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

# Basics of wireless communication systems

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Master's Degree in Cybersecurity [WCY-LM]

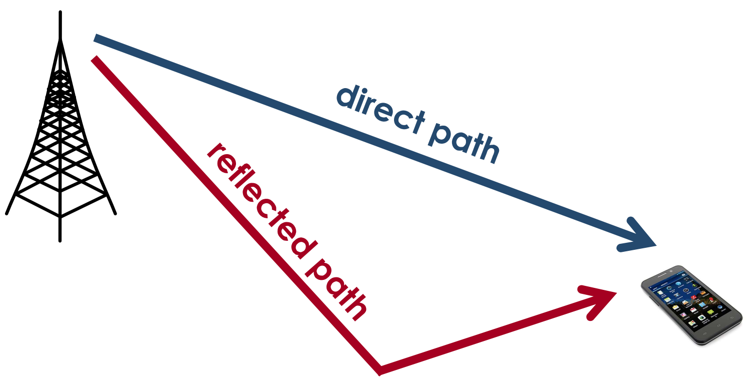
# Multipath propagation: frequency selectivity

# Static frequency-selective channels (1/4)

Suppose now that the hypothesis $\sigma_\tau \ll T$ does **not** hold: this means that we now have

$$y(t) = \sum_{\ell=1}^{L} \rho_\ell e^{j\theta_\ell} x\left(t - \tau_\ell\right)$$

For the sake of simplicity, let's consider the **two-ray channel**, i.e., $L = 2$:




$$y(t) = \underbrace{\rho_1 e^{j\theta_1} x\left(t - \tau_1\right)}_{\text{direct (LoS) path}} + \underbrace{\rho_2 e^{j\theta_2} x\left(t - \tau_2\right)}_{\text{reflected path}}$$

# Static frequency-selective channels (2/4)



To simplify the notation, let us take:

$$\rho_1 = 1, \quad \theta_1 = 0, \quad \tau_1 = 0$$
$$\rho_2 = \rho, \quad \theta_2 = \theta, \quad \tau_2 = \tau$$

**received signal:** $$y(t) = x(t) + \rho e^{j\theta} x(t-\tau)$$

**Fourier transform:** $$Y(f) = X(f) \cdot \left[1 + \rho e^{j\theta} e^{-j2\pi f \tau}\right]$$

The **frequency response** of the channel is

$$H(f) = \frac{Y(f)}{X(f)} = 1 - \rho e^{-j2\pi(f - f_{\mathrm{N}})\tau}$$

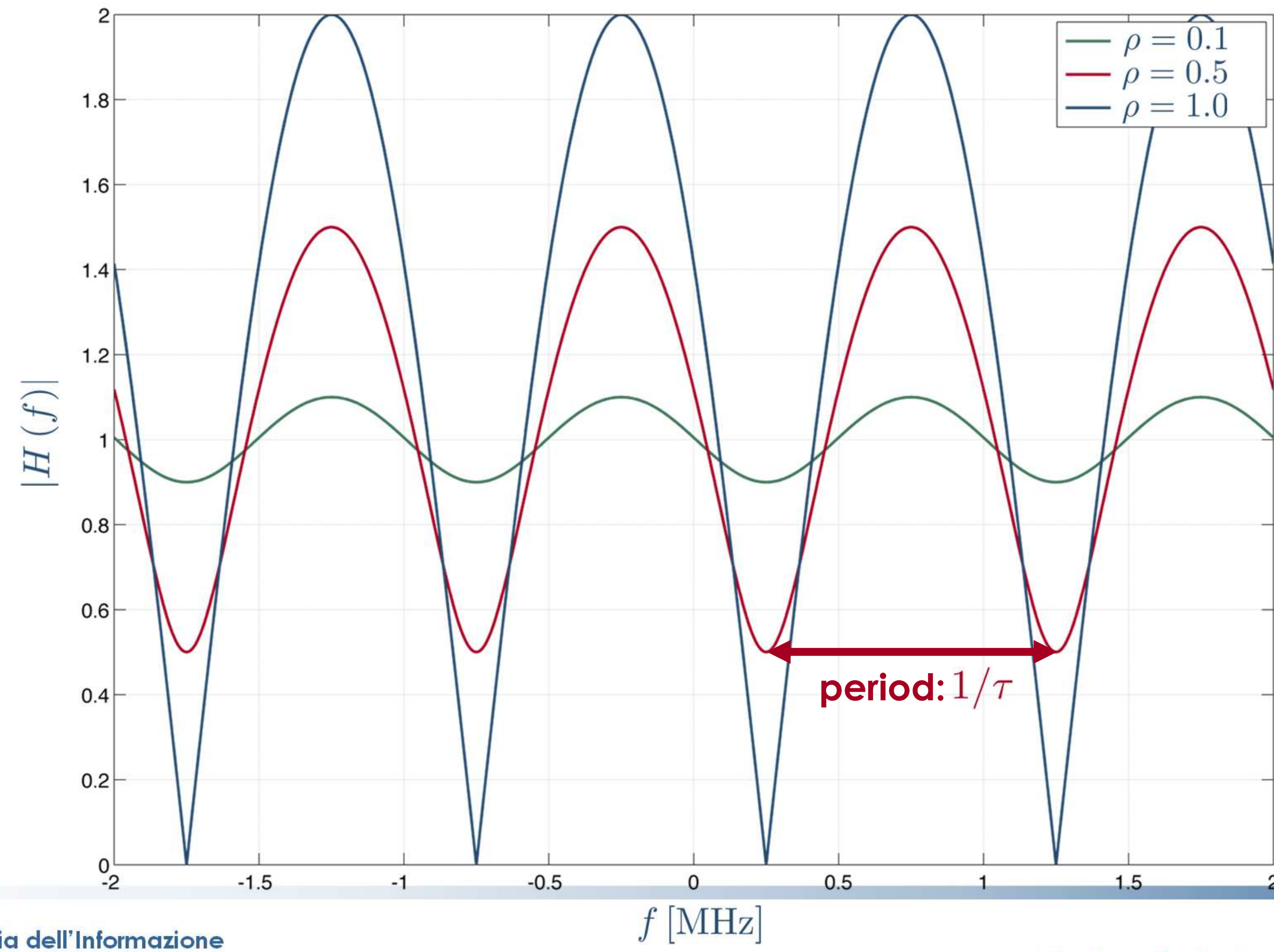
where $f_{\mathrm{N}} = \frac{1}{2\tau} + \frac{\theta}{2\pi\tau}$ is the **notch frequency** of the channel

