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

Basics of wireless communication systems

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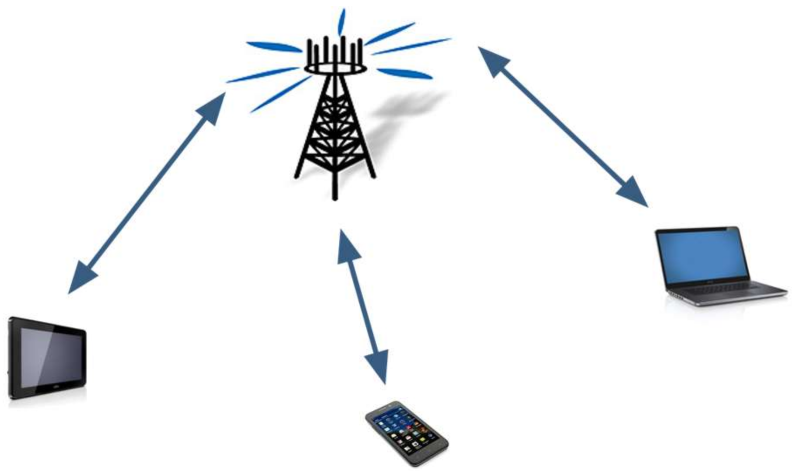
Basic concepts

Wireless communication systems

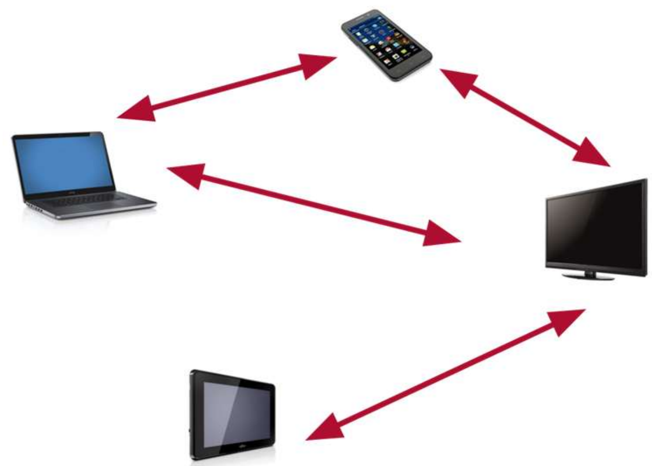
infrastructure networks



- higher rates
- lower latencies

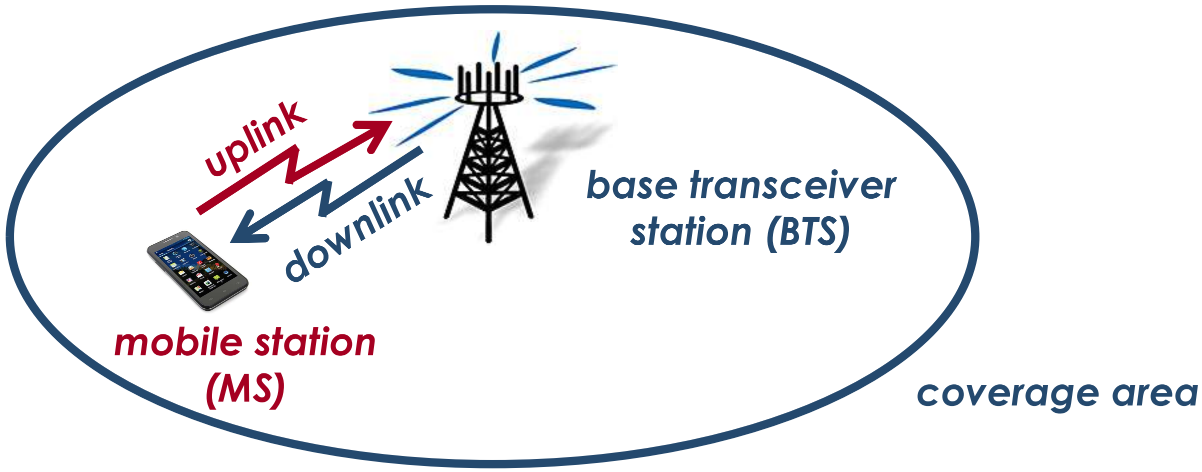
Examples:
- *cellular networks*
- *WLANs*
- *paging systems*

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:

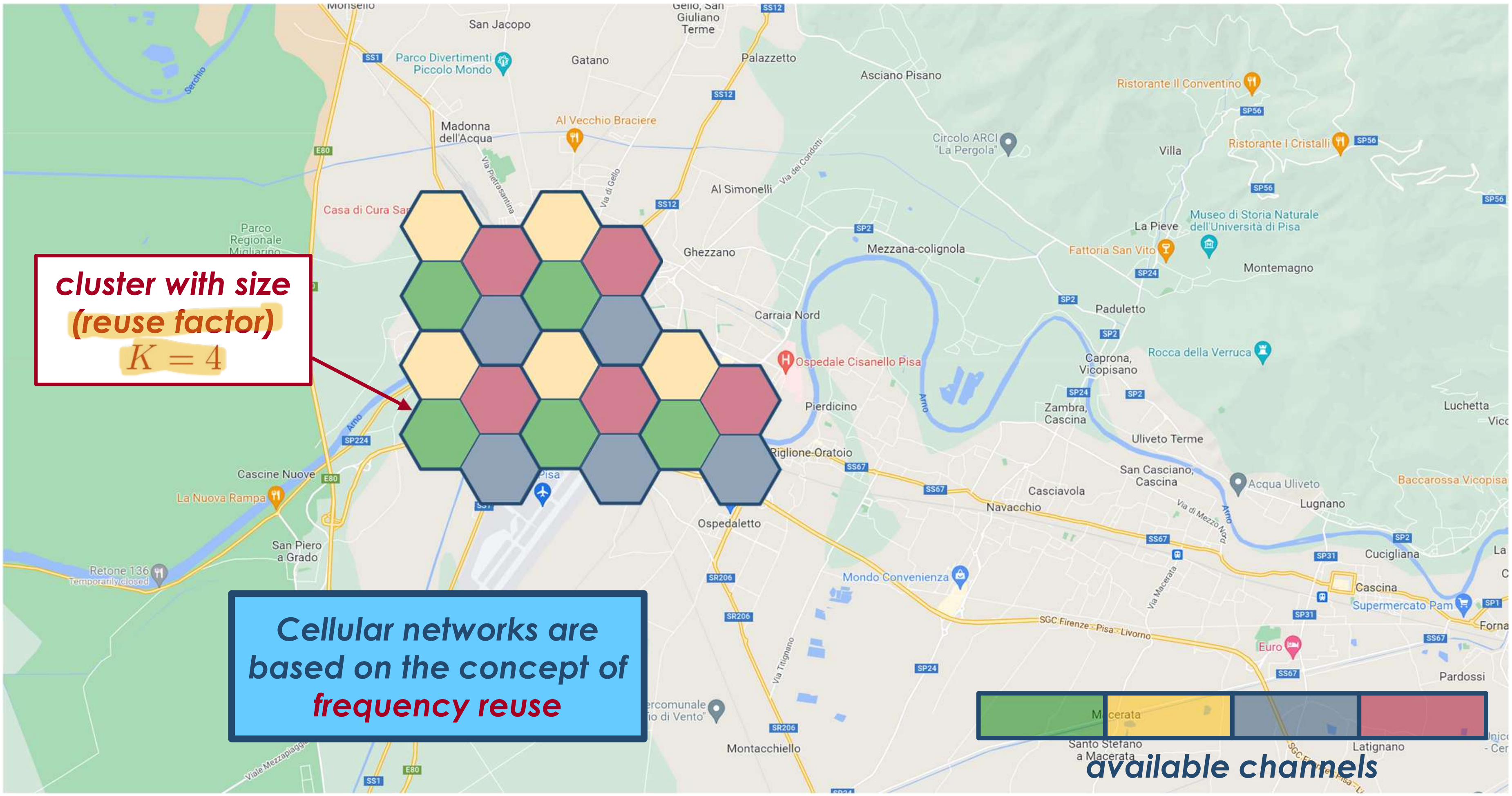
- limited frequency range (due to licensed spectrum)
- limited coverage area (due to power masks)

Features:

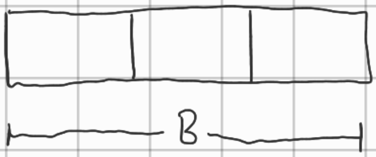
- low density of users (per unit of area)
- discontinued service when exiting the coverage area

The concept of a cellular network (1/4)

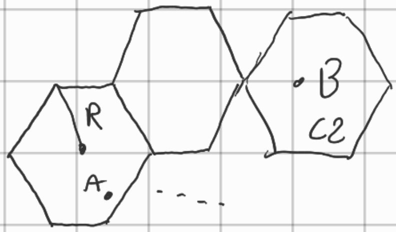
End of 1950s/beginning of 1960s: introducing cells to provide seamless coverage



Approach: divide spectrum into subsets.



Then we define different BTSs and for each cell we assign to them different subsets:



By doing this yes you might increase coverage but you have less band to work with. Density of users doesn't improve.

But! Remember: $P_R(d) = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^m$

So this means that if you are in A, you will receive a $P_R(r) \geq \bar{P}_R$ which is the minimum required power for communication.

If we are in B, the $P_R(r) \leq \bar{P}_R$. So the received power generated from that base station is quite low. Idea is that if you put a base station near B using the same subset of frequency we have more useful signal over interference, which is key. In C2, the interference received from C1 is quite low.

↓ for that cell

γ (signal to interference + noise ratio) $= \frac{S}{N+I}$

with non orthogonal users we can have interference that wasn't present with modulation.

