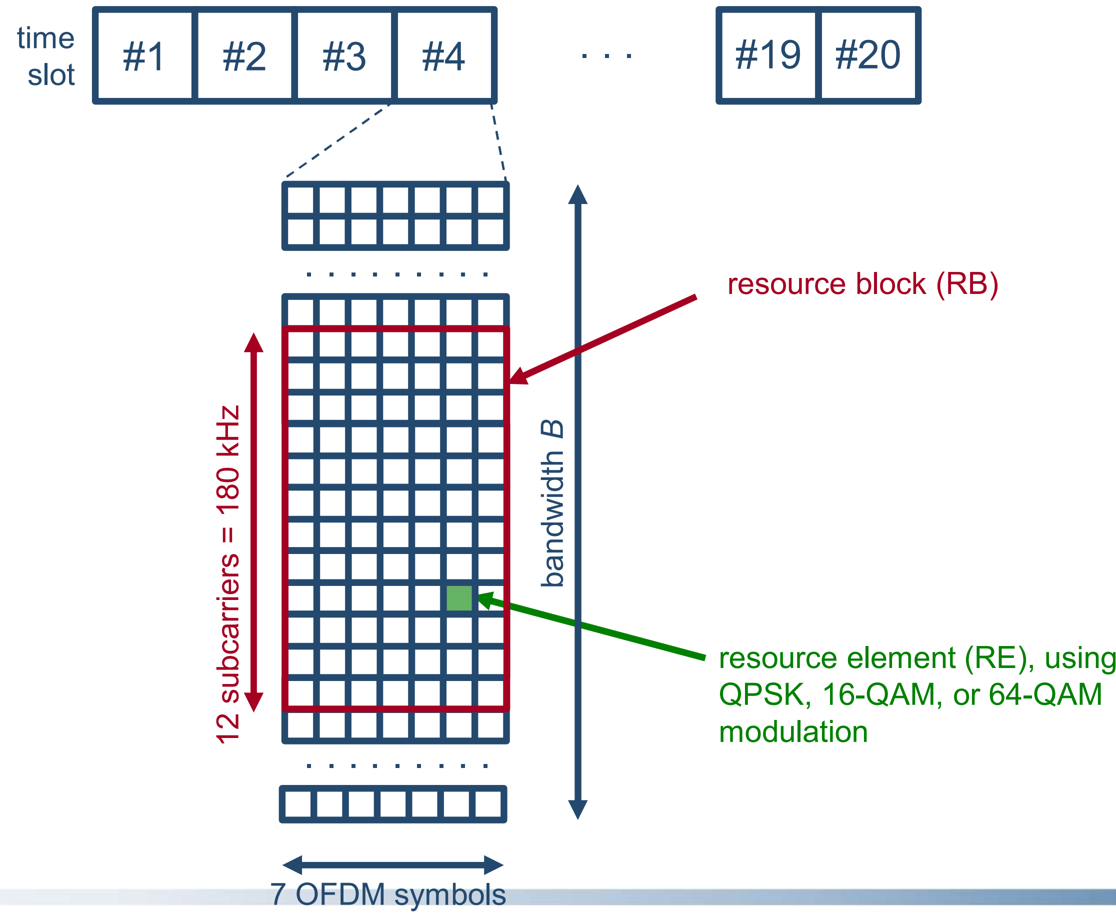


Extended configuration: One slot (0.5 ms) is composed by 6 OFDM symbols, again with "net" duration $T = 1/\Delta f = 66.7\,\mu\text{s}$



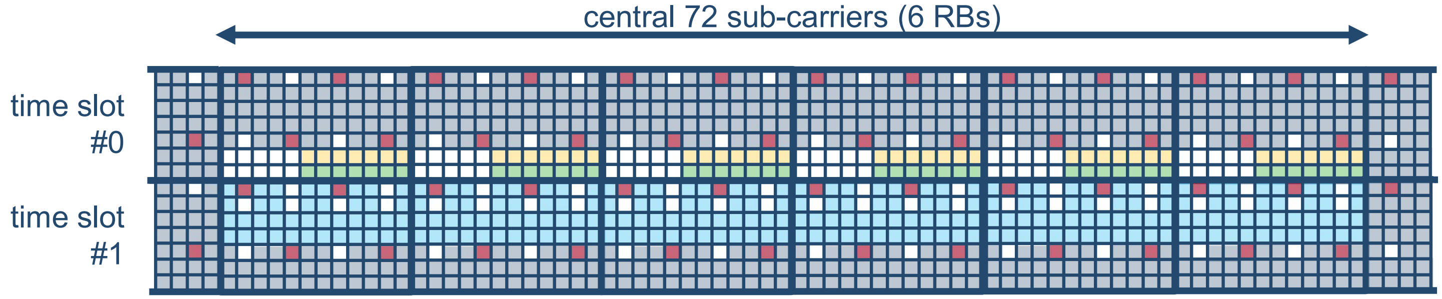
The cyclic prefix has a duration $T_p = 16.7\,\mu\text{s}$, which is suitable for larger cell sizes (radius up to 5 km)

Frame structure type I (FDD)



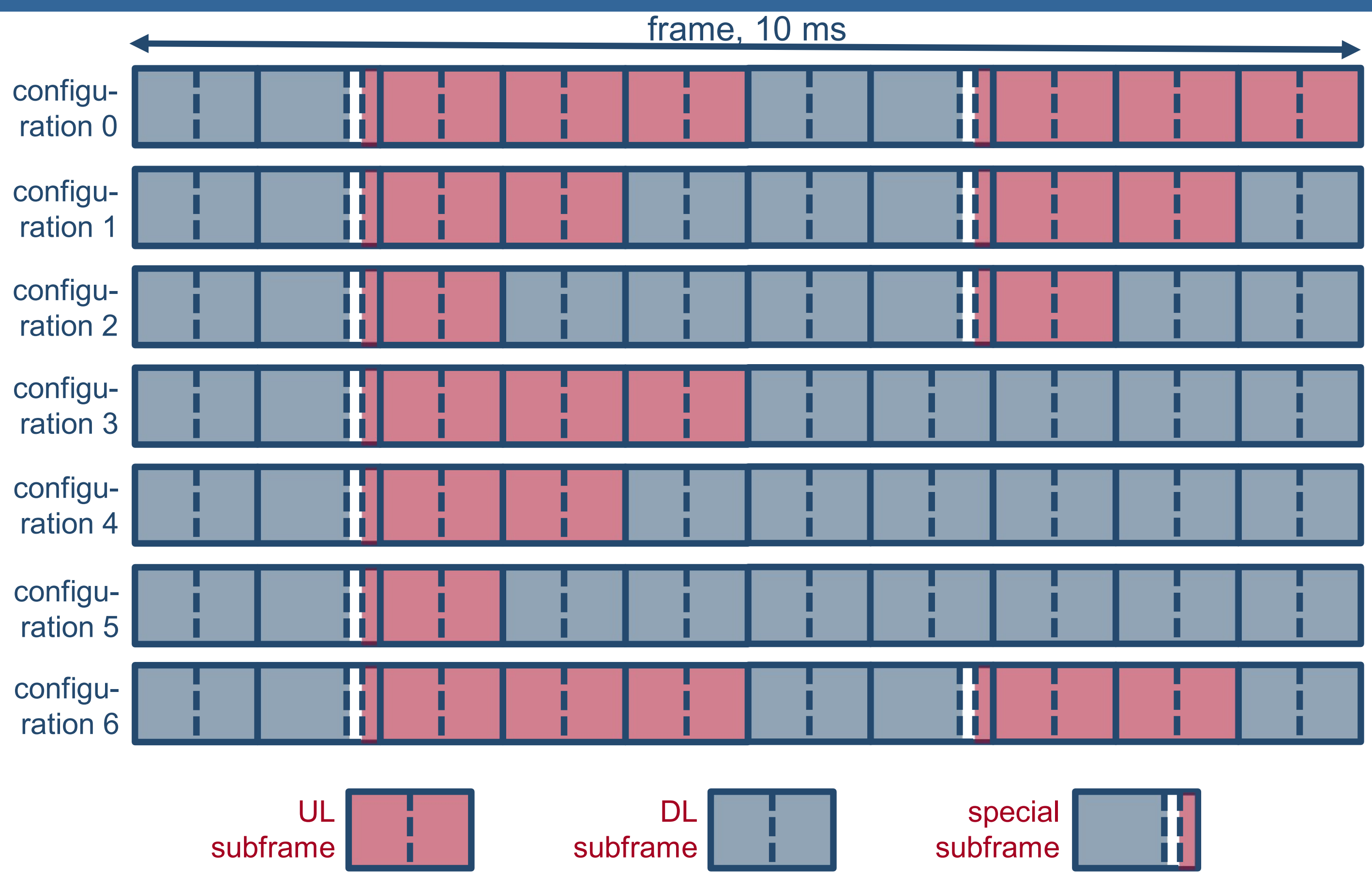
Example of resource element mapping

RE mapping for DL frame using the FDD mode (type I), normal CP, 10- or 20-MHz bandwidth, and single-input single-output configuration:



- primary synchronization signal (PSS)
- secondary synchronization signal (SSS)
- reference signal (RS)
- physical broadcast channel (PBCH)
- physical DL shared channel (PDSCH)
- not used

Frame structure type II (TDD)



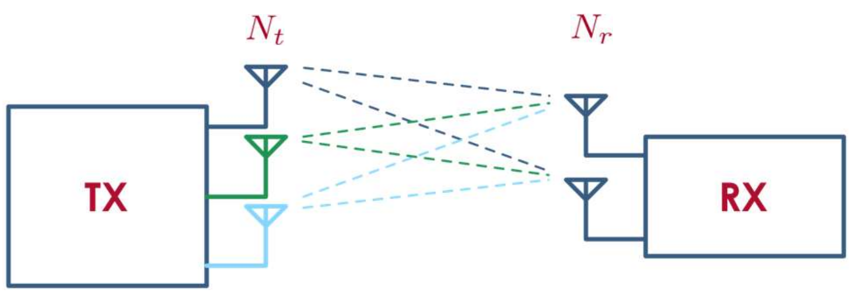
Bandwidth options

channeliza-tion [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

Multiple-input multiple-output (MIMO) systems

Multiple-input multiple-output (MIMO) systems

Another technology that is widely adopted in 4G standards to meet the ITU-advanced requirements is MIMO:



SISO: $N_t = N_r = 1$

MISO: $N_t > 1, N_r = 1$

SIMO: $N_t = 1, N_r > 1$

MIMO: $N_t > 1, N_r > 1$

$$\underbrace{\mathbf{y}}_{N_r \times 1} = \underbrace{\mathbf{H}}_{N_r \times N_t} \underbrace{\mathbf{x}}_{N_t \times 1} + \underbrace{\mathbf{n}}_{N_r \times 1}$$

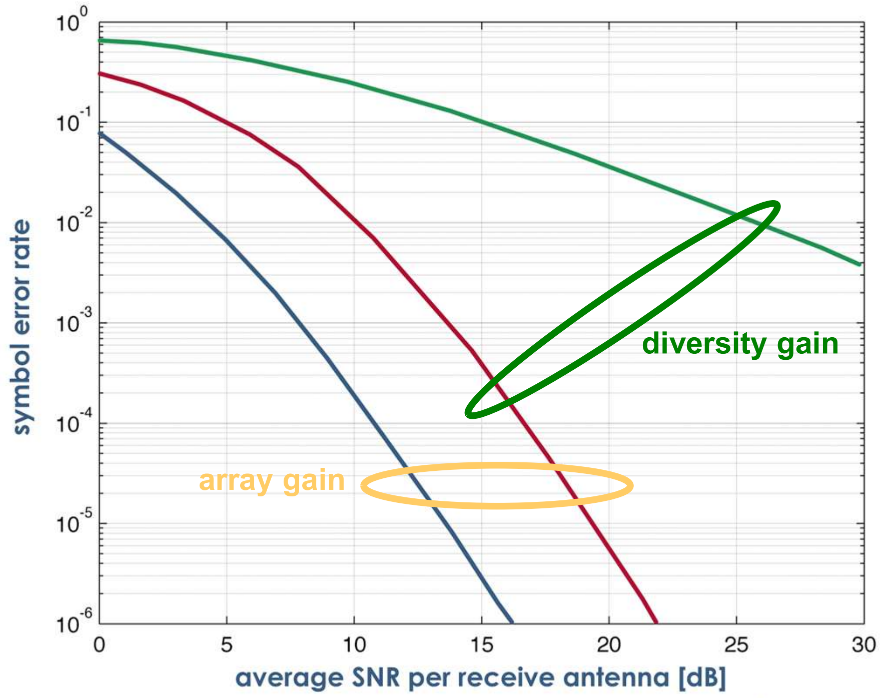
Benefits of MIMO (1/2)

- array gain: the signal-to-noise ratio (SNR) can be increased by beamforming at the transmitter and/or coherent combining at the receiver

- diversity gain: channel fading can be mitigated by combining independent copies of the transmitted signal in space, frequency, or time

- spatial multiplexing: the throughput can be increased by transmitting multiple, independent (at most, $\min\{N_t, N_r\}$) data streams, thus increasing the capacity of the network

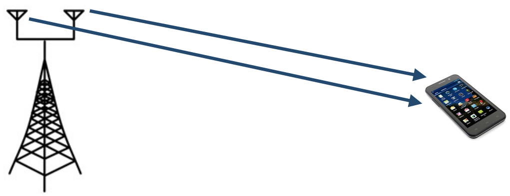
Benefits of MIMO (2/2)



spatial multiplexing: increase in the system capacity

An example of array gain: Transmit beamforming

Let's suppose to have a multiple-input single-output (MISO) system:



To transmit the information symbol b to the receiver, the transmitter can apply a beamforming precoder $\mathbf{w} \in \mathbb{C}^{N_t \times 1}$: $\mathbf{x} = \mathbf{w}b$

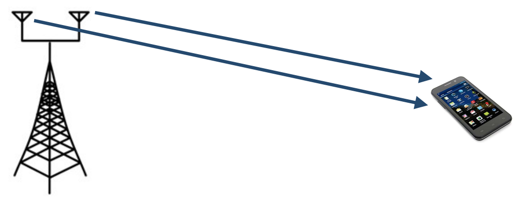
$$y = \mathbf{h}\mathbf{x} + n = \mathbf{h}\mathbf{w}b + n$$

By selecting $w_m = h_m^* / \|\mathbf{h}\|$ (maximal-ratio combining) for all $m = 1, \ldots, N_t$, we can increase the received SNR by a factor $\|\mathbf{h}\|^2$ wrt to the SISO configuration

- channel state information (CSI) at the transmit side is required

An example of diversity gain: Alamouti code

Let’s consider a 2×1 MISO system:



$$\mathbf{x} = \begin{bmatrix} b_1 & -b_2^* \\ b_2 & b_1^* \end{bmatrix}$$

first time slot second time slot

$$y(1) = h_1 b_1 + h_2 b_2 + n(1)$$
$$y(2) = -h_1 b_2^* + h_2 b_1^* + n(2)$$

To exploit the space diversity, we can combine the two received signals as follows:

$$h_1^* y(1) + h_2 y(2)^* = \left(|h_1|^2 + |h_2|^2\right) b_1 + h_1^* n(1) + h_2 n(2)^*$$
$$h_2^* y(1) + h_1 y(2)^* = \left(|h_1|^2 + |h_2|^2\right) b_2 + h_2^* n(1) + h_1 n(2)^*$$

Amplification factors:

- signal: $\left(|h_1|^2 + |h_2|^2\right)^2$
- noise: $|h_1|^2 + |h_2|^2$

- CSI at the receive side is required
- generalization: orthogonal space-time block codes

An example of spatial multiplexing: SVD (1/2)

Let us suppose to have a MIMO system:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

We can apply the singular value decomposition (SVD) to the channel matrix $\mathbf{H}$:

$$\mathbf{H} = \mathbf{U}\mathbf{D}\mathbf{V}^H$$

- $\mathbf{U}\mathbf{U}^H = \mathbf{I}_{N_r}$
- $\mathbf{V}\mathbf{V}^H = \mathbf{I}_{N_t}$
- $\mathbf{D} = \mathrm{diag}\{\mathbf{d}\}$ where $d_m = \sqrt{\lambda_m}$ with λ_m denoting the *m*-th eigenvalue of $\mathbf{H}\mathbf{H}^H$

An example of spatial multiplexing: SVD (2/2)

By precoding the stream of information symbols $\mathbf{b}$ by $\mathbf{V}$, and by processing the received vector $\mathbf{r}$ by $\mathbf{U}^H$, we can get

$$\begin{aligned}\mathbf{y} &= \mathbf{U}^H(\mathbf{Hx}+\mathbf{n}) \\ &= \mathbf{U}^H(\mathbf{HVb}+\mathbf{n}) \\ &= \mathbf{U}^H\mathbf{UDV}^H\mathbf{Vb}+\mathbf{U}^H\mathbf{n} \\ &= \mathbf{Db}+\mathbf{U}^H\mathbf{n}\end{aligned}$$

$\mathbf{U}^H\mathbf{n}$ has the same statistical properties of $\mathbf{n}$

We can obtain $\mathrm{rank}\left(\mathbf{HH}^H\right) \leq \min\left(N_t, N_r\right)$ independent information streams, thus enhancing the system capacity

- CSI at both the transmitter and the receiver is needed

Limits of MIMO

- it is not possible to exploit all the degrees of freedom to simultaneously obtain array gain, space diversity, and spatial multiplexing: some fundamental tradeoffs in terms of system performance need to be taken
- in most cases, full CSI at both the transmitter and the receiver cannot be guaranteed in a realistic environment: the actual performance is poorer than the maximum achievable one
- some tradeoffs between system complexity and performance are needed to reduce the intensive computational load of MIMO: suboptimal algorithms are necessary

Channel state information (1/3)

In order to implement feasible MIMO configurations, LTE-A adopts the following parameters as channel state information (CSI), to be fed back in the uplink from the MSs to the eNodeB:

- channel quality indicator (CQI)
- rank indicator (RI)
- precoding matrix indicator (PMI)

Channel state information (2/3)

- The channel quality indicator (CQI) indicates the maximum data rate that the MS can handle with a block error ratio of at most 10%, depending on received SINR and implementation of the receiver architecture

CQI	modu-lation	coding rate	CQI	modu-lation	coding rate
0	n/a	n/a	8	16-QAM	490/1024
1	QPSK	78/1024	9	16-QAM	616/1024
2	QPSK	120/1024	10	64-QAM	466/1024
3	QPSK	193/1024	11	64-QAM	567/1024
4	QPSK	308/1024	12	64-QAM	666/1024
5	QPSK	449/1024	13	64-QAM	772/1024
6	QPSK	602/1024	14	64-QAM	873/1024
7	16-QAM	378/1024	15	64-QAM	948/1024

Channel state information (3/3)

- The rank indicator (RI) reports the maximum number of layers that the MS can successfully receive, and is connected to the configuration of spatial multiplexing of the link
- The precoding matrix indicator (PMI) is used for closed-loop spatial multiplexing, and indicates, via a look-up table available at the eNodeB, the best pre-calculated precoding matrix that better fits the actual pre-coding matrix $\mathbf{V}$

Network management

Mobility management

The choice of mobility management procedures depends on the MS state:

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

Interoperability with 3GPP and non-3GPP systems (1/2)

Interoperation with other mobile communication systems has been crucial for an effective rollout in the early stage of the LTE and LTE-A technology

3GPP technologies (GSM and UMTS):

- LTE-A specifications support mobility between LTE and UMTS or GSM in both idle and connected MS status, and include the option for optimized handovers that transfer mobiles with no packet loss and with a minimal break in communications
- inter-operation architectures require enhancements at both the 2G/3G packet-switched domain and the 4G EPC