# Static frequency-selective channels (3/4)



## The amplitude response of the two-ray channel is

$$|H(f)| = \sqrt{1+\rho^2 - 2\rho\cos\left[2\pi\left(f - f_{\mathsf{N}}\right)\tau\right]}$$

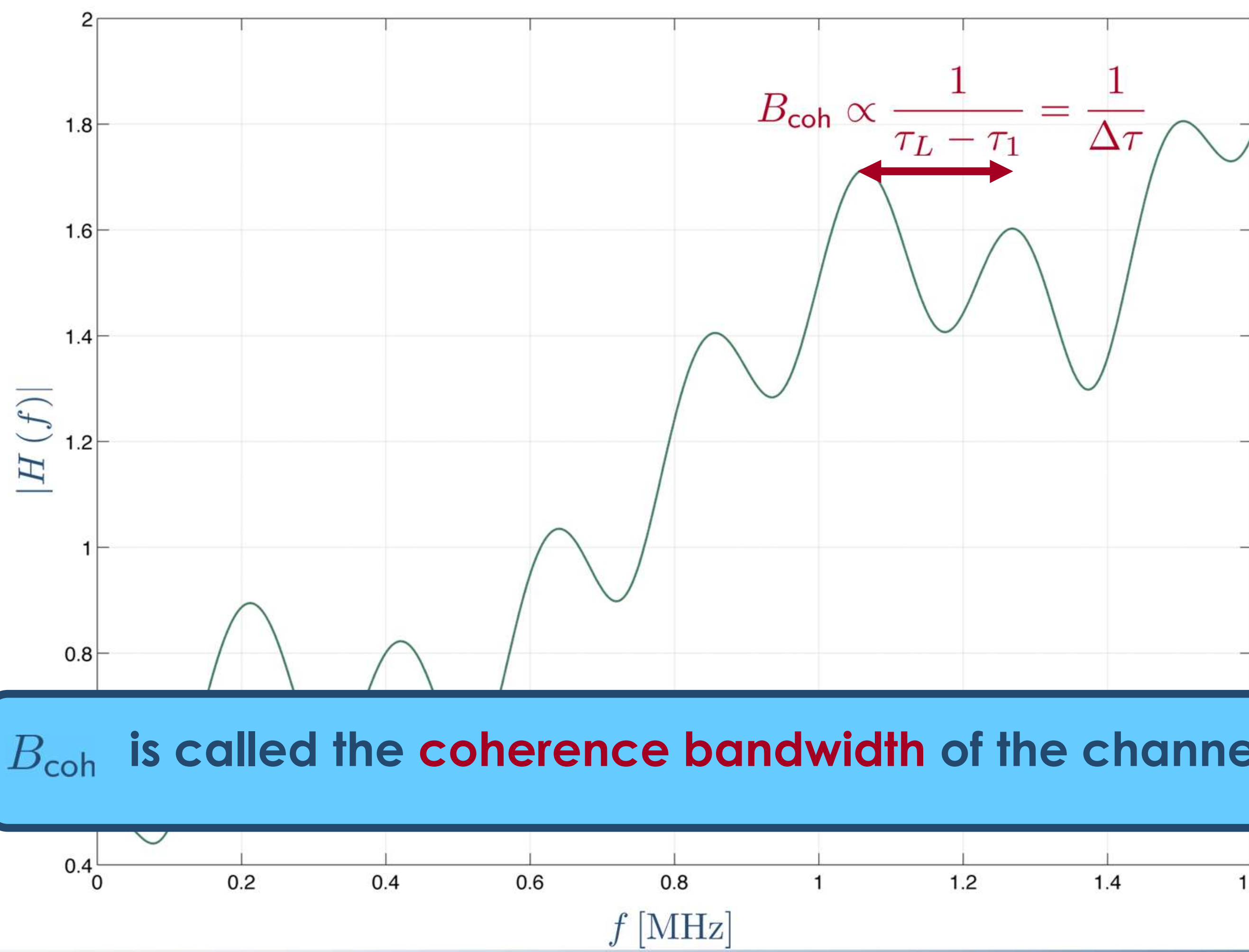



$\tau = 1\,\mu\mathrm{s}$
$f_{\mathsf{N}} = 0.25\,\mathrm{MHz}$
$\theta = -\pi/2$