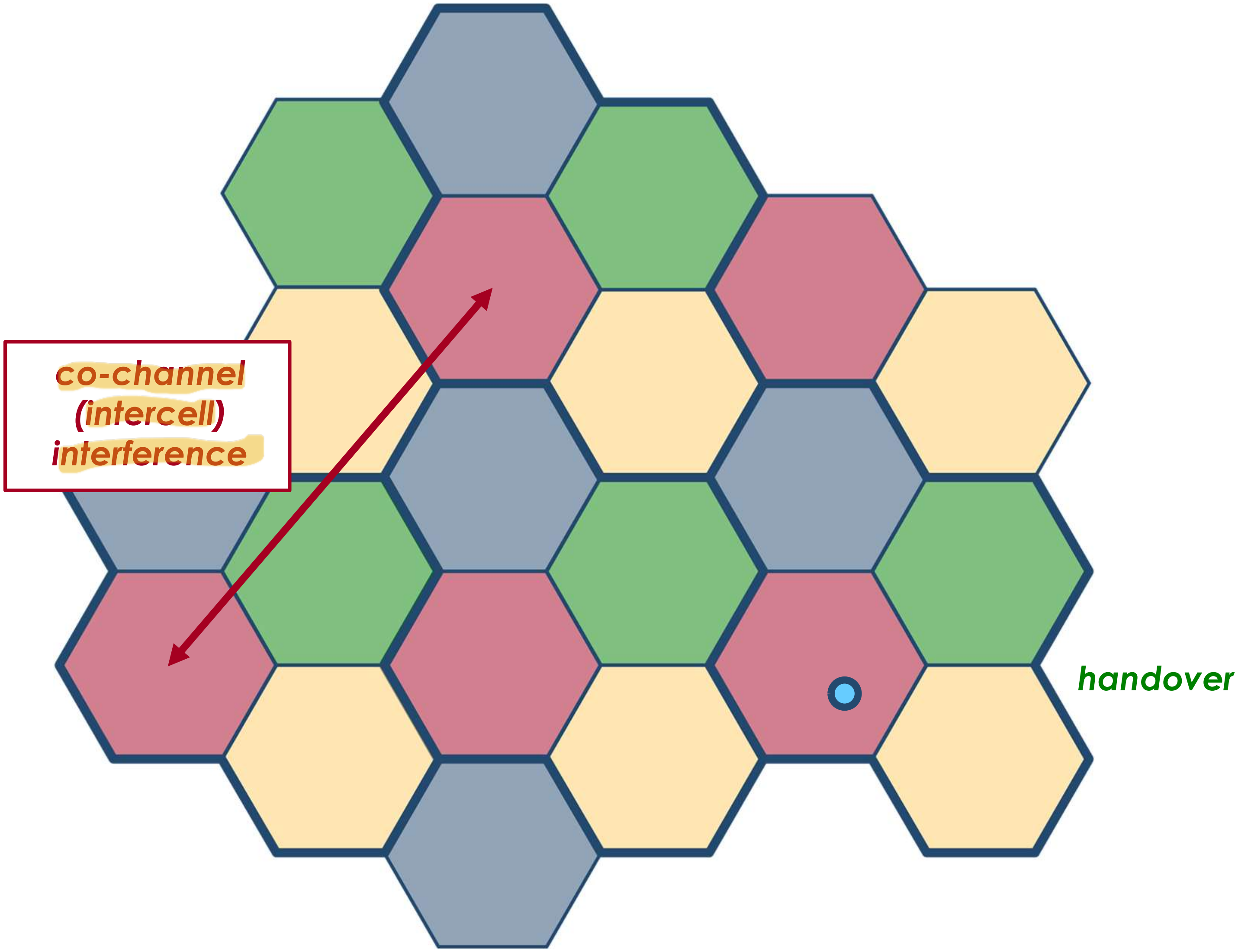
So this helps for coverage and usage of resources because you are always using the same bandwidth. This is a cellular network. Hexagons because they remind circles but it's used for better design.

Here $K=3$, and 1 block of K cells that use different bandwidths and are adjacent is called a cluster. Creating a network is copy pasting clusters.
K = cluster size or reuse factor.

So okay, I gave full coverage to a user. But if the user moves in a different cell they need to switch the frequency. This process is called HANDOVER.
In this case it is up to the control plane to switch frequencies. This needs to be done quickly to avoid losing connectivity. This will be communicated by the network, but as long as there's a spot and not all the frequencies have already been used.

Too much handover is not good because we need to keep track of where the user is.
This is how you can do frequency reuse btw: at some point received power is so small that you can reuse it.

The concept of a cellular network (2/4)



The concept of a cellular network* (3/4)

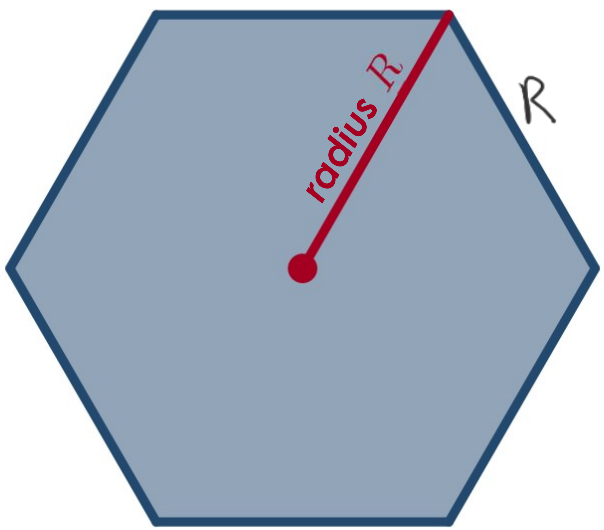
The **handover** (or **handoff**) procedure can be managed:

- 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

assistance of the mobile user

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

Goal

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

Degrees of freedom:

- Reuse factor K
- Cell radius R

System KPIs:

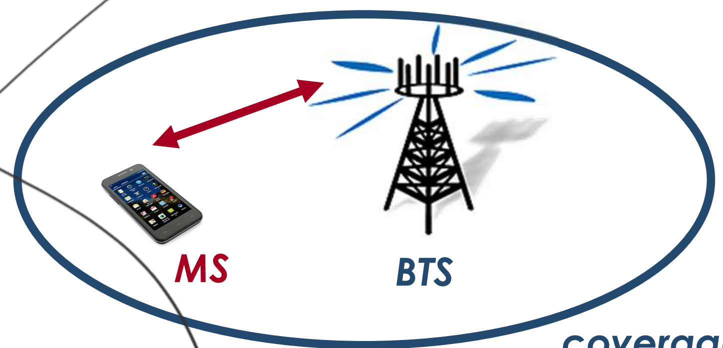
- Transmit power P_T
- Handoff rate μ_H
- User density u
- Minimum SIR $\underline{\xi}$

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:

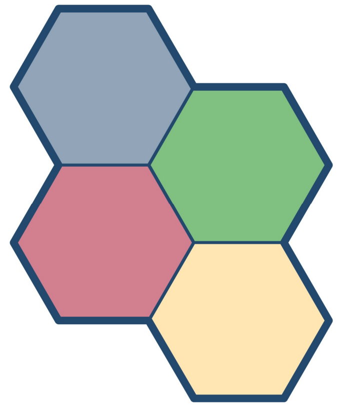
$$u = \frac{N}{A_{\text{cell}}}$$

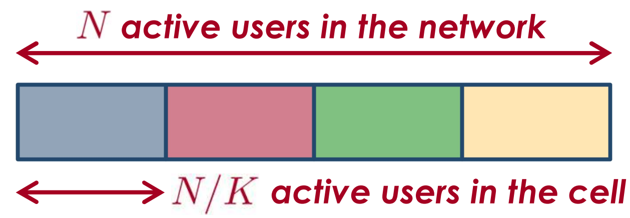
where N is the maximum number of simultaneously active users in the network, and A_{cell}, is the coverage area of the system

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)

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

$N_{\text{cell}} = \frac{N}{K}$

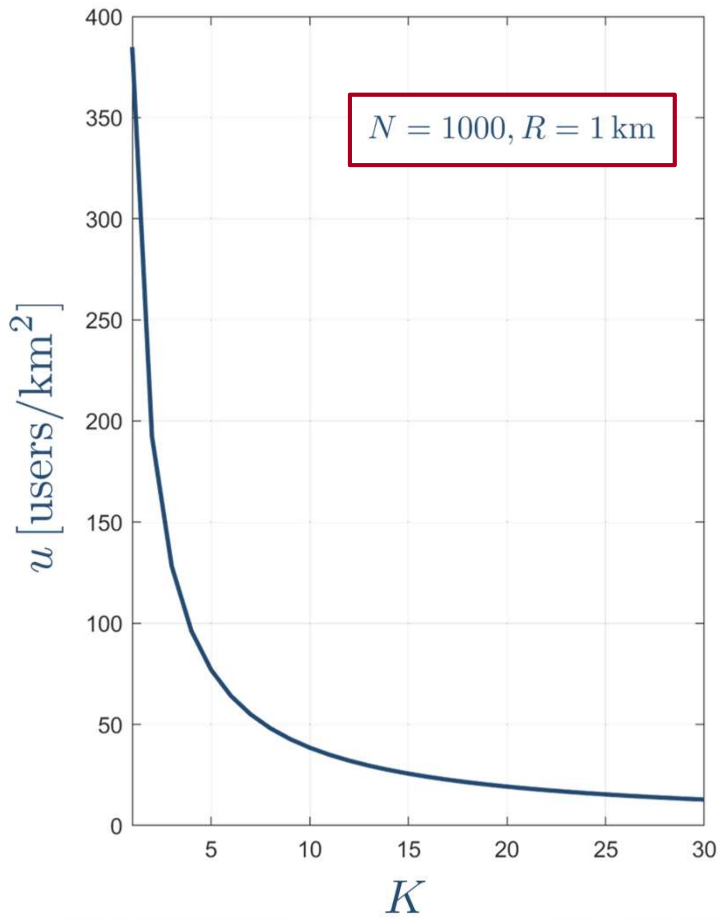
$$u = \frac{N_{\text{cell}}}{A_{\text{cell}}}$$

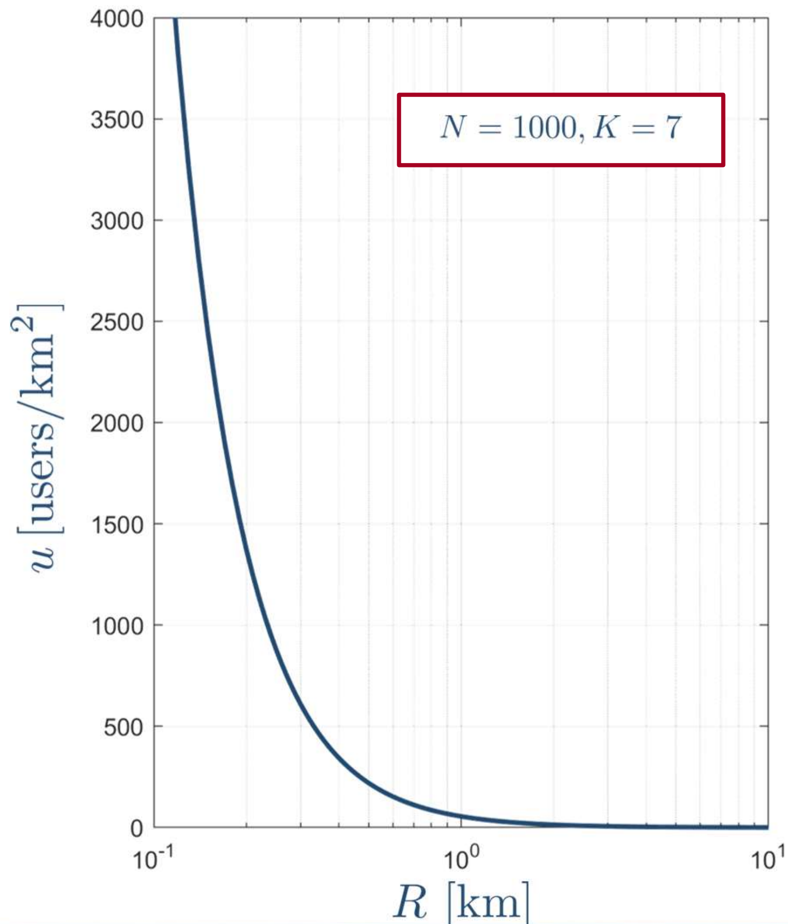
number of users you can put in a cell / Area of cell

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

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:

What happens if a increase?