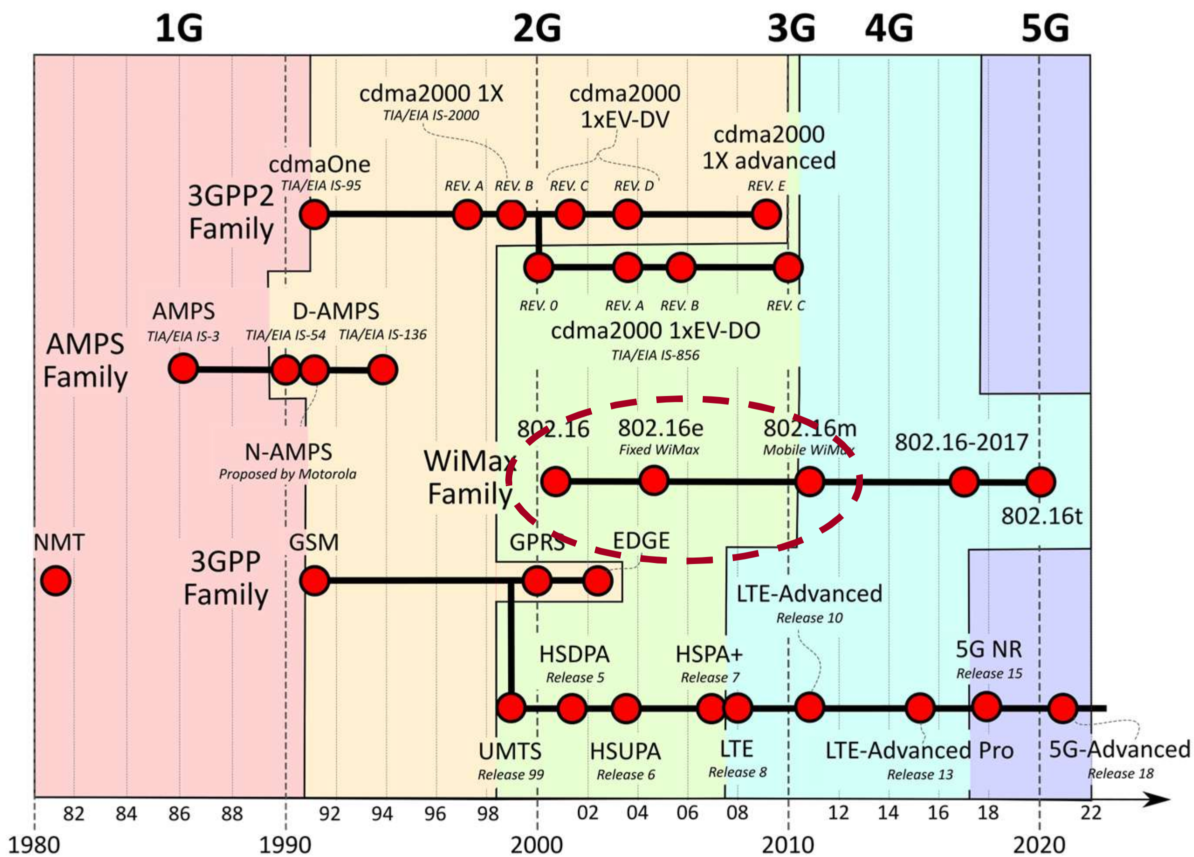
Interoperability with 3GPP and non-3GPP systems (2/2)

Non-3GPP technologies (e.g., cdma2000, IEEE 802.16 and WLAN):

- the main challenge is to maintain IP addresses and connections with external server, without the support for optimized handovers
- specific procedures must be adopted in order to authenticate the nodes using either trusted or untrusted access networks

IEEE 802.16m standard

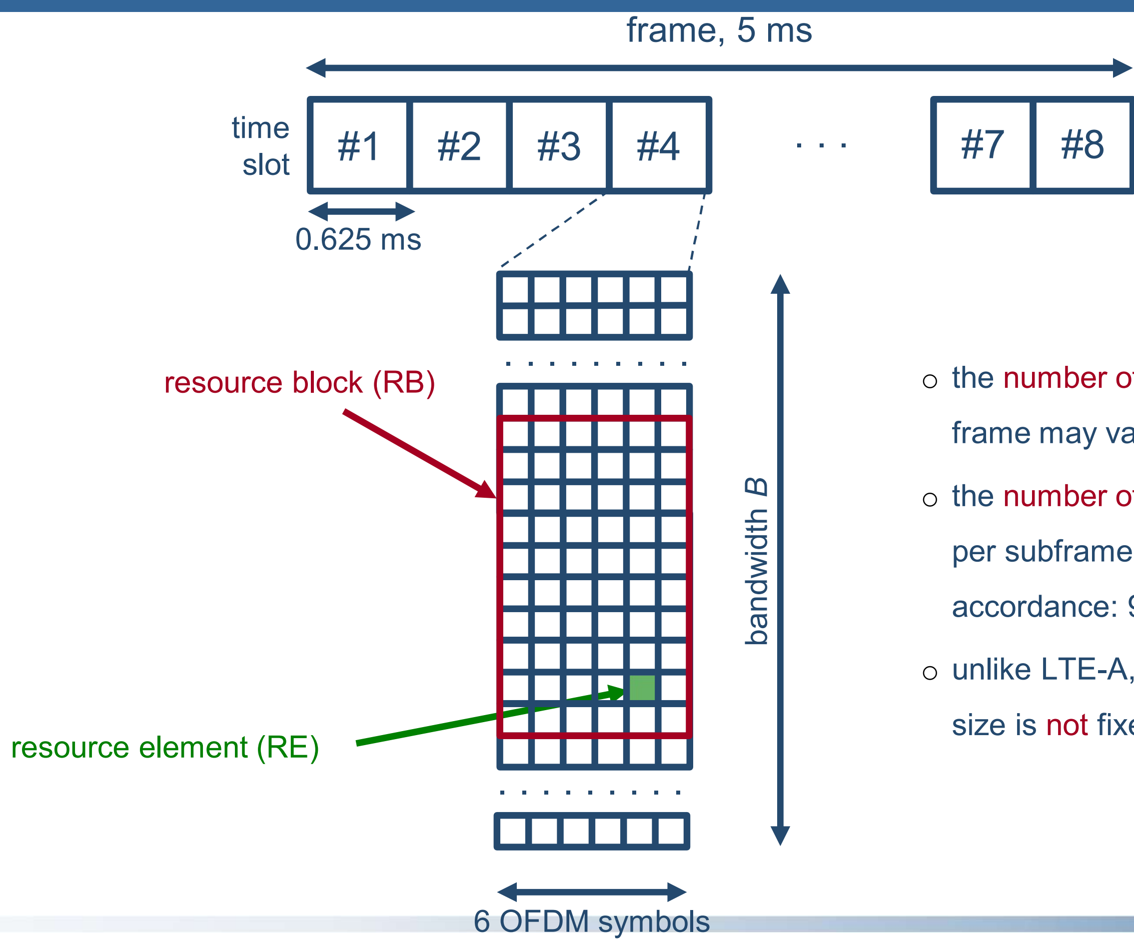
History of IEEE 802.16 releases



IEEE 802.16m

- The IEEE 802.16m (a.k.a. WirelessMan v. 2) has been standardized by the IEEE in February 2012
- IEEE 802.16m adopts OFDMA for both the DL and the UL, achieving peak rates of 1 Gb/s (DL) and 0.5 Gb/s (UL) , and maximum latency 10 ms
- Carrier frequencies: 2300 MHz, 2500 MHz, 3500 MHz, 5800 MHz
- Carrier spacing: 10.94 kHz
- Bandwidths: 3.5 MHz, 5 MHz, 7 MHz, 8.75 MHz, 10 MHz, 20 MHz
- Constellations: QPSK, 16-QAM, 64-QAM

Structure of the IEEE 802.16m frame

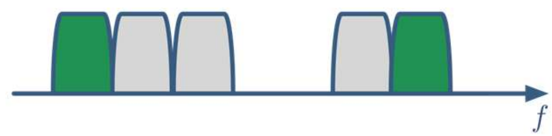


- the number of subframes per frame may vary: 5, 6, 7, and 8
- the number of OFDMA symbols per subframe goes in accordance: 9, 7, 5, and 6
- unlike LTE-A, the resource block size is not fixed

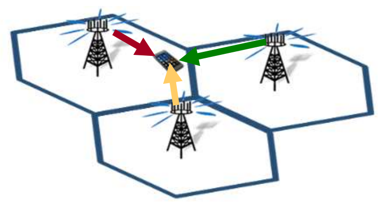
Enabling technologies for 4G standards

Enabling technologies for 4G standards

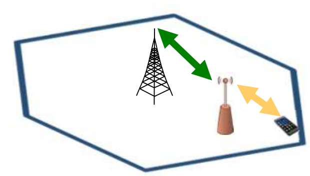
- **carrier aggregation**



- **network MIMO**



- **relaying**



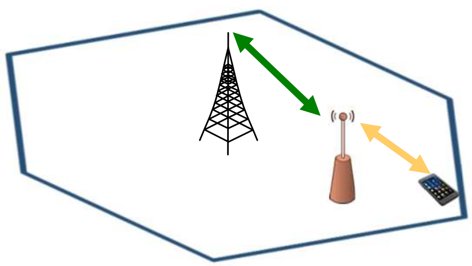
Carrier aggregation

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

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

Relaying

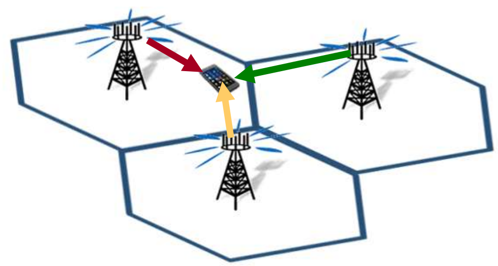
Since Release 10, relay nodes can be introduced in the network as low-power BTSs, to provide enhanced system performance



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

Network MIMO

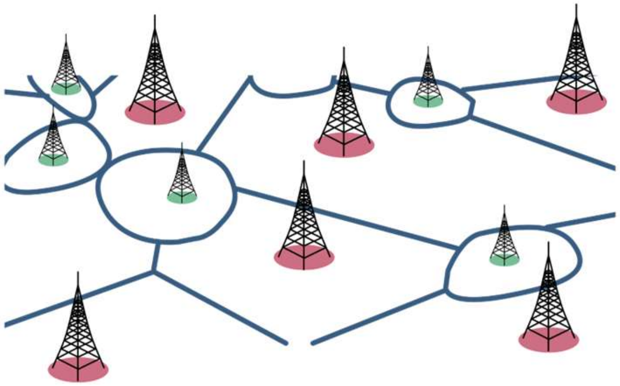
Network MIMO, known as coordinated multipoint (CoMP) in LTE-A, and coordinated MIMO (CO-MIMO) in IEEEE 802.16m, consists in coordinating (at the transmit side) or combining (at the receive side) signals using multiple antennas



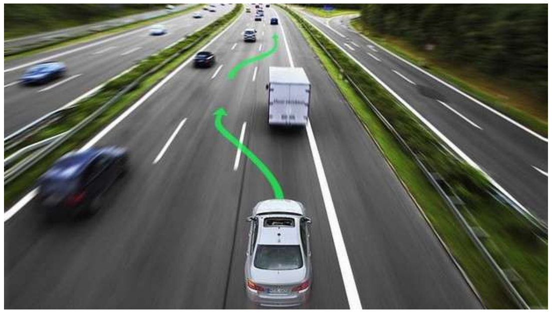
- this form of distributed MIMO achieves significant performance improvements, especially for cell-edge users (improving coverage and cell-edge rates)
- it requires a significant feedback overhead to exchange CSI across BTSs

Additional technologies supported by 4G standards (1/2)

- Heterogeneous, multi-tier dense networks: small cells, relays, etc.