# Static frequency-selective channels (4/4)



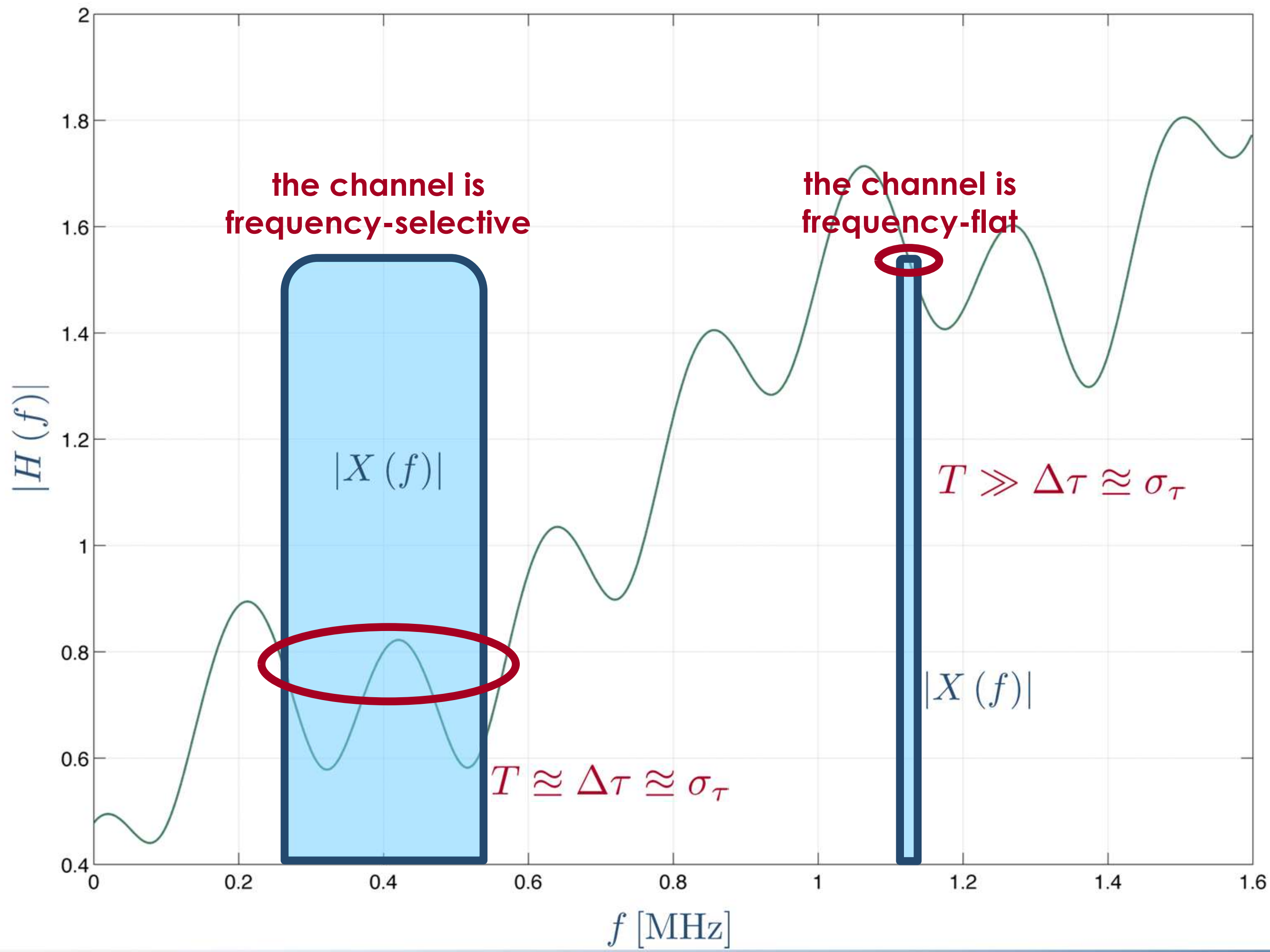
When extending the calculations to the $L$-ray channel, we get




$B_{\text{coh}}$ is called the **coherence bandwidth** of the channel

# The concept of frequency selectivity (1/2)

**We know that the bandwidth of a signal $x(t)$ is $B \propto 1/T$**



# The concept of frequency selectivity (2/2)

**The frequency selectivity depends on the statistics of the channel and of the input signal**

**There is a practical way to assess the frequency selectivity of a channel:**

- $B \ll B_{\mathsf{coh}} \Leftrightarrow T \gg \sigma_\tau$ : **frequency-flat channel**
- $B \approxeq B_{\mathsf{coh}} \Leftrightarrow T \approxeq \sigma_\tau$ : **frequency-selective channel**

**Example:**

- **urban scenarios:** $\sigma_\tau \approxeq 1\,\mu\mathrm{s} \Rightarrow B_{\mathsf{coh}} \approxeq 1\,\mathrm{MHz}$
- **4G and 5G signals:** $B \geq 1.5\,\mathrm{MHz}$

**Some form of equalization is needed to combat the frequency selectivity**

# Multipath propagation: time selectivity

# Multipath propagation model*

In a multipath scenario, the received signal is a linear **combination** of a number of different propagation paths, **each** having its own attenuation, phase rotation, and time delay:

$$y(t) = \sum_{\ell=1}^{L(t)} \rho_\ell(t)\, e^{j\varphi_\ell(t)} x(t - \tau_\ell(t)) e^{-j2\pi f_0 \tau_\ell(t)}$$

$$= \sum_{\ell=1}^{L(t)} \rho_\ell(t)\, e^{j\theta_\ell(t)} x(t - \tau_\ell(t))$$

$L(t)$ : number of propagation paths

$\rho_\ell(t)$: attenuation of the $\ell$-th path

$\theta_\ell(t)$ : phase delay of the $\ell$-th path

$\tau_\ell(t)$ : time delay of the $\ell$-th path



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# Time-varying frequency-flat channels* (1/4)



**Due to the relative motion between the transmitter and the receiver, the communication medium (the wireless channel) evolves through time:**

$$y\left(t\right)=\sum_{\ell=1}^{L(t)}\rho_{\ell}\left(t\right)e^{j\theta_{\ell}(t)}x\left(t-\tau_{\ell}\left(t\right)\right)$$