Degrees of freedom:

- Reuse factor K
- Cell radius R

System KPIs:

MINIMISE
- Transmit power P_T
- Handoff rate μ_H → frequency of switching frequencies

MAXIMISE
- User density u → how many users per sq. Km
- Minimum SIR $\underline{\xi}$ → Signal to interference ratio

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

conflicts

Let's simplify degrees of freedom to be just reuse factor K and cell radius R.
The performances will be evaluated based on those 4 key performance indicators.

* There's more probability that network becomes saturated so you switch frequencies even when not changing cells.

NOTE!

Better to maximise the ξ. $\underline{\xi} = \min \xi$
Usually you get the minimum in worst conditions.
So if we maximise the minimum you are ensuring certain conditions.

Assumption: if I maximise minimum ξ performance is better.
• 2. The power of the noise is generally much smaller than I, so $\xi = \frac{S}{N+I} \simeq \frac{S}{I}$

NOTE: S = Received power for a user within the cell, so $P_R(d)$, with $d \le R$ (focusing on downlink).
$P_R(d) = P_T G_T G_R \left(\frac{1}{4\pi d}\right)^n$. The interferences are from other base stations.
So with $K=3$, you have 6 close interferences and others negligeable.

So; $\xi = \frac{S}{I} = \frac{P_R(d)}{\sum_i P_R(d_i)}$

this means considering the average power

Assumption: neglecting distortion introduced by the channel. To get the minimum value we have to consider a user on the border of the cell.

$$\underline{\xi} = \frac{P_R(R)}{\sum_i P_R(d_i)}$$

To make this easier I make this assumption: $d_i \approx D$ for the first round of interferences. D is the REUSE DISTANCE

$$\xi = \frac{P_R(R)}{\sum_i P_R(d_i)} \simeq \frac{P_R(R)}{6\,P_R(D)}$$

1st approx: only the closest 6 cells are considered for interference

Another assumption: All the Basestations use same antennas (isotropic antenna, this for receiver too. Antenna that can receive from all the directions; drawback you can't amplify) And P_T is the same everywhere too. So:

$$\xi = \frac{\cancel{P_T}\,\cancel{G_T}\,\cancel{G_R}\left(\cancel{\frac{\lambda}{4\pi}}\right)^m\left(\frac{1}{R}\right)^m}{6\,\cancel{P_T}\,\cancel{G_T}\,\cancel{G_R}\left(\cancel{\frac{\lambda}{4\pi}}\right)^m\left(\frac{1}{D}\right)^m} = \frac{1}{6}\cdot\left(\frac{D}{R}\right)^m$$

NOTE that cluster size K has to satisfy: $K = i^2 + j^2 + i \cdot j$, $i, j \in \mathbb{N}^+$ (also 0)

How to find cells of equal colour? Given i and j, you move across i cells through one of the sides, rotate of 120 degrees and move across j cells.

JMP 23

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)

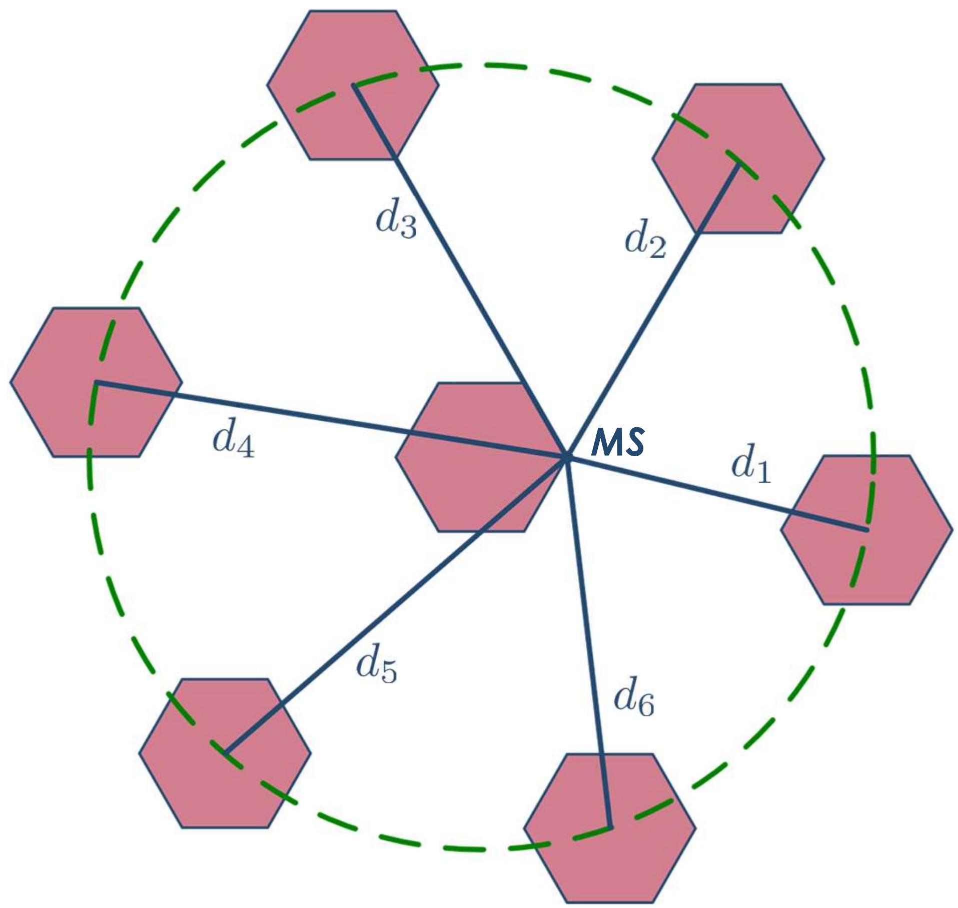
In general, the **received power** depends on the transmitter-receiver distance d according to

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

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

Downlink SIR (1/5)

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



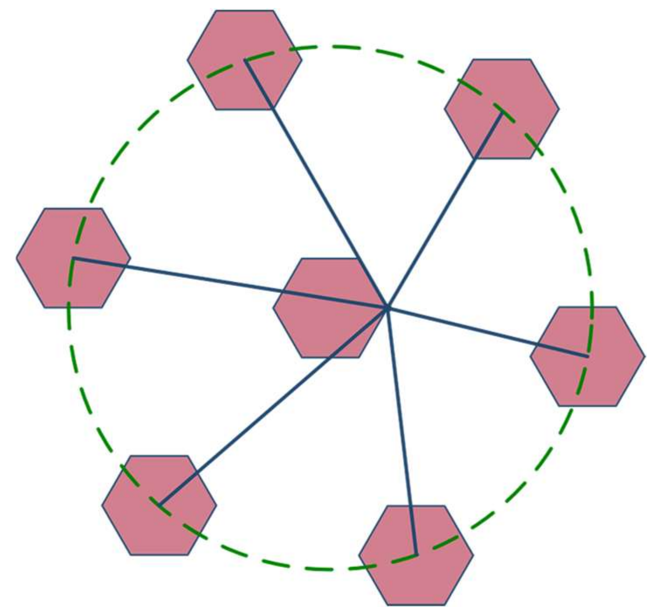
$d_k \approxeq D \quad \forall k$

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

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

$$\boxed{\xi = \frac{C}{\sum_{k=1}^{6} I_k} = \frac{\chi / R^n}{6\chi / D^n}}$$

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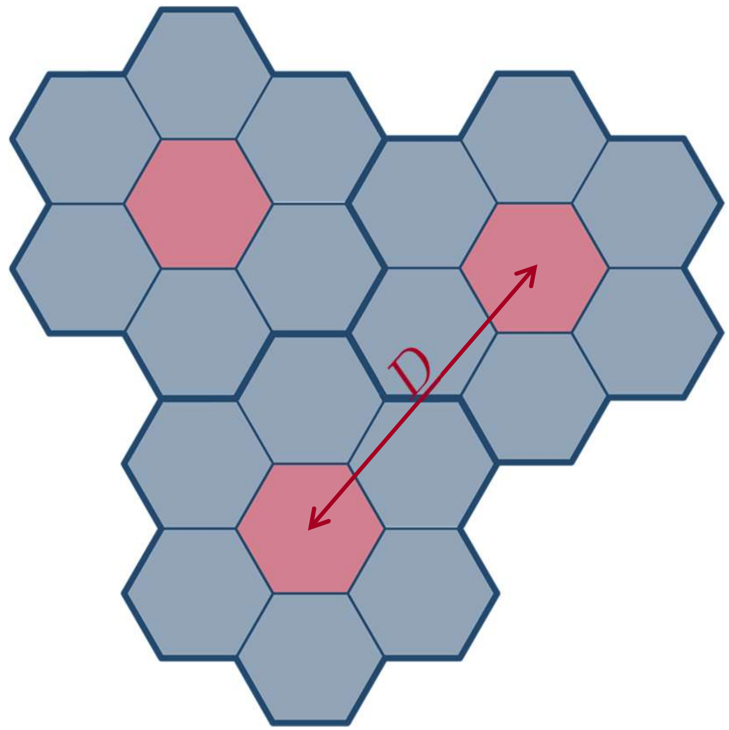
Reuse distance (1/4)