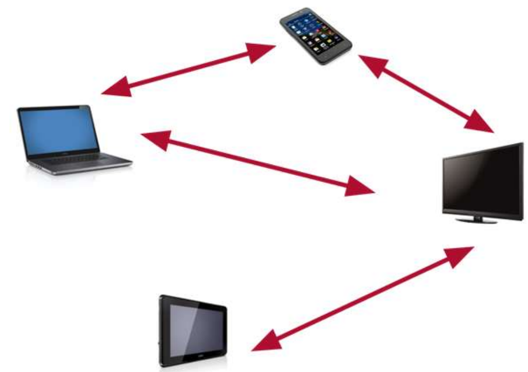
- Device-to-device (D2D) communications and proximity services (ProSe)



- Overload control techniques for machine-type communications (MTC)

Additional technologies supported by 4G standards (2/2)

D2D communication is a radio technology that enables devices to communicate directly with each other, that is without routing the data paths through a network infrastructure



Applications:

- safety applications and disaster scenarios
- novel commercial proximity services (ProSe) scenarios
- network traffic offloading
- industrial automation and machine-to-machine communication

D2D communications can be profitably integrated with cellular networks, to complement and enrich the network topology

5G technologies

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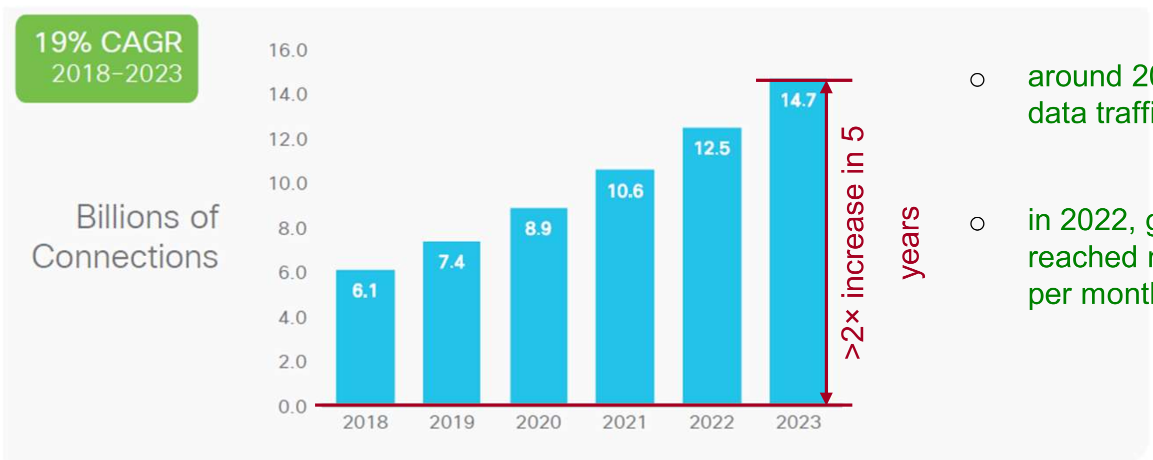
5G technologies (1/3)

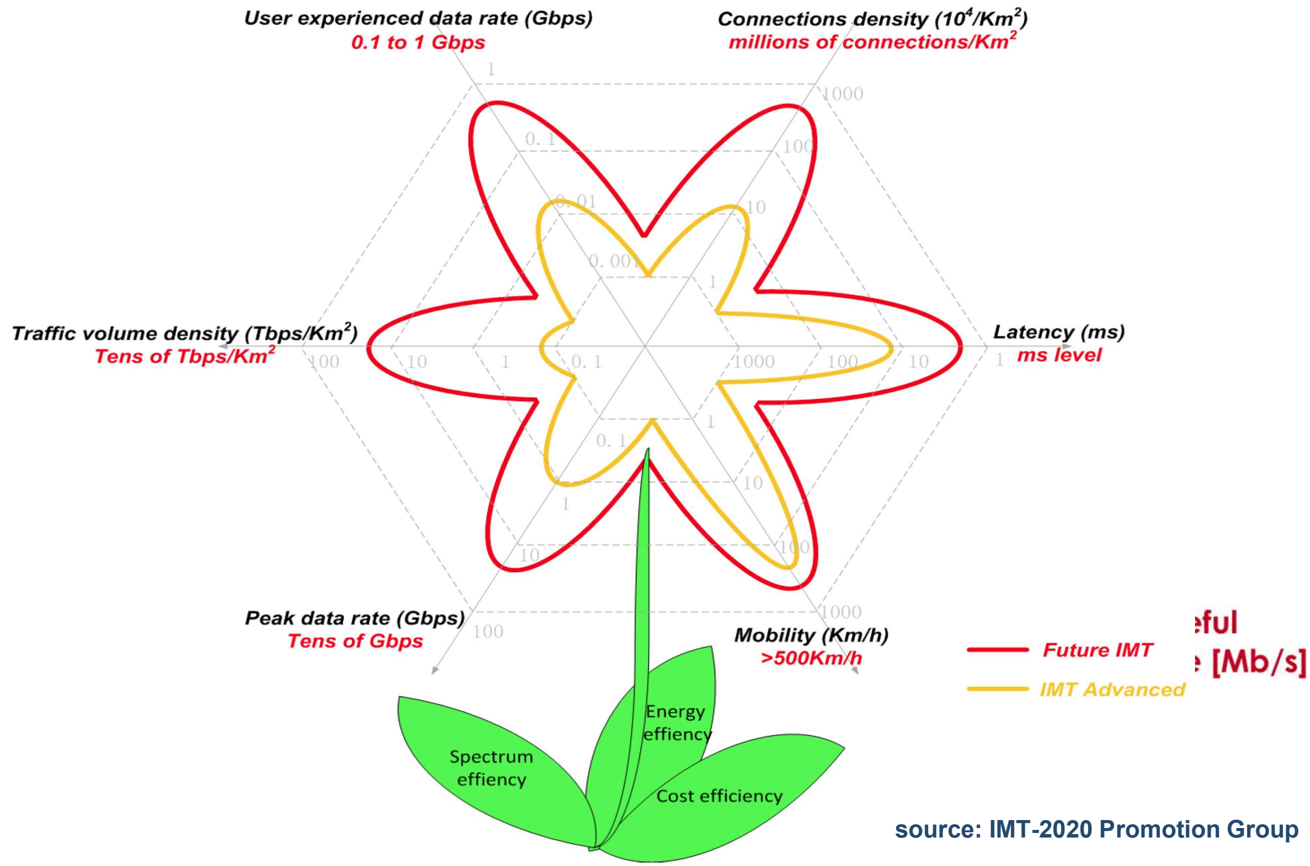
Do we really need 5G?



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 (3/3)

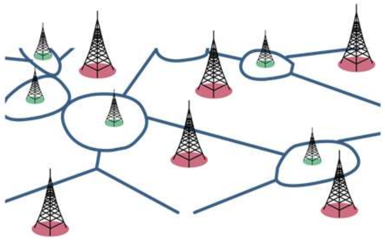


source: IMT-2020 Promotion Group

Technology drivers

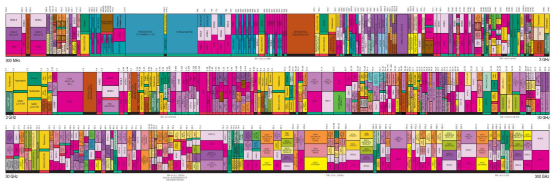
Technology drivers

- network densification



- massive MIMO

- mm-wave technology



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

Dip. Ingegneria dell'Informazione
University of Pisa, Pisa, Italy

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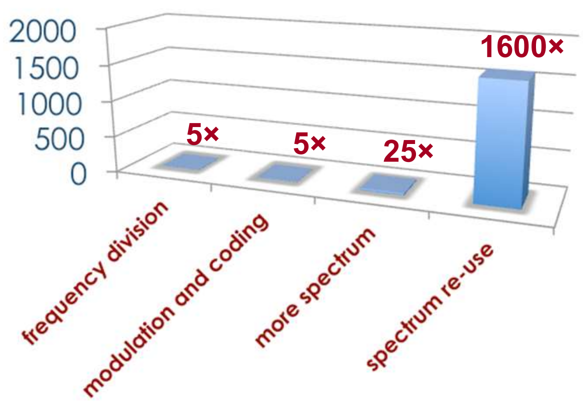
Network densification (1/3)

Cooper's "law": the wireless capacity has doubled every 30 months over the last century ⇨ in the last fifty years, capacity has increased about a million times!



The right path to pursue is network densification: very dense deployment of BTSs

Network densification (2/3)

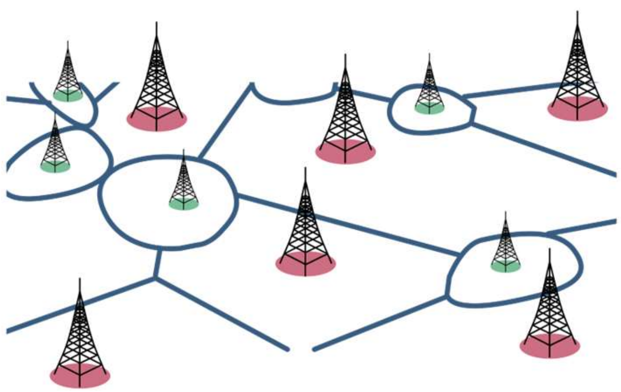
Shannon's law:

$$\mathcal{C} \propto N \cdot B \cdot \log_2(1+\gamma) \qquad [\mathrm{b/s/Hz}]$$

adaptive coding and modulation, interference management (γ)

number of antennas (N) **bandwidth** (B)

With extreme network densification, we can reuse Shannon's law everywhere, thus increasing the area spectral efficiency (in b/s/Hz/m^2)



heterogeneous, multi-tier dense networks: small cells, relays, etc.