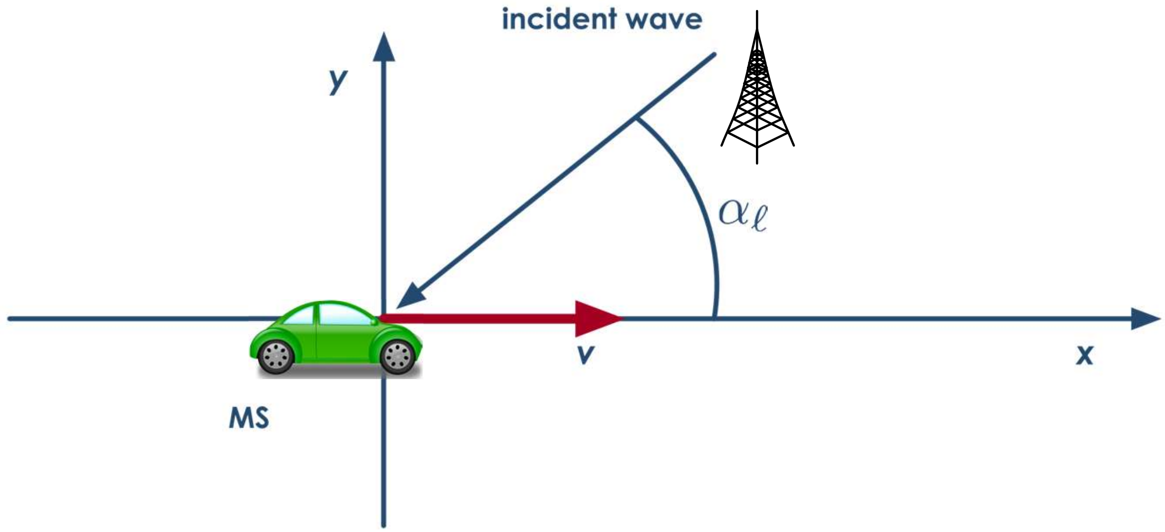
**For simplicity, let's assume a frequency-flat channel:** $\sigma_{\tau}\ll T\Rightarrow\tau_{\ell}(t)\approxeq\overline{\tau}\quad\forall\ell$

**Similarly to the static case,**

$$\begin{aligned}y\left(t\right)&\approxeq x\left(t-\overline{\tau}\right)\cdot\textstyle\sum_{\ell=1}^{L(t)}\rho_{\ell}\left(t\right)e^{j\theta_{\ell}(t)}\\&=\overline{\rho}\left(t\right)\cdot e^{j\overline{\theta}(t)}\cdot x\left(t-\overline{\tau}\right)\\&=\underbrace{A\left(t\right)}_{\text{fading process}}\cdot x\left(t-\overline{\tau}\right)\end{aligned}$$

# Time-varying frequency-flat channels (2/4)

To study time and frequency characteristics of $A(t)$, let us use the **kinematic model** for the MS:




Due to **Doppler effect**, each band pass frequency $f \in \left[f_0 - \frac{B}{2}, f_0 + \frac{B}{2}\right]$, where $f_0$ is the carrier frequency, is shifted at the receive side by its **Doppler shift** $\Delta f$:

$$\Delta f = \frac{v}{c} \cdot f \cdot \cos\left(\alpha_\ell\right)$$

## Time-varying frequency-flat channels* (3/4)

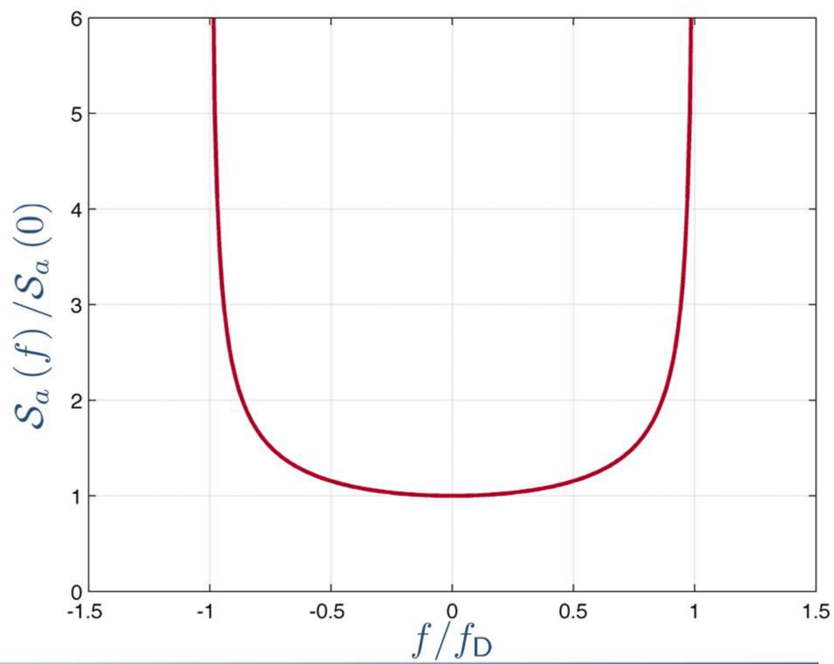
**The behavior of $A(t)$ is given by the impact of the Doppler effect over all signal frequency components** $f \in \left[f_0 - \frac{B}{2}, f_0 + \frac{B}{2}\right]$

**A key parameter is the maximum Doppler shift at the carrier frequency $f_0$, called the Doppler spread $f_\mathrm{D}$:**

$$f_\mathrm{D} \triangleq \max_{\alpha_\ell} |\Delta f| = \frac{v}{c} \cdot f_0$$

**Using the Clarke's model, we can compute the power spectral density (PSD) of the random process $A(t)$:**

$$S_a(f) = \frac{\sigma_\rho^2}{2\pi f_\mathrm{D}} \cdot \frac{1}{\sqrt{1-(f/f_\mathrm{D})^2}}$$