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

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

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

2G

1G

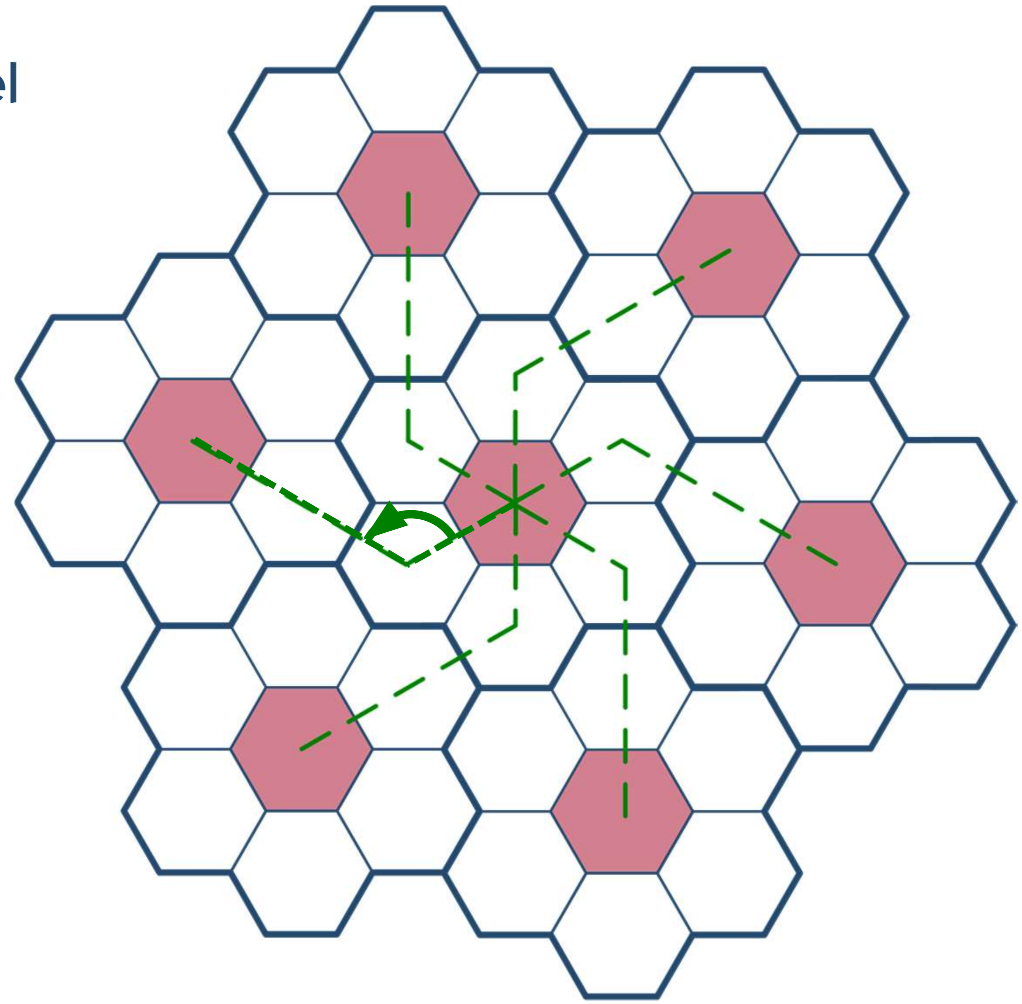
Reuse distance (3/4)

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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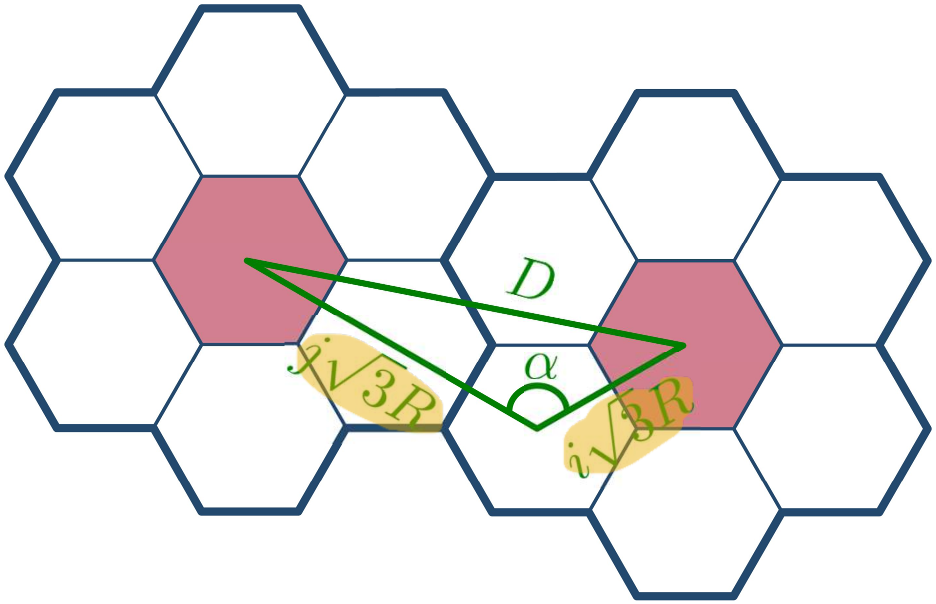
Reuse distance (4/4)



$c = \sqrt{a^2+b^2-2ab\cos\alpha}$

Using Carnot's theorem,

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

$$= \sqrt{3(i^2+j^2+ij)}R = \sqrt{3K}R$$

$\cos(120) = -\frac{1}{2}$

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So, $\underline{\xi} = \dfrac{(D/R)^m}{6} = \dfrac{1}{6}\left(\sqrt{3K}\right)^m$ R goes away but it makes sense. It's just a scaling factor.

So if I increase R, $\underline{\xi}$ doesn't change. If I increase K, $\underline{\xi}$ increases. Good!

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 $D = \sqrt{3K}R$

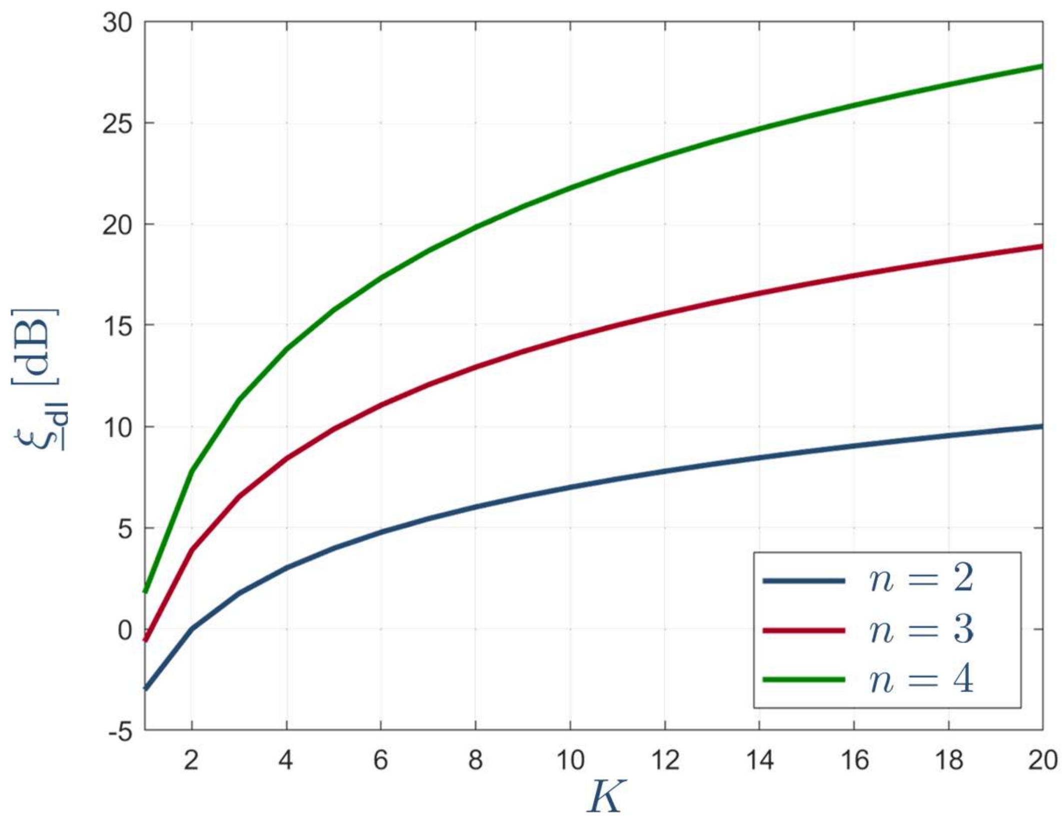
$$\xi \geq \xi_{\text{dl}} \triangleq \frac{(3K)^{n/2}}{6}$$

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

Downlink SIR (5/5)

improvement is bigger as N becomes larger.

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



Summary of the main tradeoffs

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

No optimal solutions! There are tradeoffs

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	$\downarrow$ (✗)	$\downarrow$ (✗)
$\underline{\xi}$	$\leftrightarrow$	$\uparrow$ (✓)

LEZ. 14 END

$$SINR = \frac{S}{I+N} \approx \frac{S}{I}$$

"Well, now I may have a little bit of a chance"

Depending on the tech, there's a minimum SIR to make it work. In 1G: $\xi \approx 10\,dB$. So we need to find the minimum value K to have $SIR = 10\,dB$.

For 2G, with digital techniques: $\xi \simeq 5\,dB$ (system is more robust). Channel coding reduces SIR.

3G: $\xi \approx -5\,dB$ (CDMA to separate users was introduced).

Why reduce K? We want to maximise user density and minimise handoff rate. (If n higher, power reduces quickly so you can reuse).

NOTE: in practice, you select R based on user density: if there are a lot of people, you have a small R, otherwise a big R.

Improving the downlink SIR* (1/3)

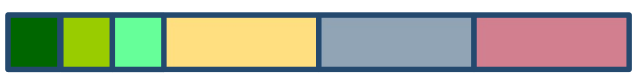
Many techniques exist to further **mitigate** the co-channel interference in the downlink

We do not use isotropic antennas, but one that divides cell in inner cells.
From 6 to 2-3 interference cells.