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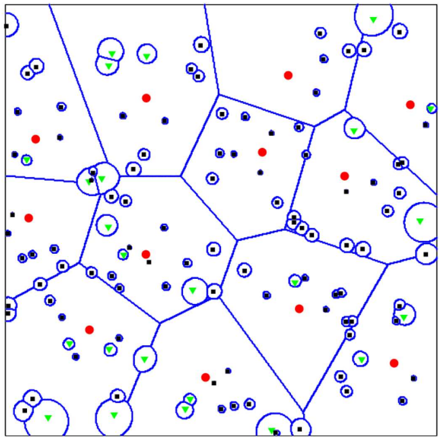
Network densification (3/3)

Open challenges include:

- self-organization, exacerbated by random/unplanned deployment of small cells
- coverage and performance prediction: stochastic geometry and random matrix theory could serve as powerful tools
- interference management and resource allocation, also considering the presence of multiple tiers



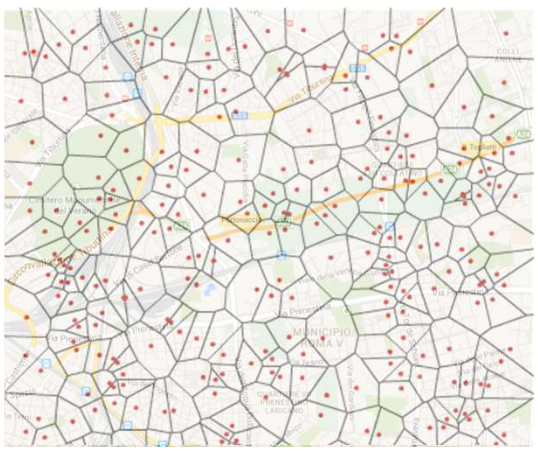
Stochastic geometry (1/2)

An effective way to study very complex geometrical patterns such as the base station locations in a heterogeneous dense network is through stochastic geometry (SG):

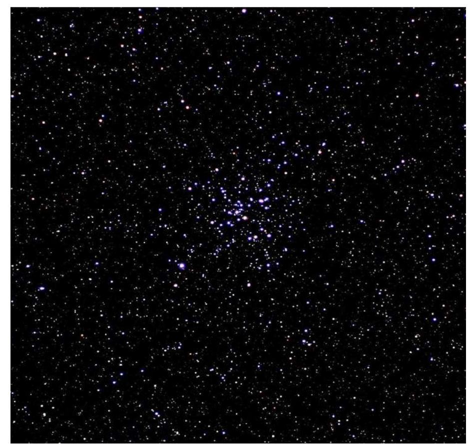
- SG is an area of mathematical research that seeks to provide suitable mathematical models and appropriate statistical methods to study and analyze random spatial patterns
- SG is a rich branch of applied probability with various applications: e.g., material science, image analysis and stereology, astronomy, biology, forestry, geology, communications

Stochastic geometry (2/2)

Basic ingredients of SG are point processes, patterns that constitute a countable random collection of points that reside in some measure space (such as the Euclidean space)



placement of BSs in the network



stars in a night sky

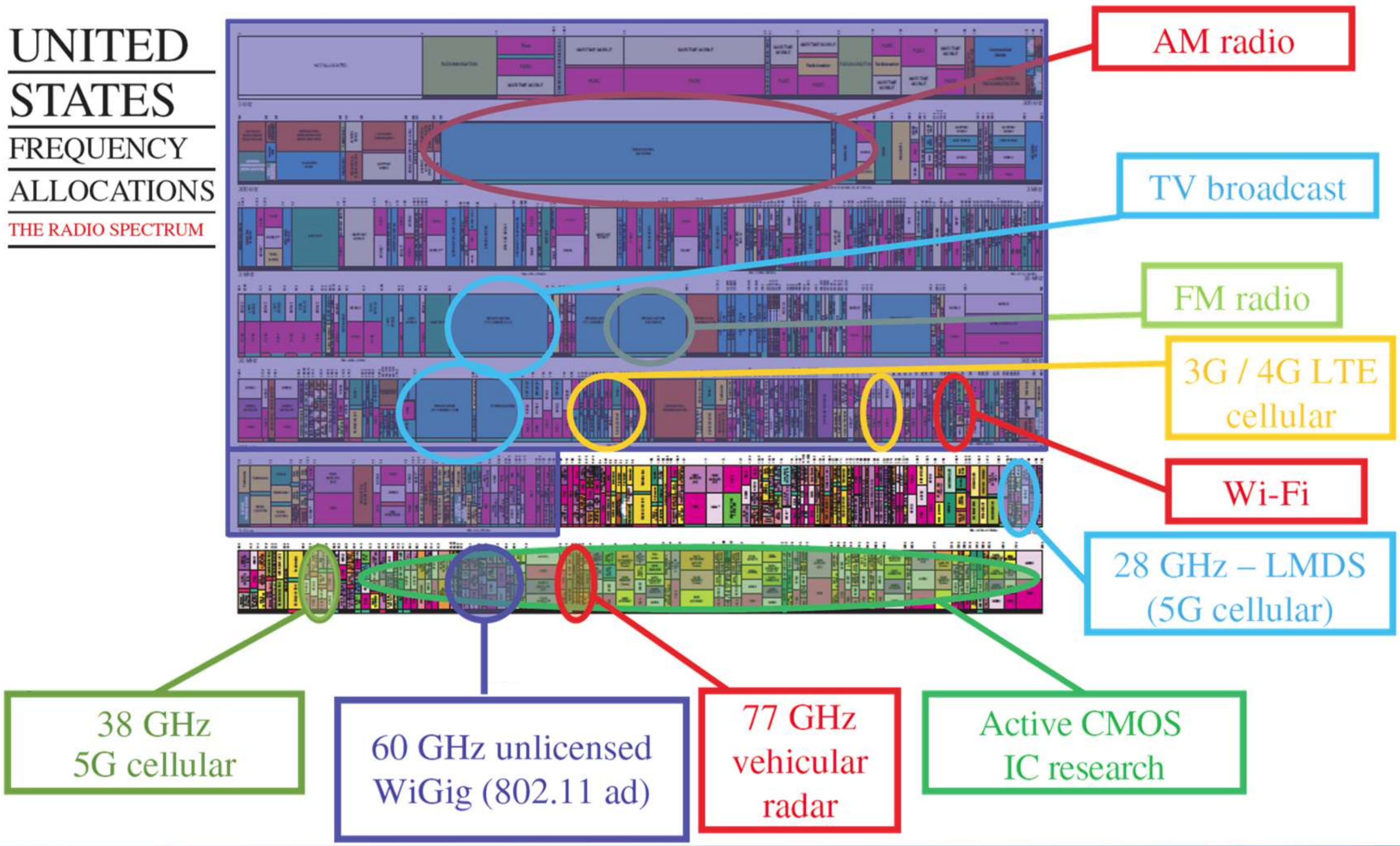
mm-wave technology

mm-wave technology: What is it?

What are mm-wave communications?

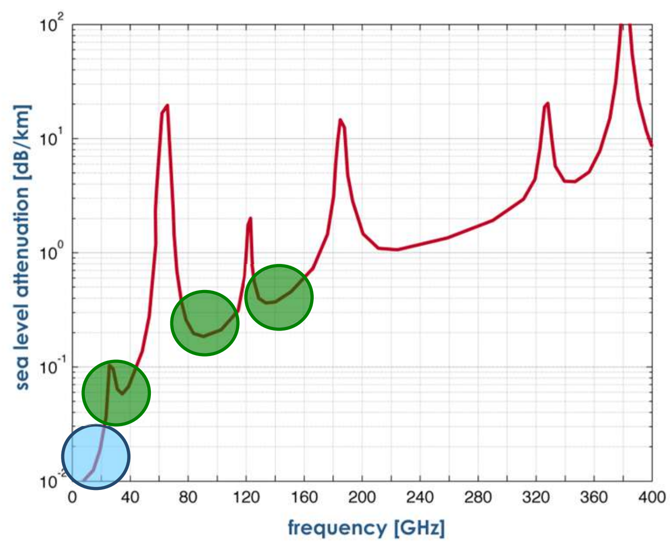
- By definition, all wireless communications that take place in the range 30÷300 GHz
- In practice, mm-wave communications target the radio spectrum above 10 GHz
- Spectrum at 28 GHz, 38 GHz, and 70÷80 GHz looks especially promising for next-generation cellular systems

Motivations



Why only today

The major impairment is the signal attenuation:



The bandwidth around 60 GHz is unlicensed almost worldwide, due to the high O_2 absorption effect interacting with atmospheric oxygen during propagation

Path loss revisited (1/2)

This is related to the Friis' formula, that considers free-space propagation to measure the received power in a perfectly uniform medium:

$$P_{\mathsf{Rx}}(d) = \frac{P_{\mathsf{Tx}}}{L(d)}$$

free-space path loss

where

$$L(d) = \frac{1}{G_{\mathsf{Tx}} G_{\mathsf{Rx}}} \left(\frac{4\pi d}{\lambda} \right)^2$$

tx-rx distance

gain of the transmit antenna

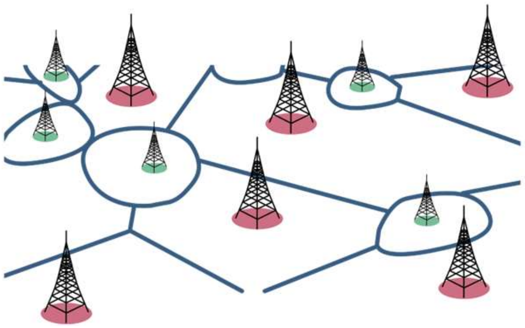
gain of the receive antenna

carrier wavelength

Path loss revisited (2/2)

However, network densification includes small cells with coverage radius $R \leq 50\,\mathrm{m}$

➡ path loss becomes acceptable:



$$L(d) = 106.4\,\mathrm{dB}\,@d = 1\,\mathrm{km},\, f_0 = 5\,\mathrm{GHz} \approxeq L(d)\,@d = 100\,\mathrm{m},\, f_0 = 60\,\mathrm{GHz}$$

$$L(d) = 100\,\mathrm{dB}\,@d = 1\,\mathrm{km},\, f_0 = 2.4\,\mathrm{GHz} \approxeq L(d)\,@d = 50\,\mathrm{m},\, f_0 = 60\,\mathrm{GHz}$$