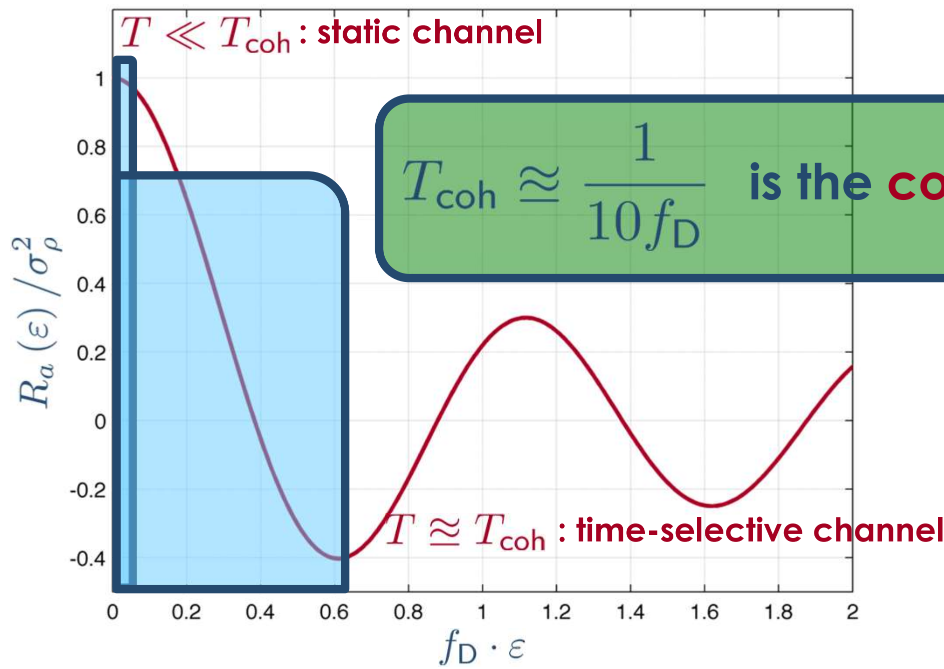


# Time-varying frequency-flat channels (4/4)

Another useful statistical parameter to investigate the properties of $A(t)$ is its **autocorrelation** function:

$$R_a(\varepsilon) = \mathcal{F}^{-1}\{\mathcal{S}_a(f)\} = \mathbb{E}\{A(t) \cdot A(t+\varepsilon)\}$$

Using again the Clarke's model,




$T_{\text{coh}} \approx \dfrac{1}{10 f_D}$ is the **coherence time** of the channel

# The concept of time selectivity

The time selectivity depends on the statistics of the channel **and** of the input signal

There is a practical way to assess the time selectivity of a channel:

- $B \gg f_\mathsf{D} \Leftrightarrow T \ll T_\mathsf{coh}$ : **static** channel
- $B \approxeq f_\mathsf{D} \Leftrightarrow T \approxeq T_\mathsf{coh}$ : **time-selective** channel

**Example (4G and 5G systems):**

- $v = 120\,\mathrm{km/h},\, f_0 = 2\,\mathrm{GHz}: T_\mathsf{coh} = 0.45\,\mathrm{ms}$
- **slot duration:** $T_\mathsf{slot} = 0.5\,\mathrm{ms}$

Some **design constraints** must be added to combat the time selectivity

# Multipath propagation: A summary

# Frequency and time selectivity: A summary (1/5)

Both time- and frequency-selectivity are functions of **both** the channel and the input signal properties:

| | frequency-flat | frequency-selective |
|---|---|---|
| static | $f_\mathrm{D} \ll B \ll B_\mathrm{coh}$ | $f_\mathrm{D} \ll B \approxeq B_\mathrm{coh}$ |
| time-selective | $f_\mathrm{D} \approxeq B \ll B_\mathrm{coh}$ | $f_\mathrm{D} \approxeq B \approxeq B_\mathrm{coh}$ |

- frequency-selective = time-dispersive
- time-selective = frequency-dispersive
- frequency-selective ≠ time-selective!

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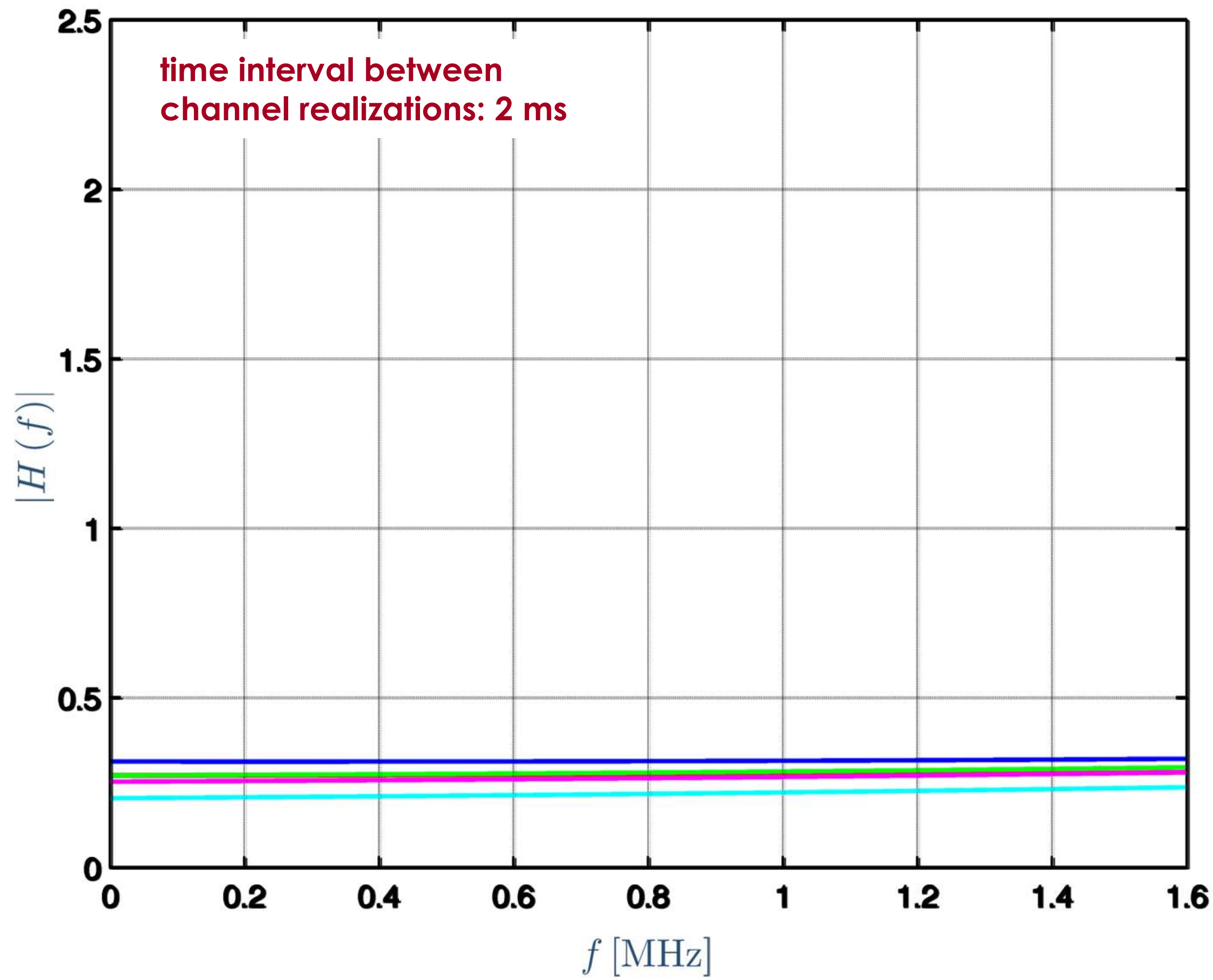
# Frequency and time selectivity: A summary (2/5)