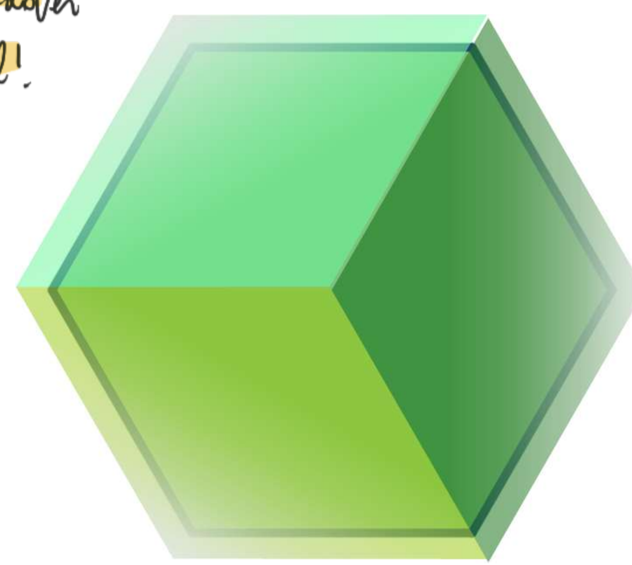
One of the simplest techniques is using **cell sectoring** at the BTS

But handover in cell!

Example: 120° antenna aperture



available channels



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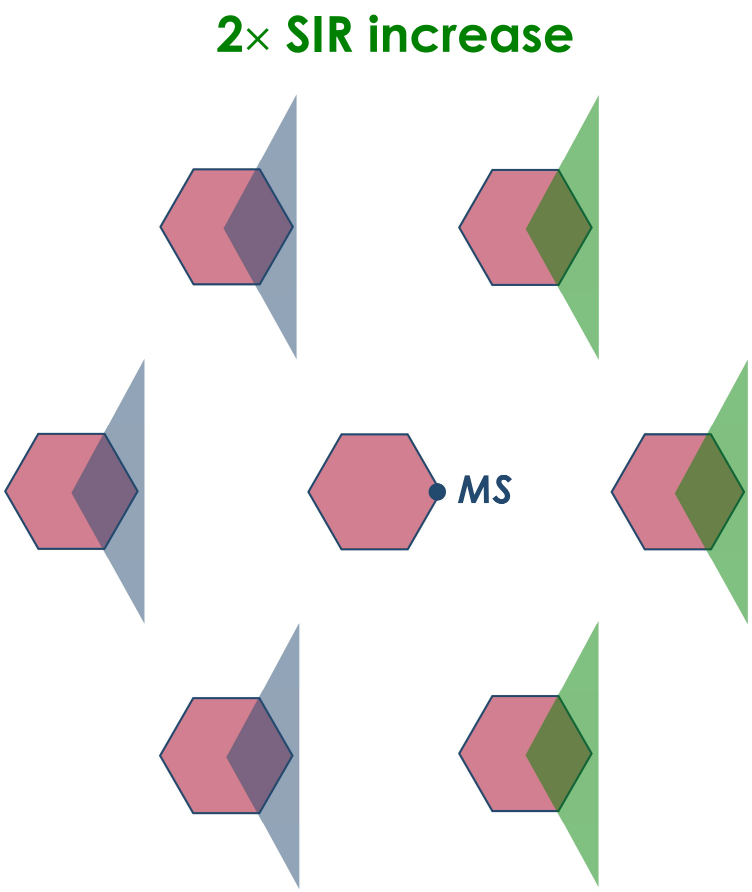
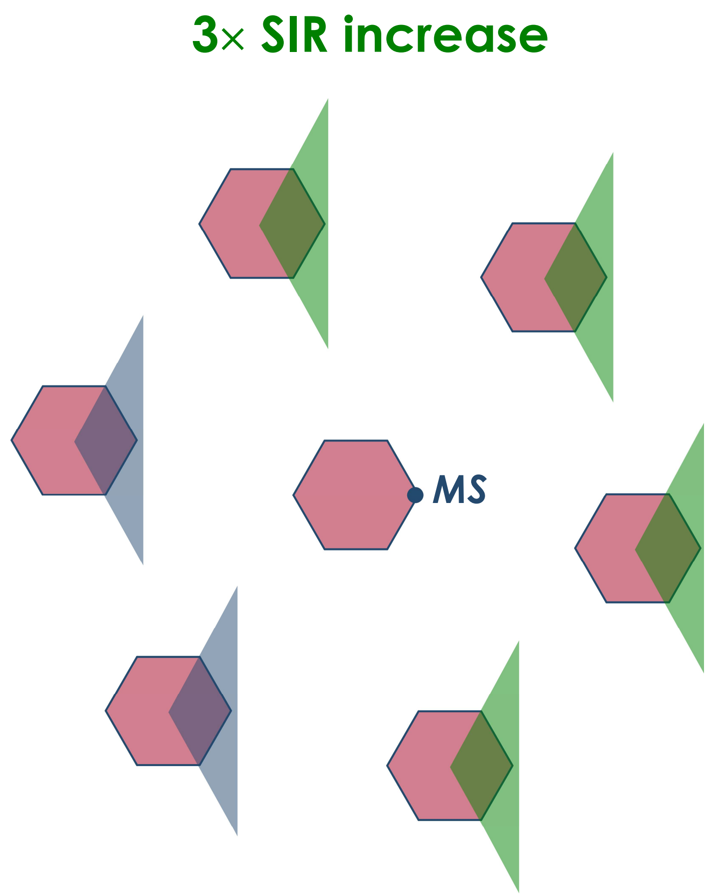
Improving the downlink SIR* (2/3)





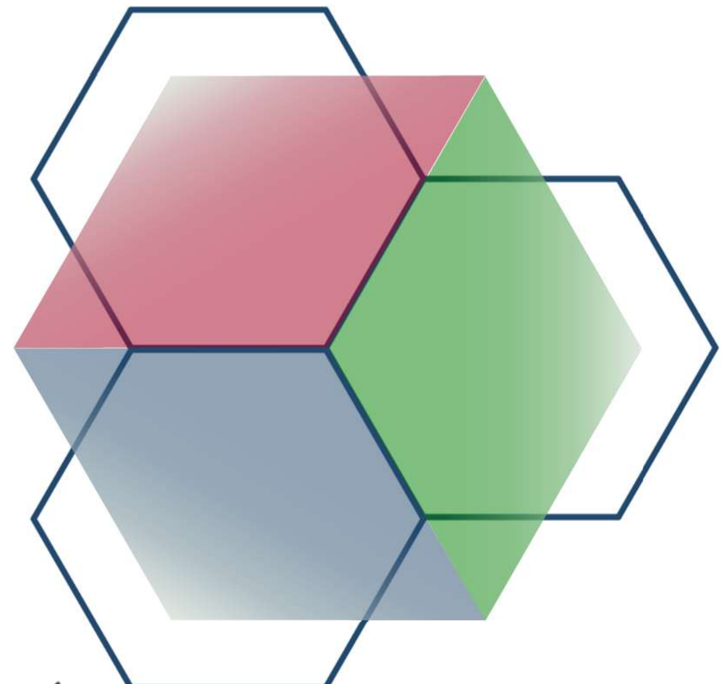
Drawbacks: increase in the number of antennas and handoffs

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

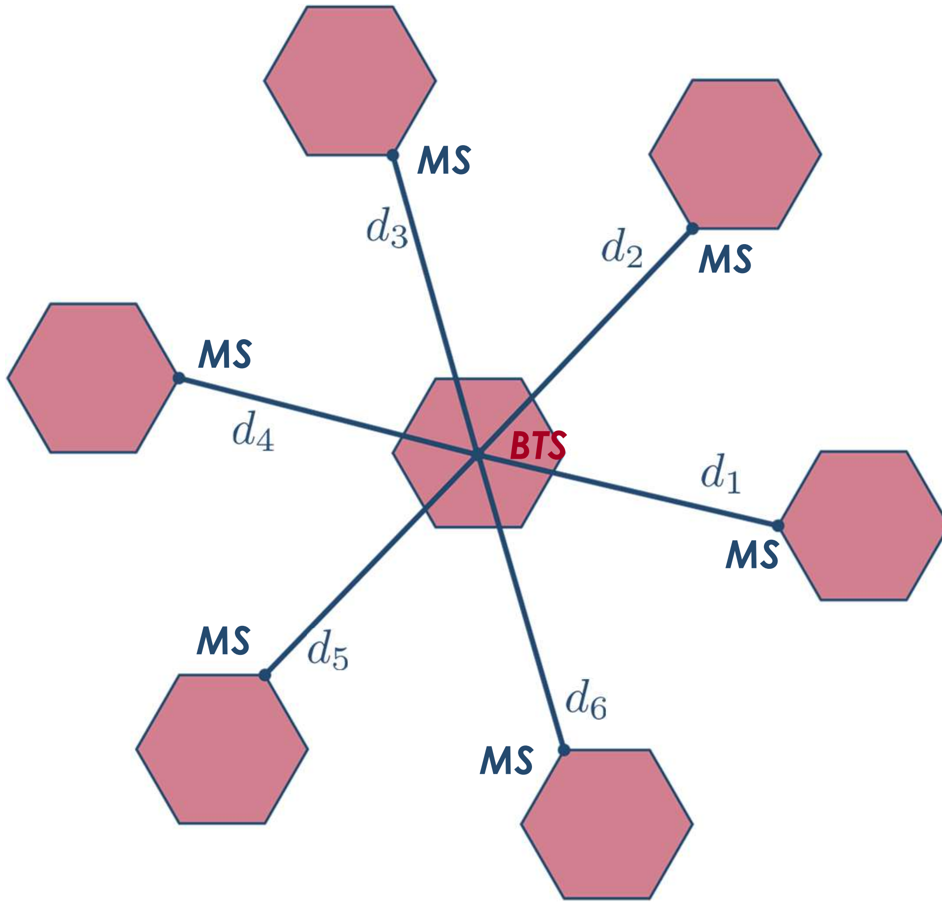


Groups of 3 in your cluster

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

Homework: 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 $K \gg 1$

Homework: Uplink SIR* (2/3)