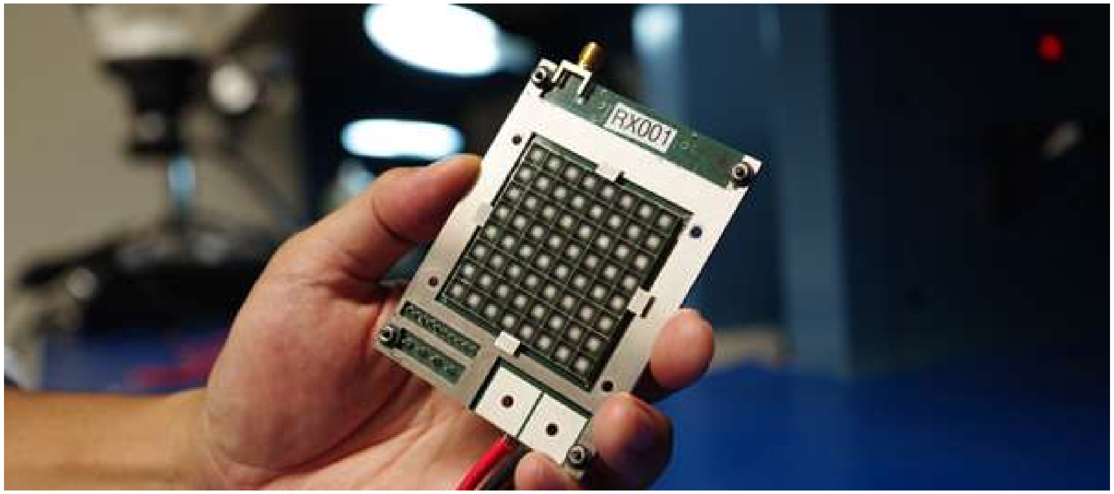
The shift-away from long- to short-range communications allows aggressive frequency reuse with simultaneously operating networks

Antenna design (1/2)

Furthermore, the path loss tells only part of the story: short wavelengths enable smaller directional antennas

Higher antenna gains can offset, and even reduce, the absolute path loss compared to UHF and microwave systems

Antenna design (2/2)

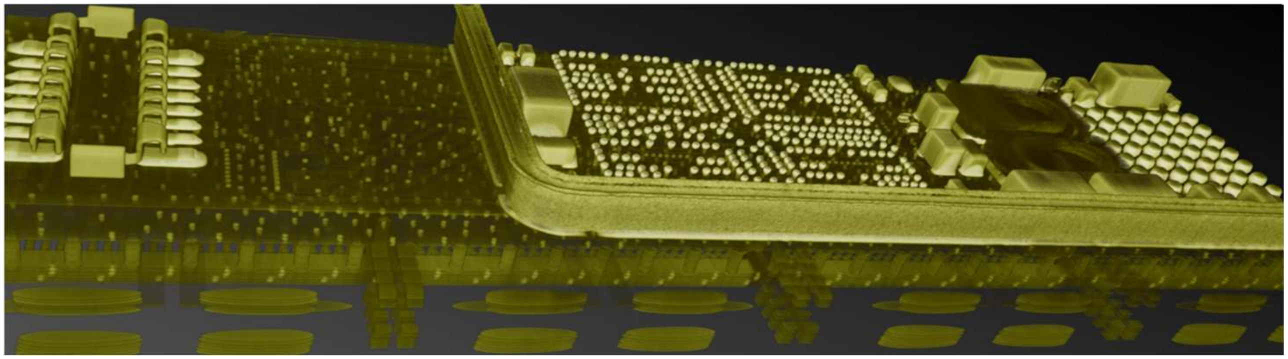


With currently available technology, we can fit more and more antennas into a small printed circuit board, or on a chip.

Highly directional antennas can also promote security as long as network protocols enable flexibly steerable antenna directions

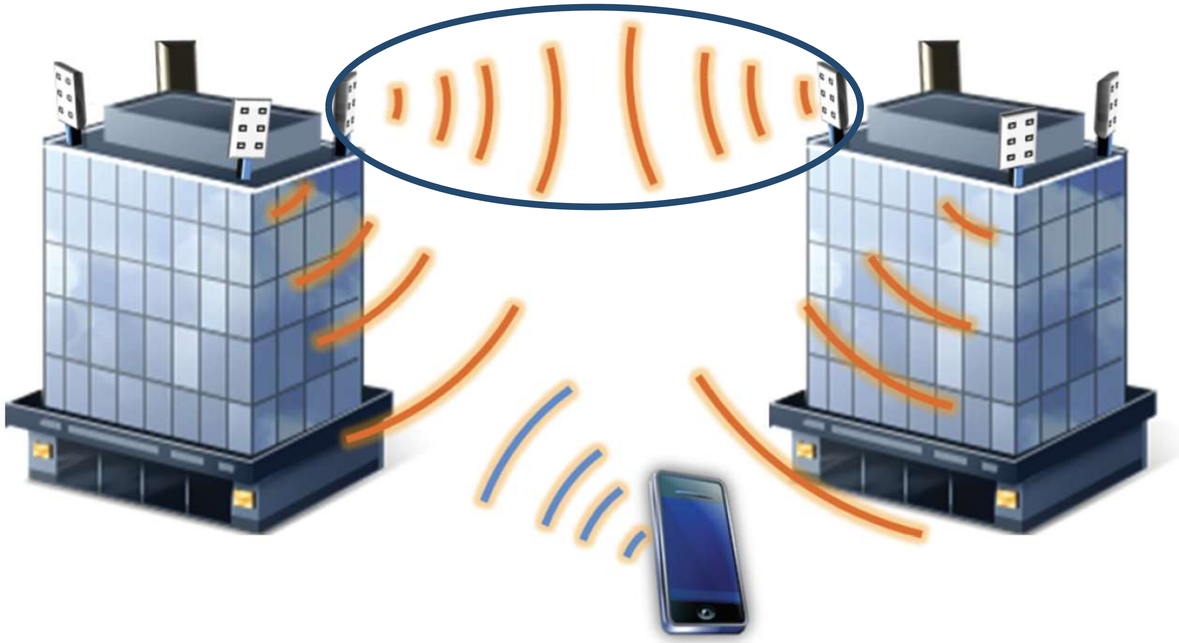
The electronics behind it

- In the past few years, mm-wave circuits have become a viable solutions in low-cost silicon
- Inexpensive circuit production processes made system-on-chip mm-wave radios possible
- For mm-wave communication, the semiconductor industry has become finally ready to produce cost-effective, mass-market products



Applications in 5G systems (1/2)

mm-wave communications can be used as a wireless backhaul in dense networks: mm-wave wireless enables a rapidly deployable and cheaper wireless fiber radio connection than dedicated or leased wired lines



Applications in 5G systems (2/2)

mm-wave communications can be also used to support the massive data rates for mobile devices, and for mobile-to-mobile communications, establishing ad-hoc networks

high directionality in sensing can be applied to equip vehicles with radars for collision avoidance

Current challenges (1/2)

Wireless channel modeling is not valid anymore: research challenges include new propagation models for mm-wave communications

For carrier frequencies higher than 28 GHz, small-scale effects are determined by myriad environmental propagation properties

As an example, physical dimensions of raindrops, hail stones, and snow flakes are on the order of the propagating wavelength

Current challenges (2/2)

Other impairments that are peculiar to mm-wave communications include:

- Decreased signal penetration through obstacles
- Directional communication due to high-gain antenna requirements
- Larger Doppler shift (and hence more severe time selectivity)

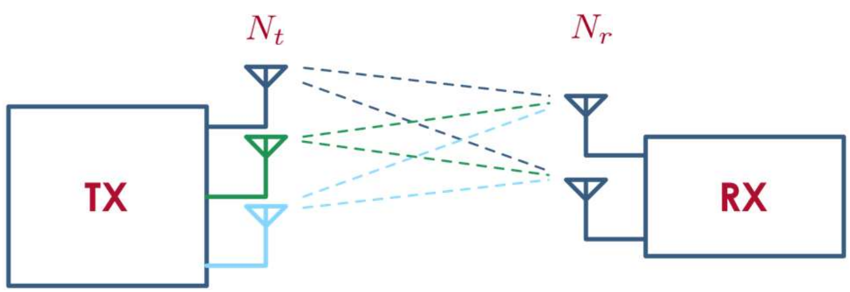
However, we can turn such issues to our advantage:

- We can better separate indoor and outdoor systems
- Having narrower beams reduces the multipath delay spread, thus observing a less severe frequency-selective fading
- Considering reduced cell sizes implies reducing users' mobility, thus limiting the impact of time selectivity

Massive MIMO

Multiple-input multiple-output (MIMO) systems

As previously seen, a technology that is widely adopted in 4G standards to meet the ITU-advanced requirements is MIMO:



SISO: $N_t = N_r = 1$

MISO: $N_t > 1, N_r = 1$

SIMO: $N_t = 1, N_r > 1$

MIMO: $N_t > 1, N_r > 1$

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

Multiuser MIMO (MU-MIMO)

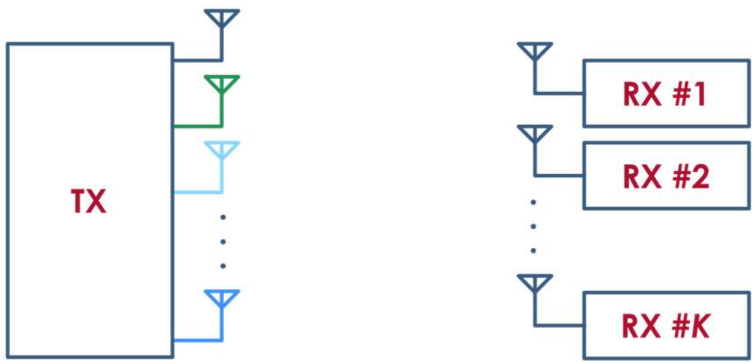
- When considering an MU-MIMO scenario, with multiple terminals, each equipped with multiple antenna, the situation becomes even more critical, especially in the downlink (broadcast channel)

- The optimum strategy consists in adopting pre-interference cancellation techniques known as dirty paper coding (DPC)

Massive MIMO (1/5)

Massive MIMO technology:

$N_t \gg 1$ antennas (hundreds)



$K \gg 1$ single-antenna terminals

$$N_t \gg K \gg 1$$

The massive MIMO concept relies on the law of large numbers, to average out frequency selectivity and thermal noise:

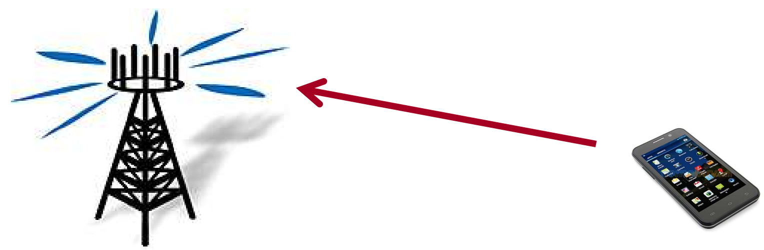
- spatial multiplexing gain $\propto K$
- array gain $\propto N_t$

Massive MIMO (2/5)

Why is massive MIMO effective compared to “classical” MU-MIMO?