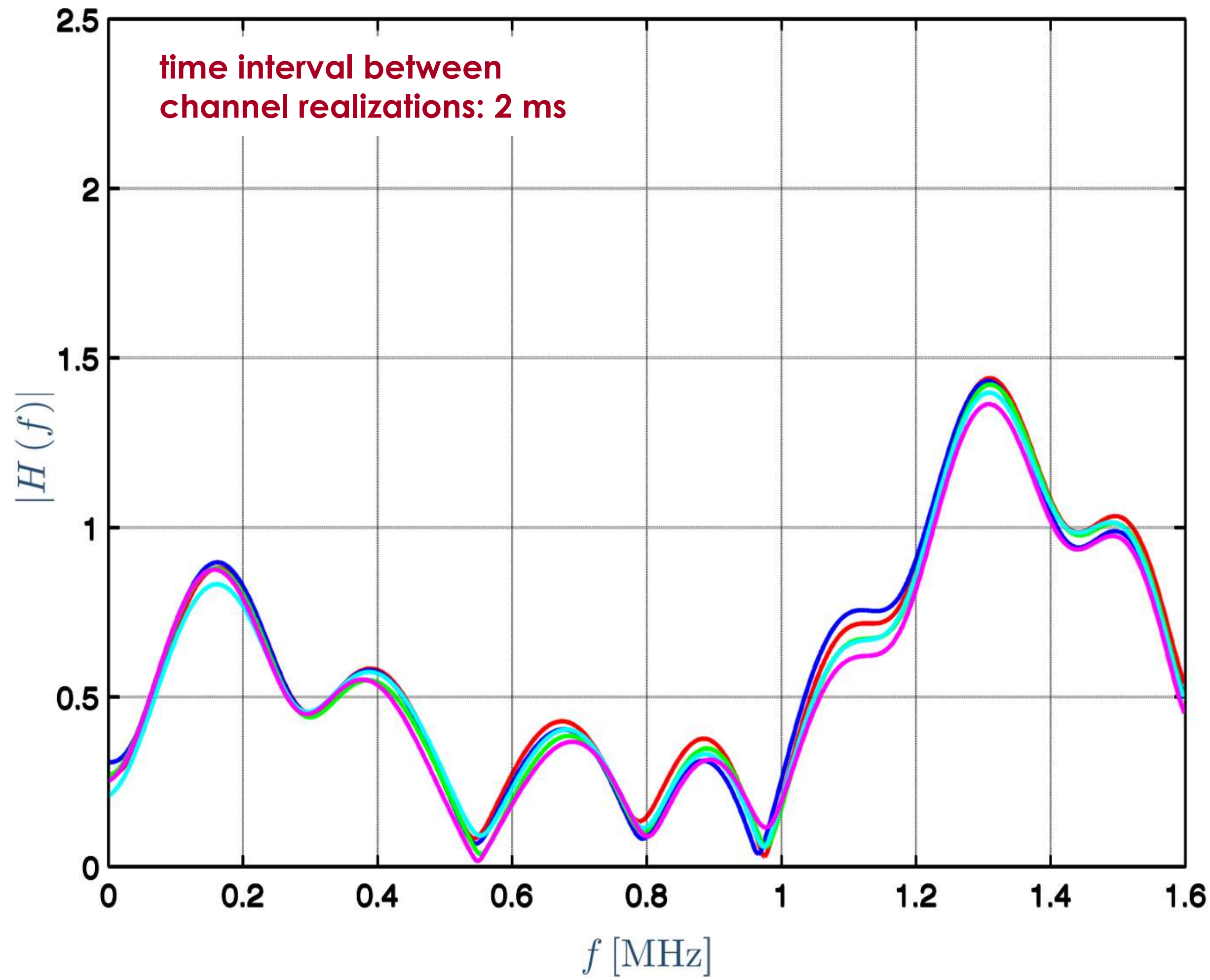
## A static frequency-flat channel ($T_{\text{coh}} = 100\,\text{ms}, B_{\text{coh}} = 10\,\text{MHz}$):