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

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

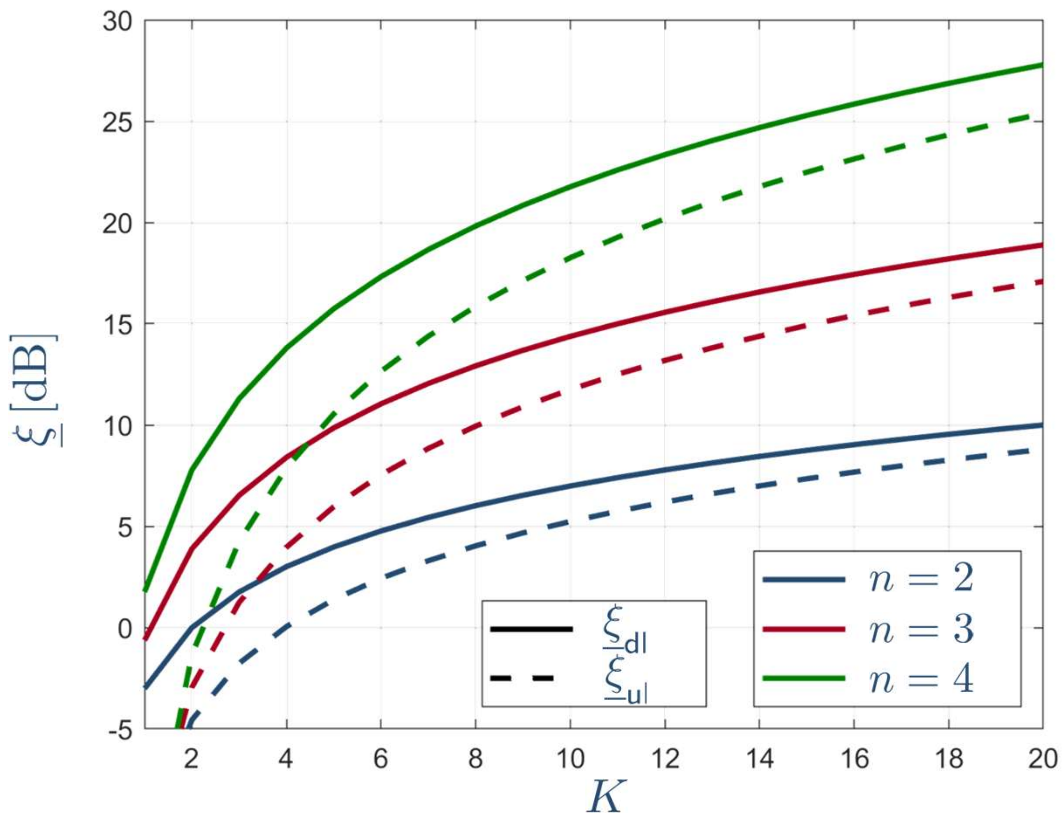
As a consequence,

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

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

Homework: Uplink SIR* (3/3)

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



Improving the uplink SIR*

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

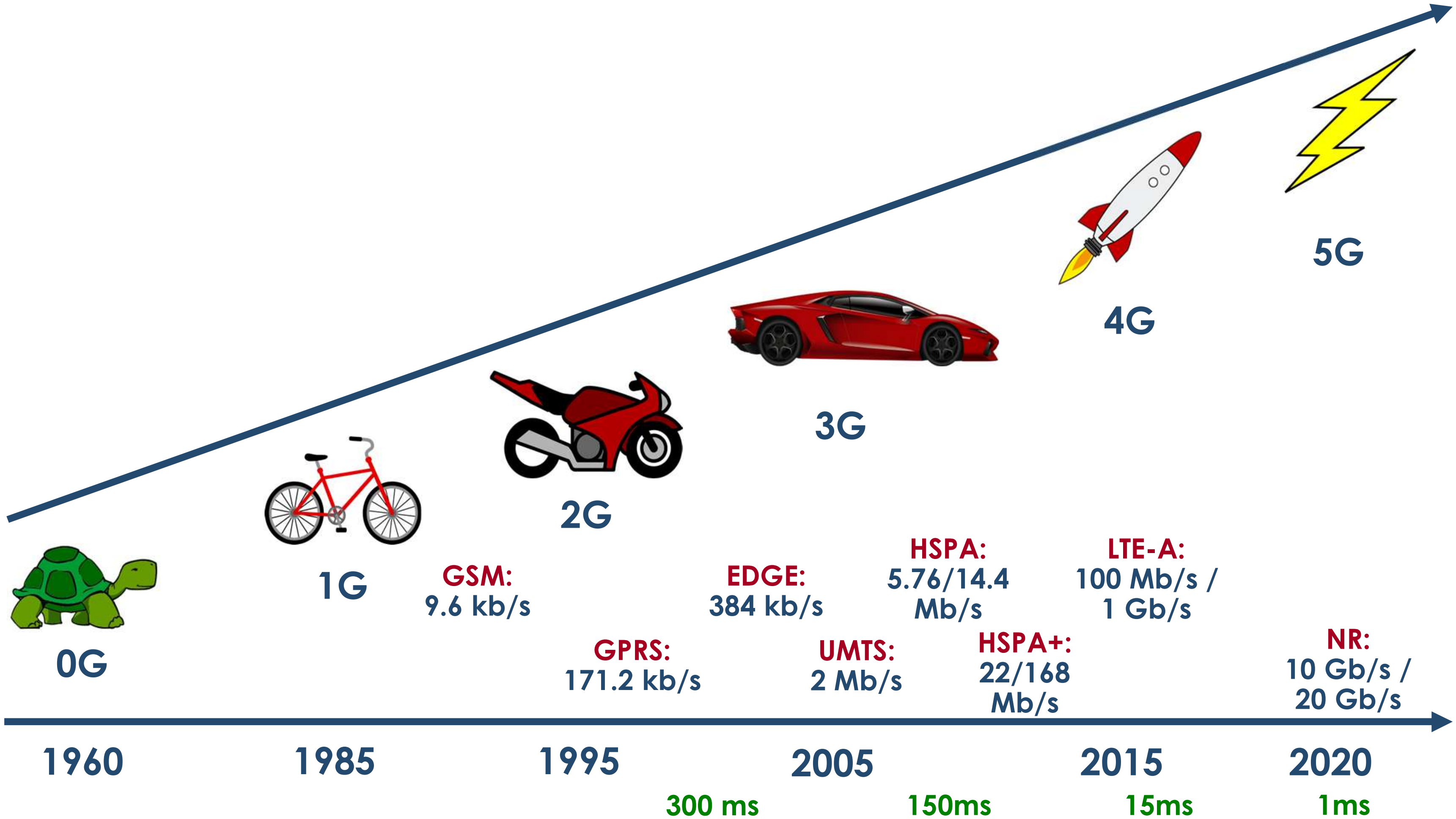
Multiple antennas: by using antennas with the proper parameters you can make narrow beams that follow the user.

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

↳ multiple antennas at the transmitter and receiver.

History of cellular communication standards

Cellular standards through time

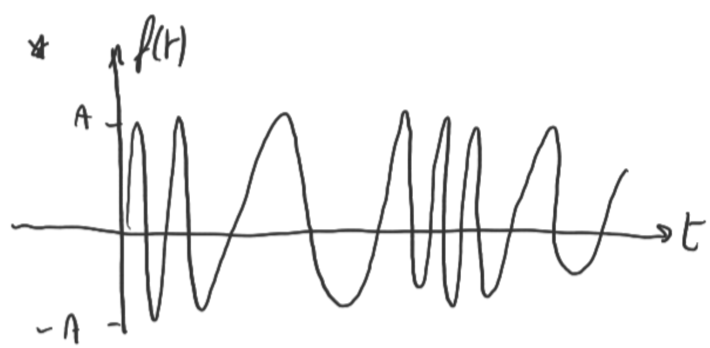


0G systems

First mobile network was not cellular. Ex: police station. They were analog system.

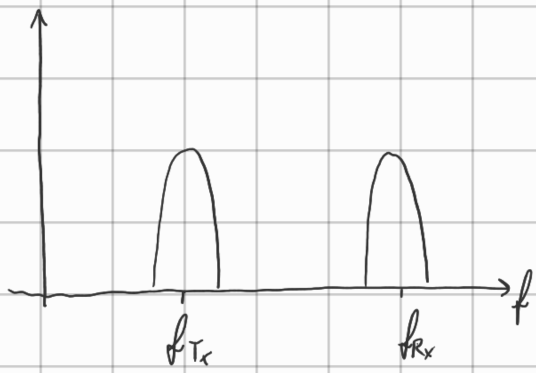
- analog single-cell systems
- frequency modulation (FM) ↗ info contained in frequency of signal *1
- FDMA as Multiple access technique (No CDMA, TDMA in analog system)
- FDD (Frequency division duplexing)
- channel spacing: [SIGNAL BANDWIDTH]
  - 1940s: 120 kHz
  - 1960s: 60 kHz
  - 1970s: 25 kHz

$\left.\right\}$ Carrier bandwidth



*1 AM would require linear amplifiers. Costly, consume a lot exc.

FDD: the way you arrange transmission and reception (that happen simultaneously).
How does it work?



You transmit and receive at different frequencies. Full duplex (doing at the same time on the same frequency) will create interception. Your transmission will generate too much interference for reception.
Other approach is TDD: same carrier frequency but you cannot do both together. Now we are getting to transition phases that are quick enough.