- User channels can be decorrelated by using reasonably large antenna arrays at base station
- Linear precoding can achieve almost the same sum rate as optimal but complex DPC technique
- Clear benefits can be seen with a relatively limited number of antennas in realistic propagation environments

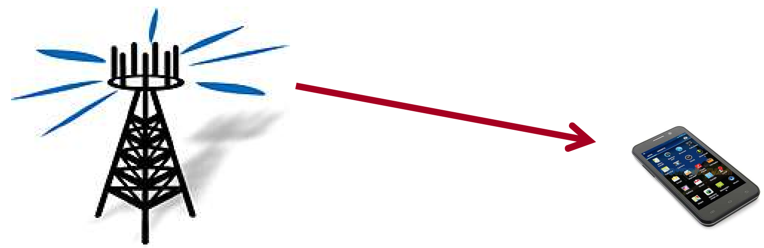
Massive MIMO (3/5)



In the uplink, the BTS:

- acquires CSI from pilot symbols
- detects the information symbols
- since $N_t \gg K$, adopts linear processing techniques (maximal ratio combining, zero forcing, minimum mean squared error), which are nearly optimal

Massive MIMO (4/5)



In the downlink, the BTS:

- uses CSI obtained in the uplink
- applies multiuser MIMO precoding, using low-complexity precoders

Massive MIMO (5/5)

- Thanks to the $N_t - K$ unused degrees of freedom, massive MIMO can obtain:
  - hardware-friendly waveform shaping
  - PAPR reduction due to multiuser precoding
- The major challenge is getting accurate CSI estimation

- Pairing massive MIMO with mm-wave technology, we can accommodate a large number of antennas at the base stations
- Pairing massive MIMO with heterogeneous networks reduces users' mobility, and hence the need for frequently updating CSI at the transmitter

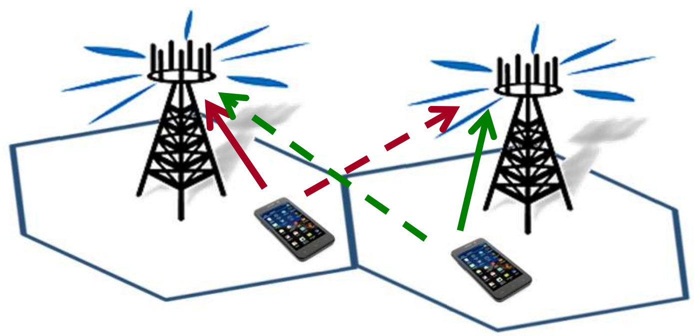
Random matrix theory (1/2)

An effective way to study the theoretical performance of massive MIMO systems is provided by random matrix theory (RMT):

- RMT allows us to reduce the system complexity and to determine the most important system parameters
- RMT is based on asymptotic assumptions. However, since massive MIMO configurations include a very large number of antennas, such assumptions are not approximations anymore, but rather close to reality

Random matrix theory (2/2)

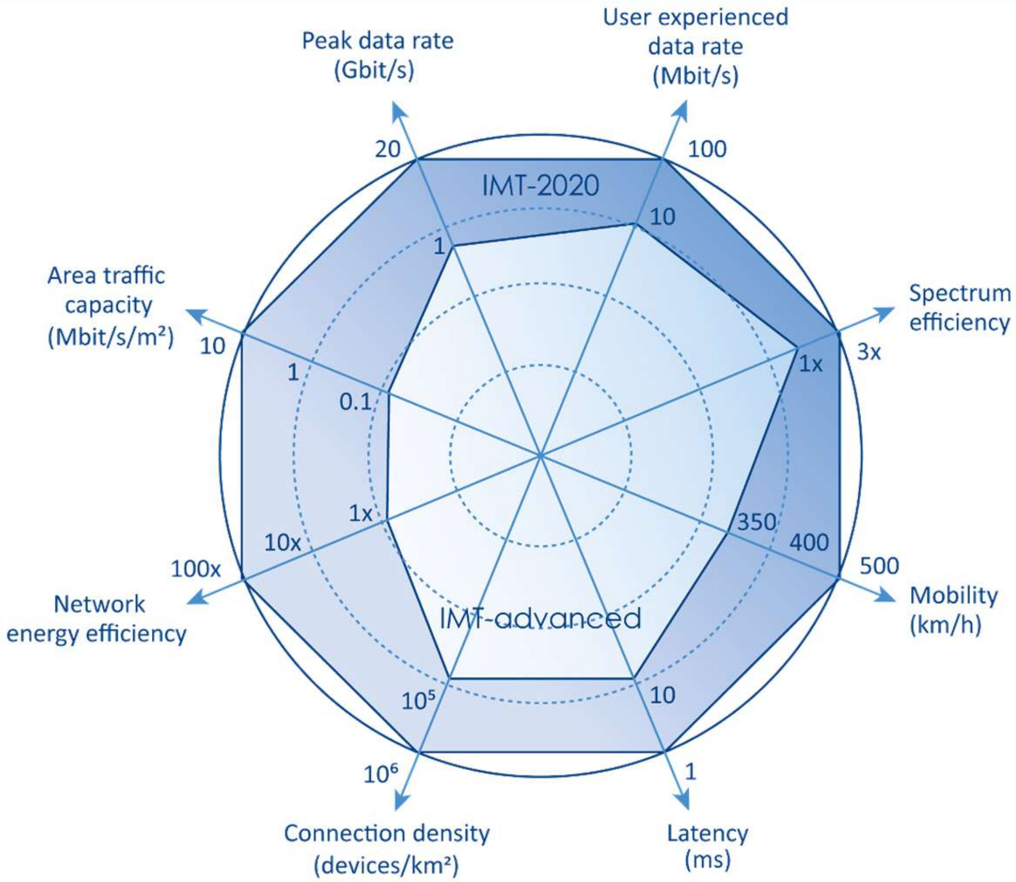
An example of successful application of RMT to massive MIMO theory is the problem of pilot contamination:



Assuming N_t and K to be very large allows us to compute the deterministic equivalents of the SINR and the achievable rates

The 5G NR standard

5G NR key capabilities



5G standard

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

5G NR has been standardized by the 3GPP in Q2 2018, as 3GPP Release 15 (current stable version: Release 19; current working version: Release 20)

5G enhancements wrt 4G

- Higher-frequency bandwidths: in 5G NR the licensed spectrum is from 1 GHz to 52.6 GHz, thus resorting to mm-wave technologies
- Ultra-lean design: in 5G NR, always-on signals used for channel estimation are transmitted only when necessary, to improve the energy efficiency of the network
- Low-latency transmissions: 5G NR reduces transmission delays in both uplink and downlink by adjusting the signal composition
- Beam-centric design: 5G NR exploits beamforming and MIMO technologies to improve coverage areas and spatial multiplexing

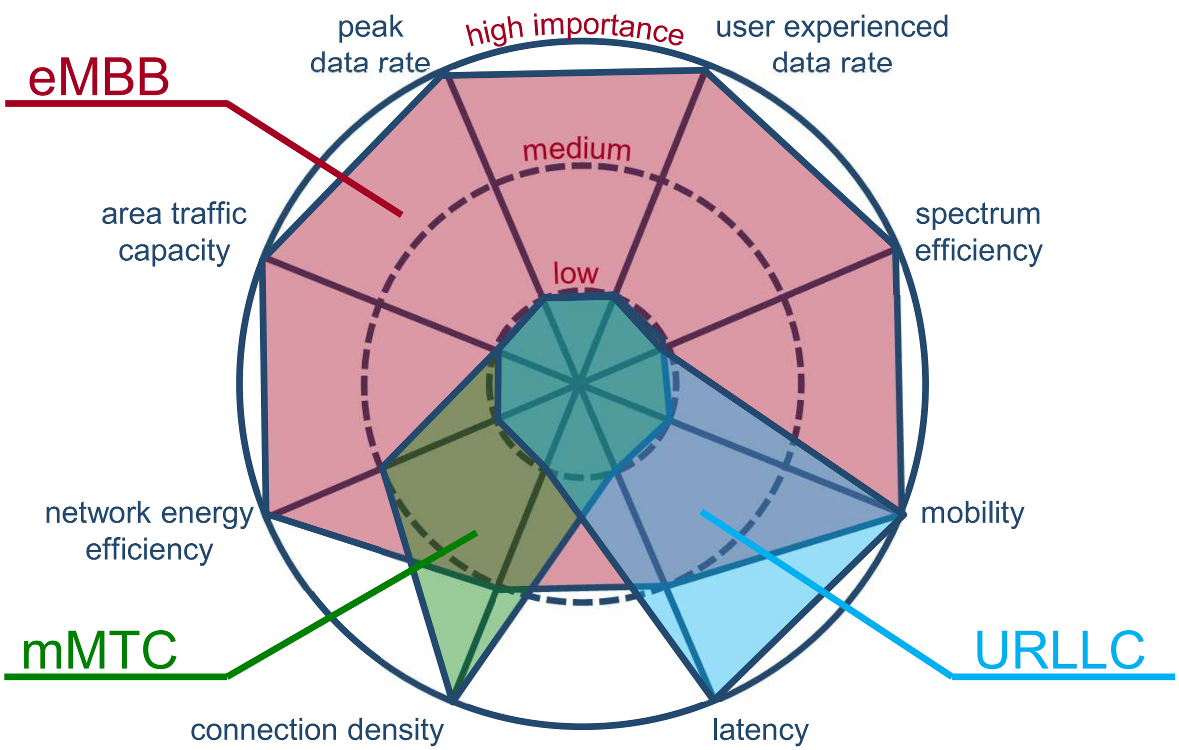
5G NR applications (1/4)