# Frequency and time selectivity: A summary (3/5)

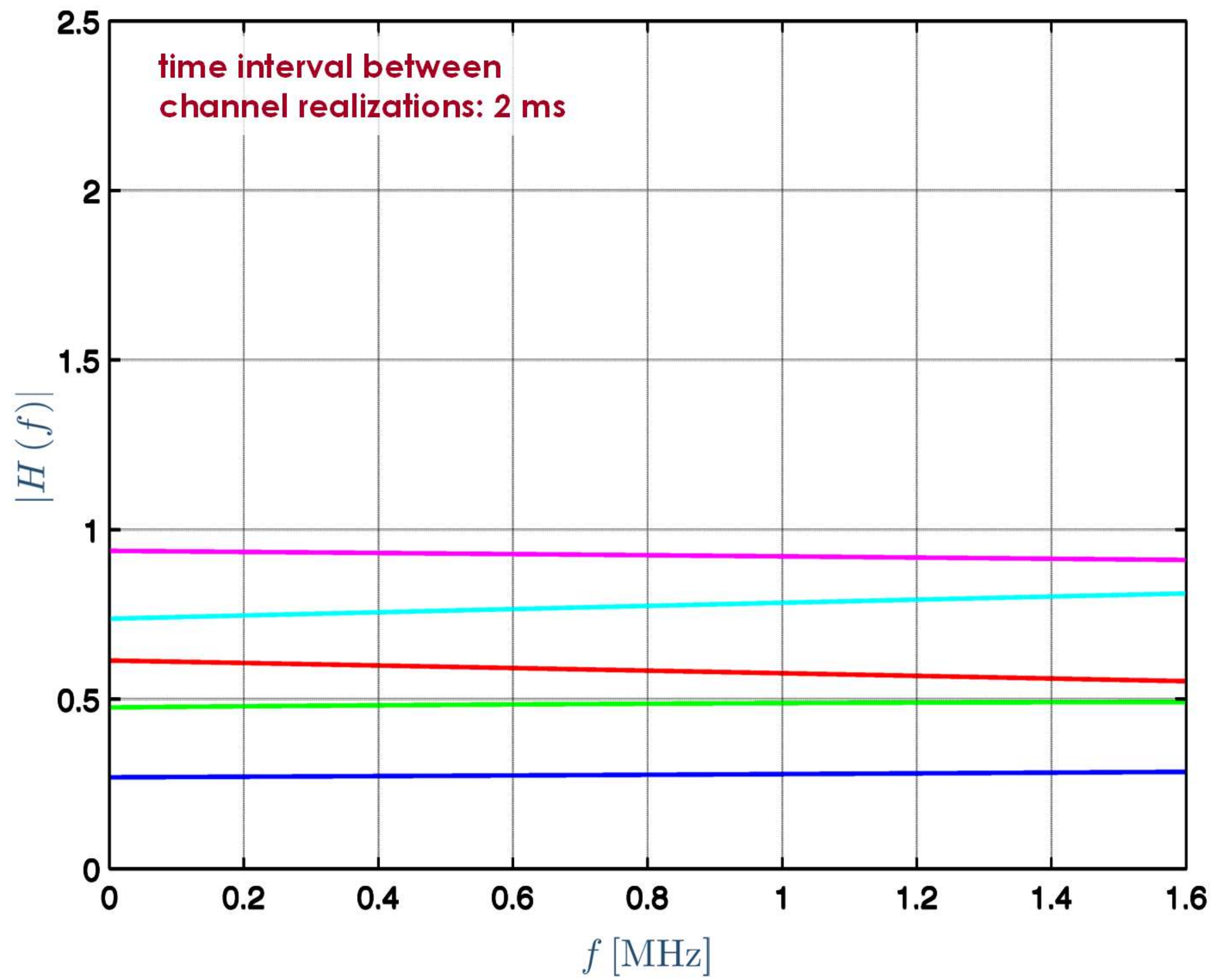


## A static frequency-selective channel ($T_{\mathrm{coh}} = 100\,\mathrm{ms}$, $B_{\mathrm{coh}} = 100\,\mathrm{kHz}$):



# Frequency and time selectivity: A summary (4/5)

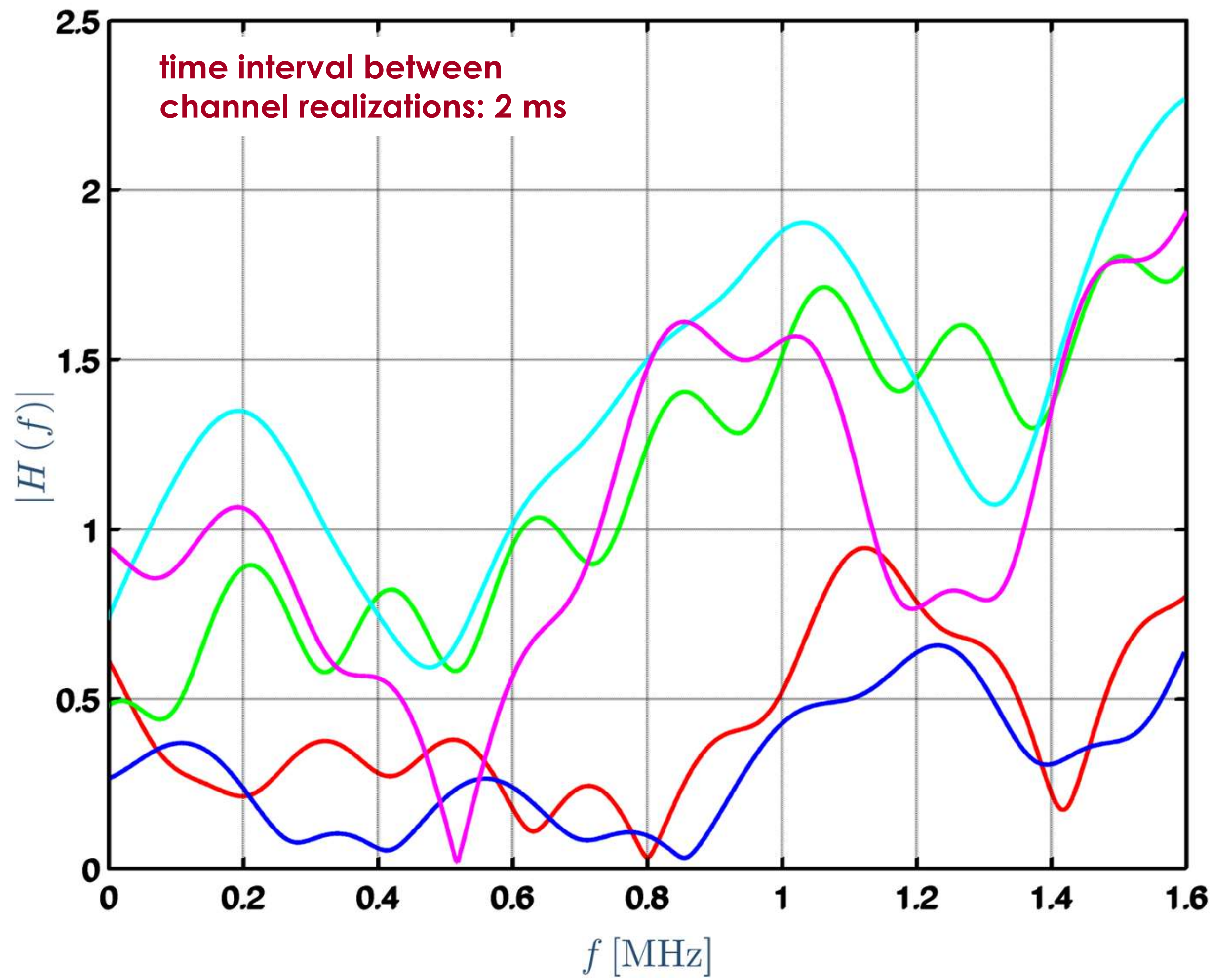
**A time-selective frequency-flat channel ($T_{\text{coh}} = 1\,\text{ms}, B_{\text{coh}} = 10\,\text{MHz}$):**