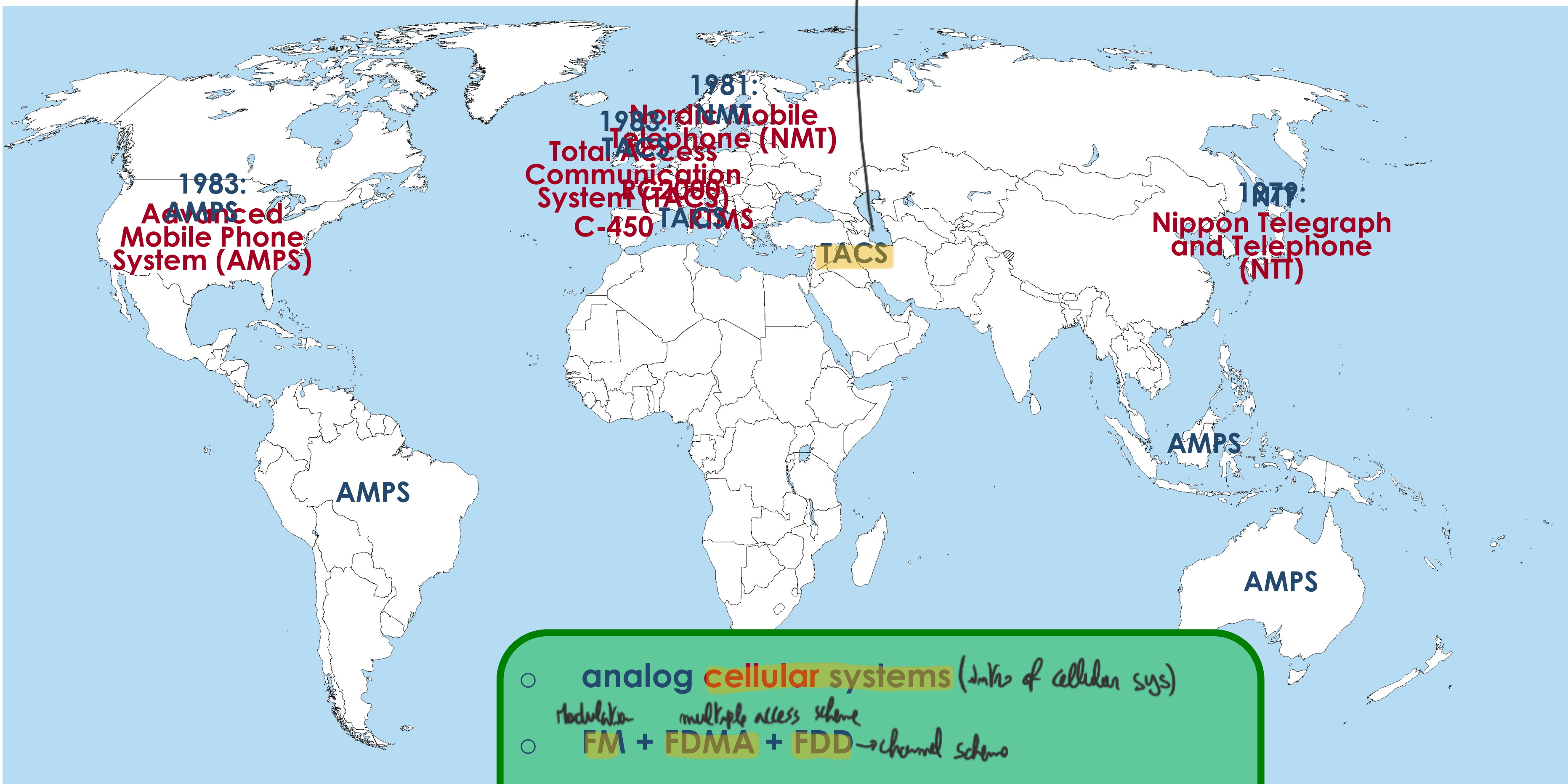
All modern systems use TDD. Because if within transmission time and reception time that fall under the coherence time, it happens this: ↳ important assumption

A ⟶ B, does channel estimation.

B ⟶ A with precoding so A doesn't need channel estimation. So you can use more resources for actual data. NOTE: the estimation is specific to the frequency we are using.

British standard, everyone in EU adopted it

1G systems



- analog cellular systems (kinds of cellular sys)
- FM + FDMA + FDD → channel scheme
  (modulation, multiple access scheme)
- carrier frequencies: 450 MHz, 900 MHz
- channel spacing: 12.5 ÷ 30 kHz squeeze voice

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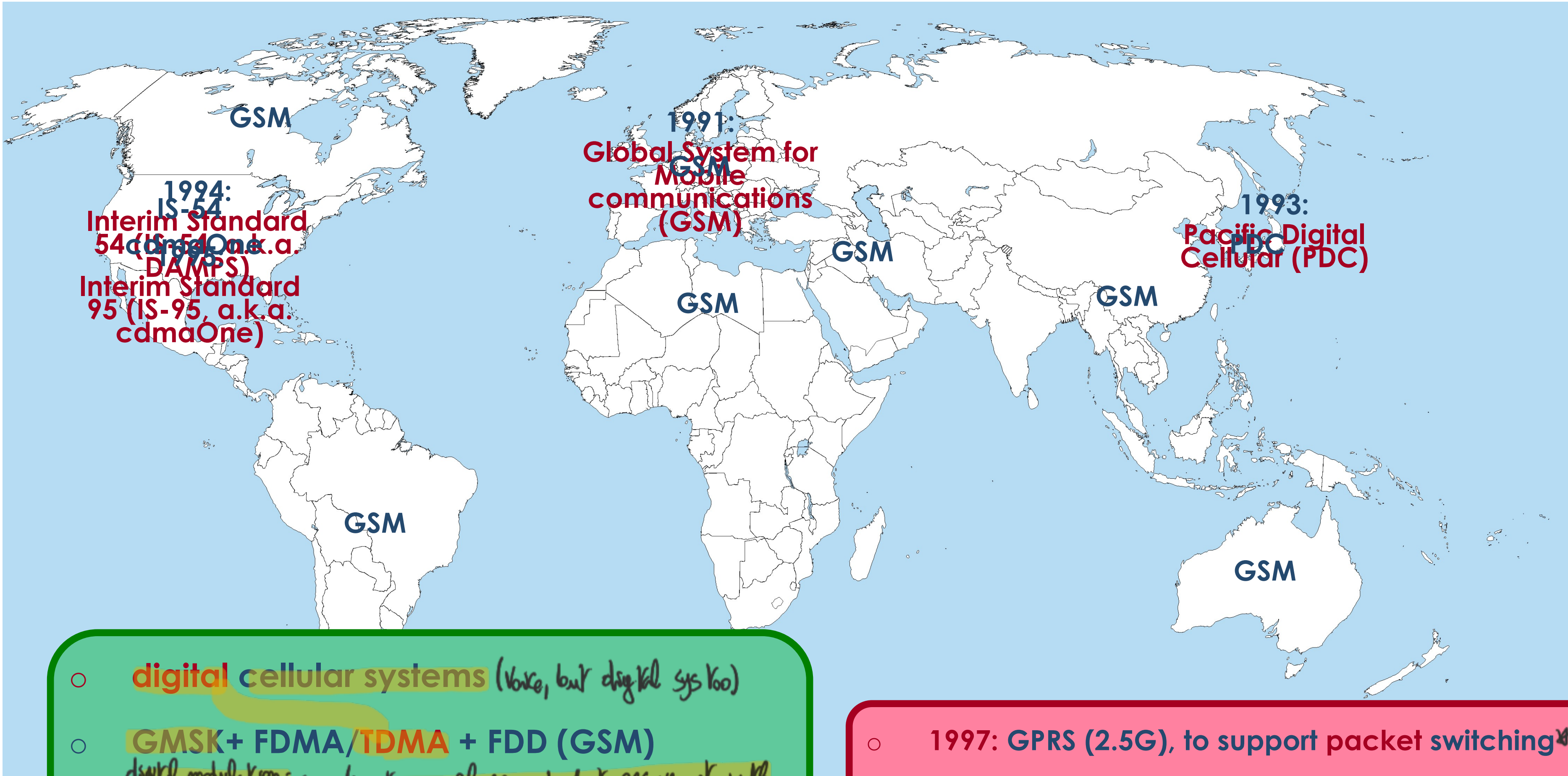
2G systems



- digital cellular systems (voice, but digital systems too)
- GMSK + FDMA/TDMA + FDD (GSM)
  digital modulation: consider it as phase mod. but receive it with an IQ modulator.
- carrier frequencies: 900 MHz, 1800 MHz
- channel spacing: 200 kHz (GSM)

You can pack more users with TDMA

- 1997: GPRS (2.5G), to support packet switching *
- 2003: EDGE (2.75G), to support higher rates ①

intermediate standard

* give more slots to a user

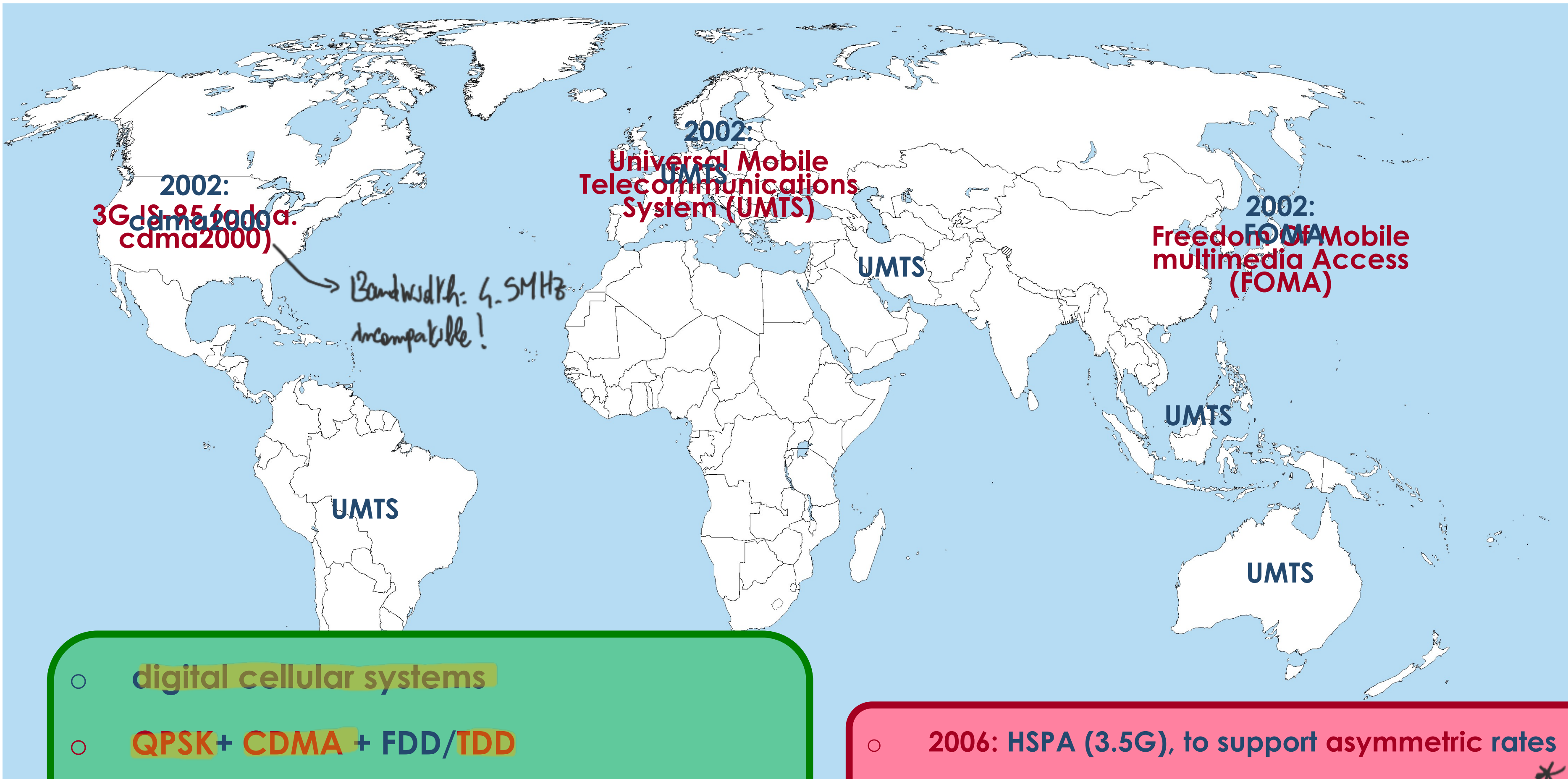
① Intro of QPSK and QAM modulation

Device could use non linear amplifiers on the Tx, IQ modulators on the receiver. This was better for cellphones.