- 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

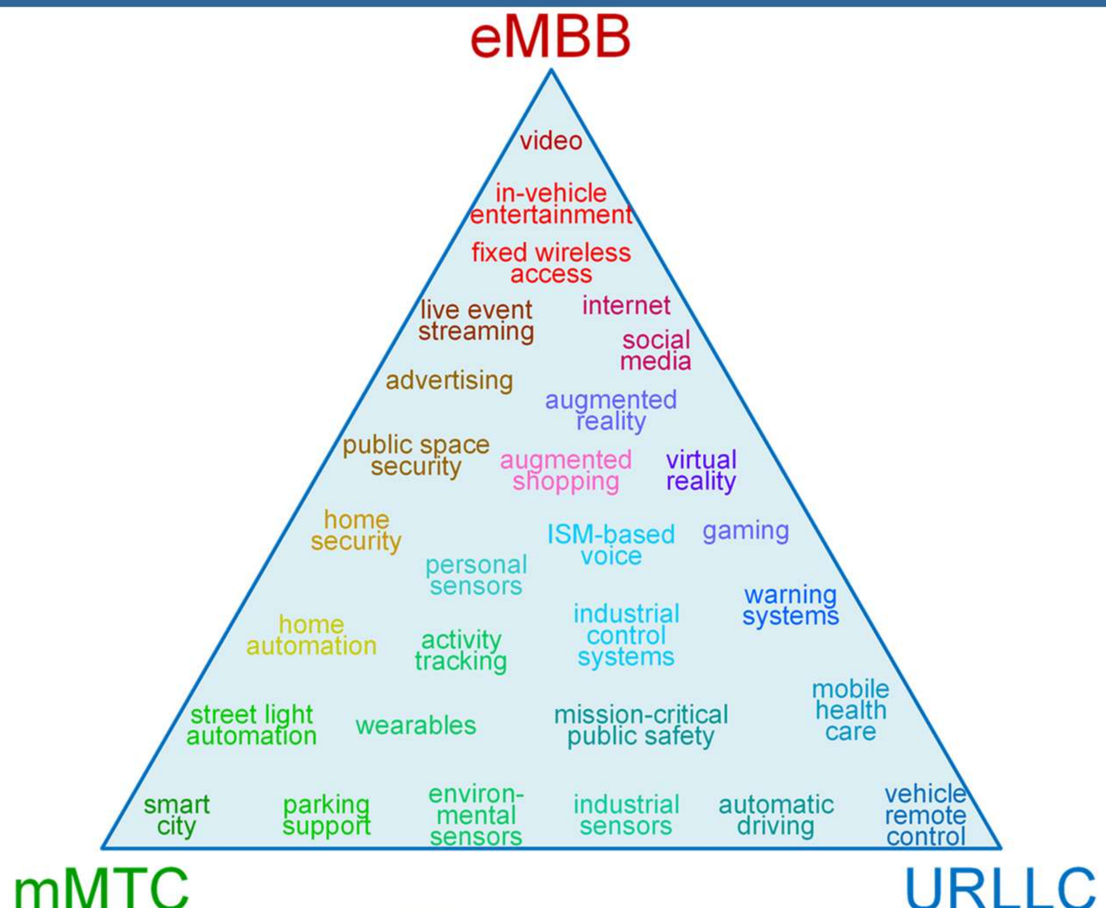
- ultra-reliable and low-latency communications (URLLC): it mostly focuses on machine connectivity, commonly referred to as internet of things (IoT), with applications on safety, wireless control of industrial equipment, remote medical surgery

- 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 (2/4)



5G NR applications (3/4)



5G NR applications (4/4)

Overview of the 5G physical layer (1/3)

5G NR adopts:

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

- Carrier frequencies: from 700 MHz to 100 GHz (from Release 17 on)
- Carrier spacing: from 15 kHz to 120 kHz
- Maximum bandwidths: from 50 MHz to 400 MHz
- Constellations: QPSK, 16-QAM, 64-QAM, 256-QAM, π/2-BPSK

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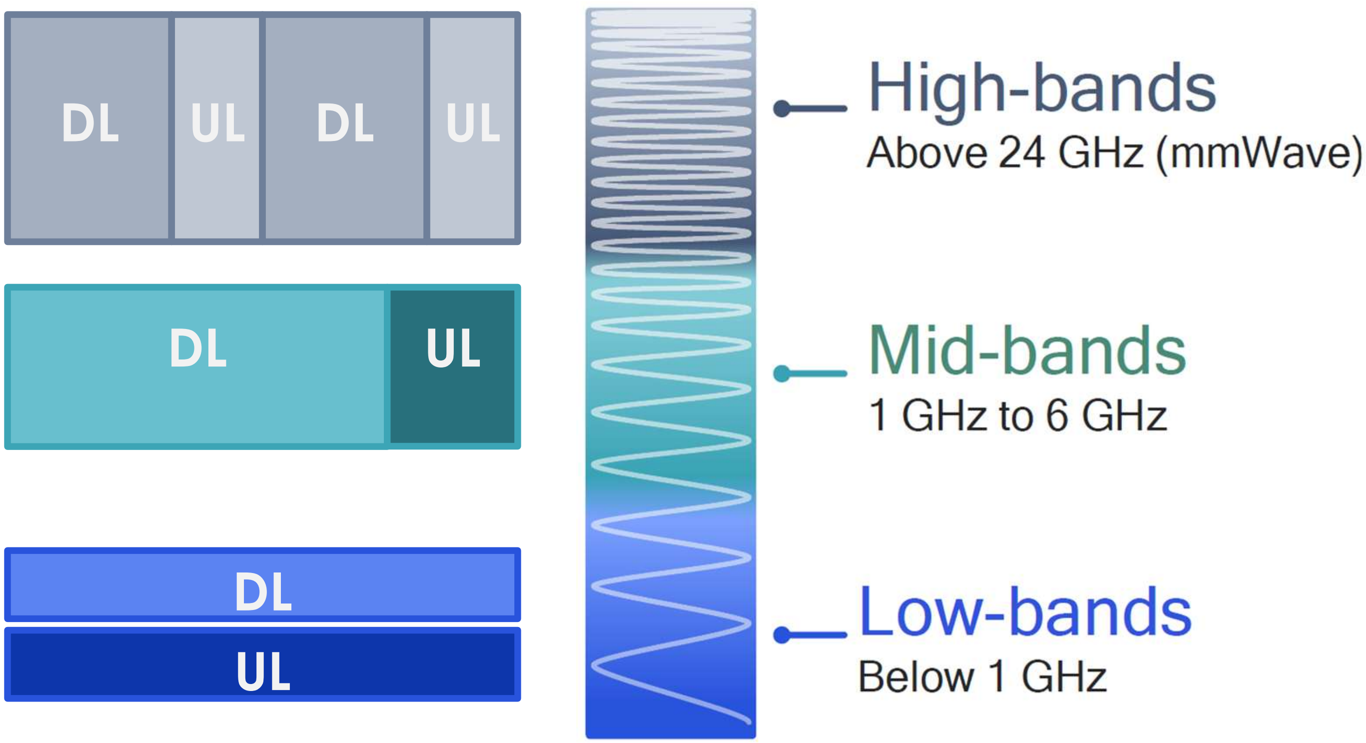
Overview of the 5G physical layer (2/3)

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

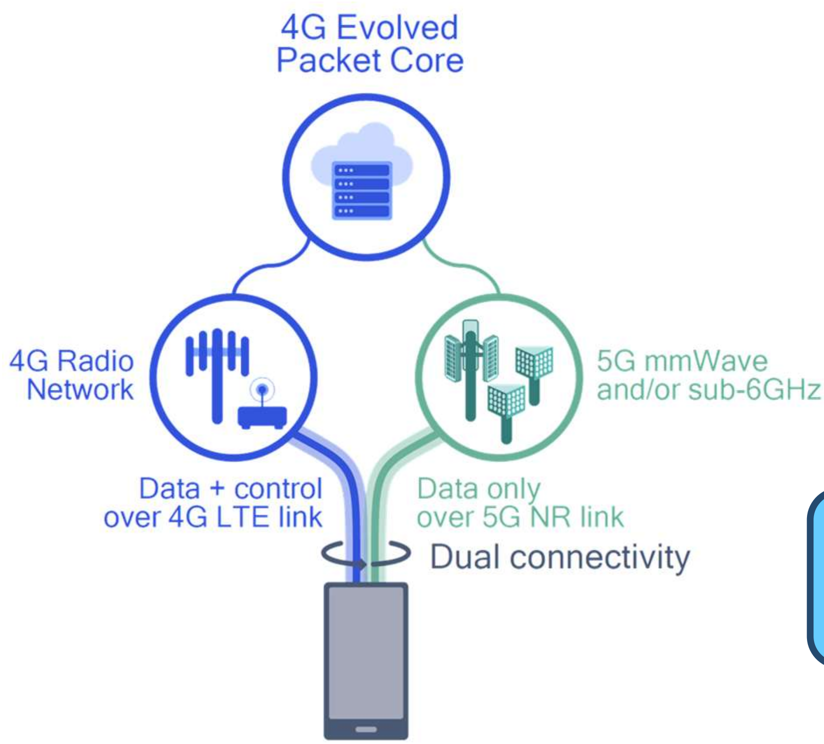
Overview of the 5G physical layer (3/3)

Modular slot structure for flexible capacity allocation (with backward compatibility with LTE):



5G architecture options (1/2)

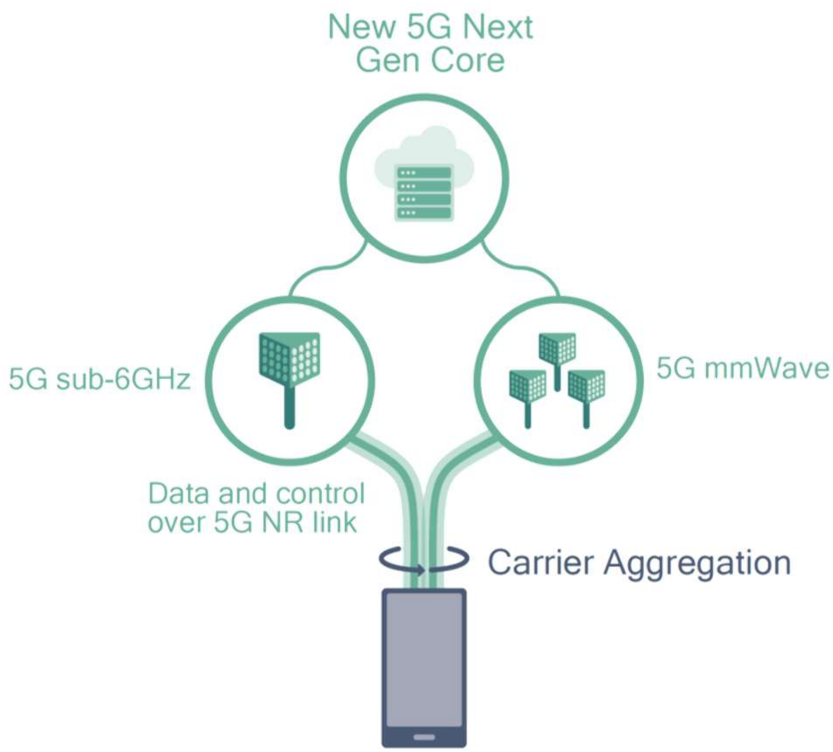
To speed up the deployment of 5G services and to leverage existing 4G investments, NR can be deployed in non-standalone (NSA) mode



- 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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