GSM users needed cellphones that worked with EDGE. But 3G was starting to be a thing.

UMTS and FOMA fully compatible.

3G systems



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

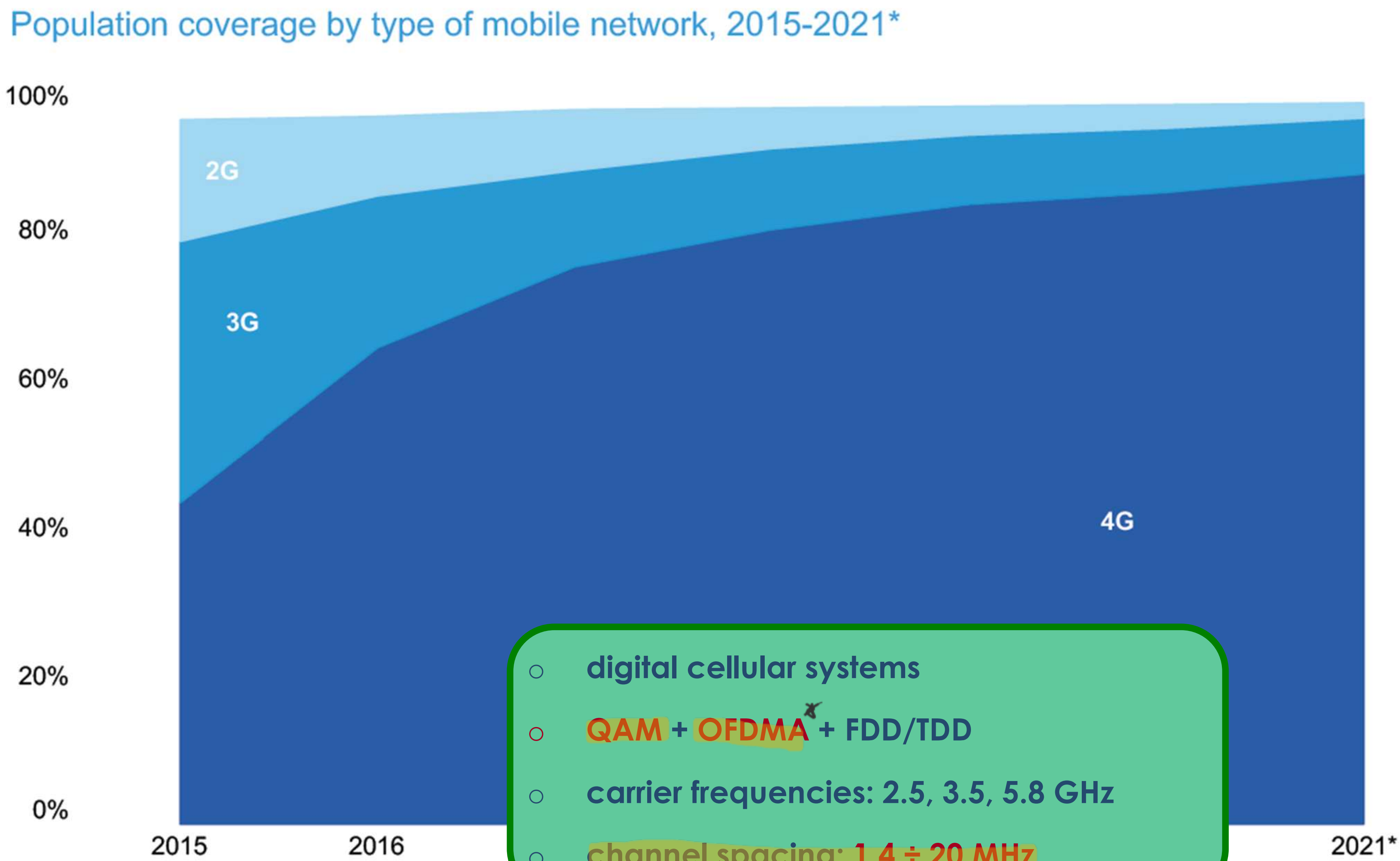
Why? To increase throughput you need to increase the bandwidth. But here frequency selectivity becomes more important.

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

With CDMA, beyond 5MHz the complexity doesn't scale linearly. The complexity of the estimation of the channel obviously.
CDMA doesn't scale with the BW.

* Putting patches but not very good. H+ = HSPA+

4G systems



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

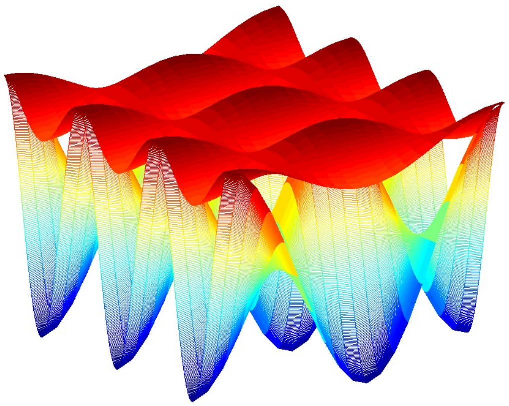
scale up to 20MHz

*ORTHOGONAL FDMA.

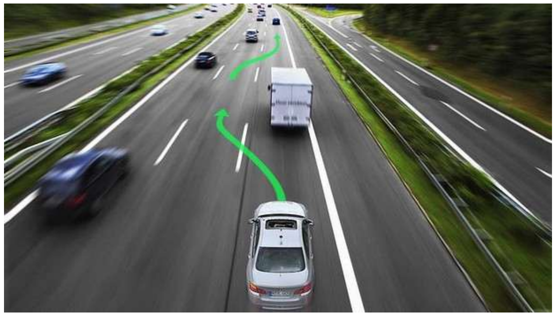
5G systems (1/2)

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)

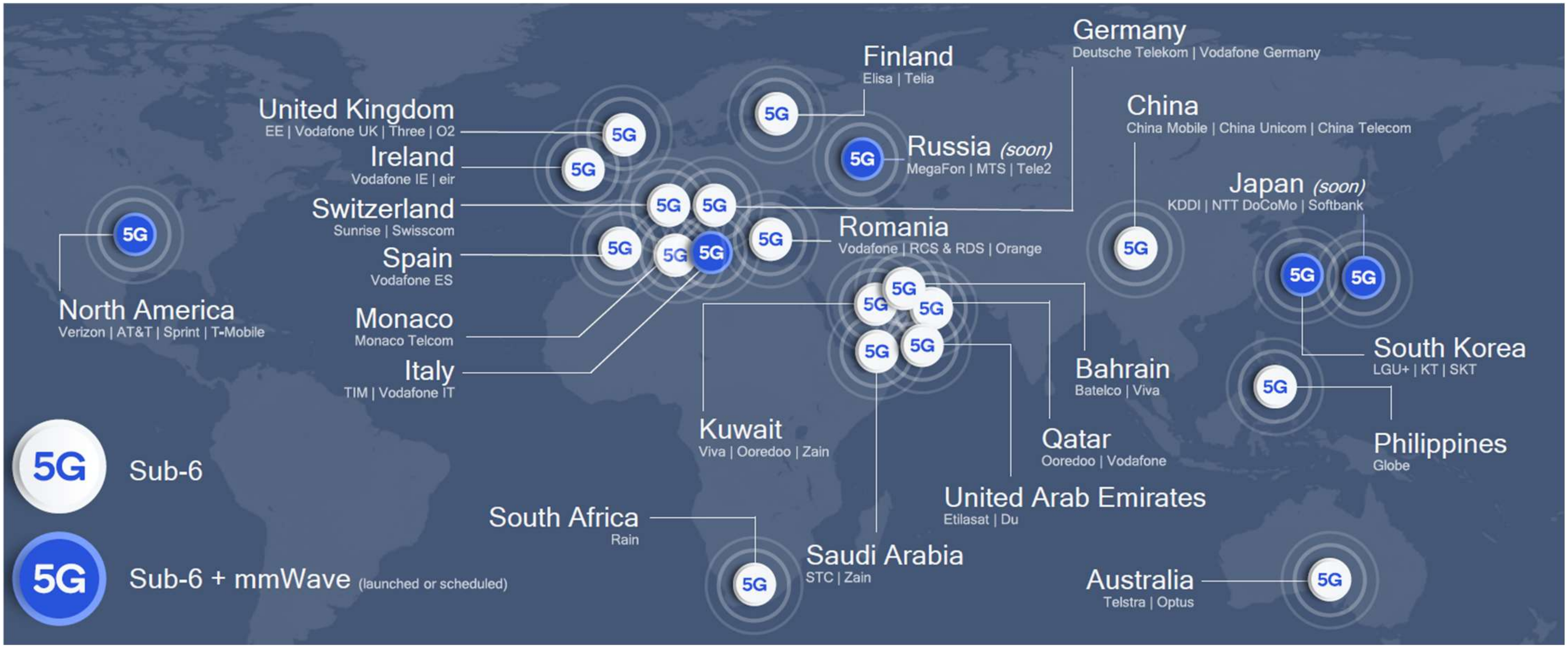


- **energy efficiency:** 100× wrt 4G

QPSK, QAM only difference is mapping. 4G is really universal.

CONTINUE

5G systems (2/2)



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?

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