# Frequency and time selectivity: A summary (5/5)



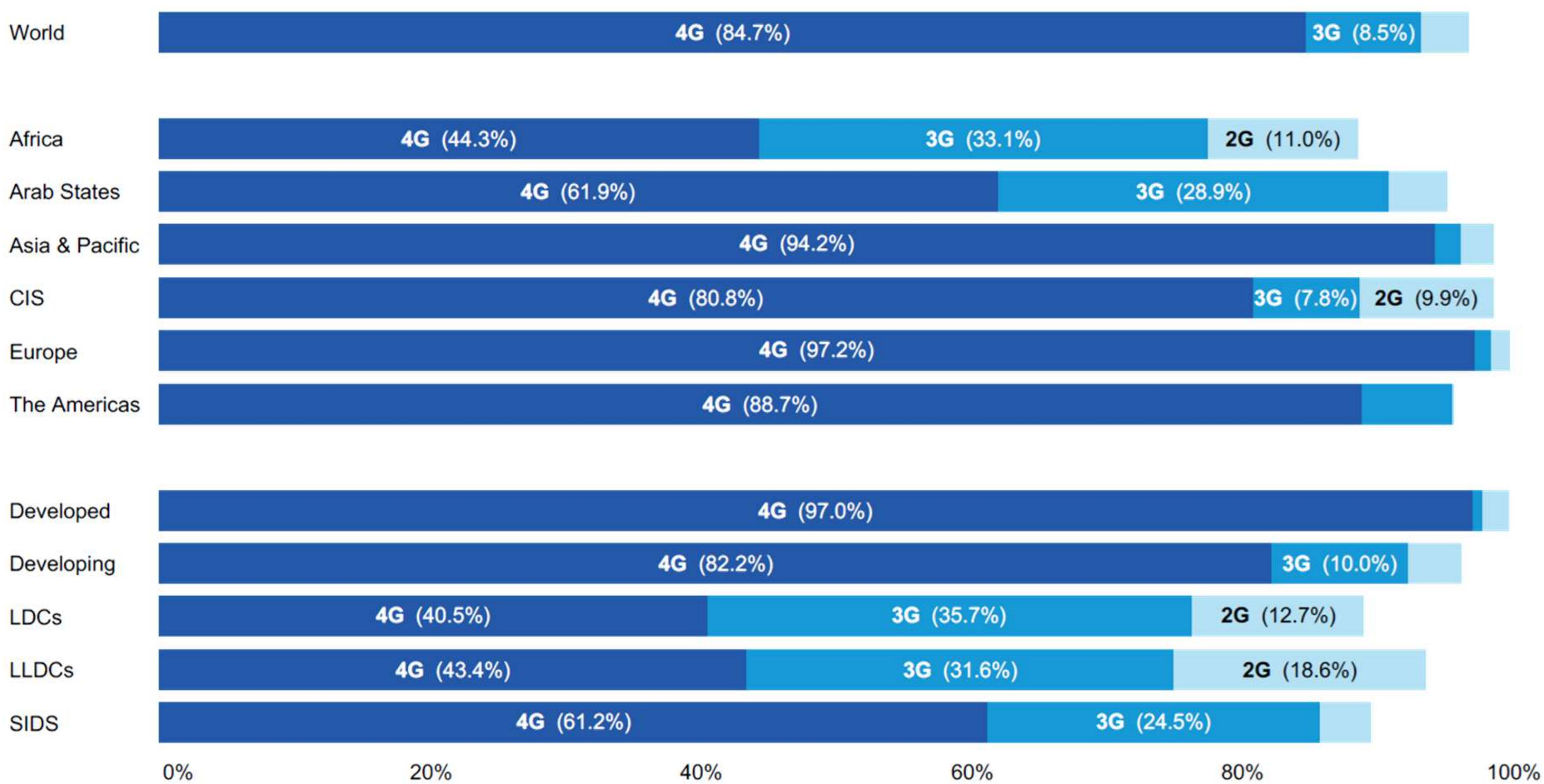
## A doubly-selective channel ($T_{\text{coh}} = 1\,\text{ms}, B_{\text{coh}} = 100\,\text{kHz}$):




Modern systems look like this one!

# Introduction to wireless communications

# Some (whopping) facts on communications* (1/3)

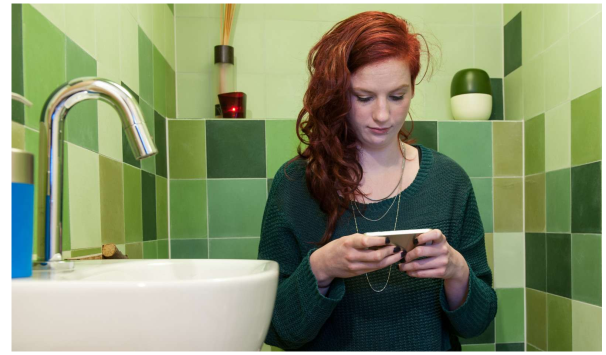



* ITU estimate. Source: ITU

- **In 2021, the number of unique mobile users are more than 5.2 billion users worldwide (>66% penetration rate)!**

# Some (whopping) facts on communications* (2/3)

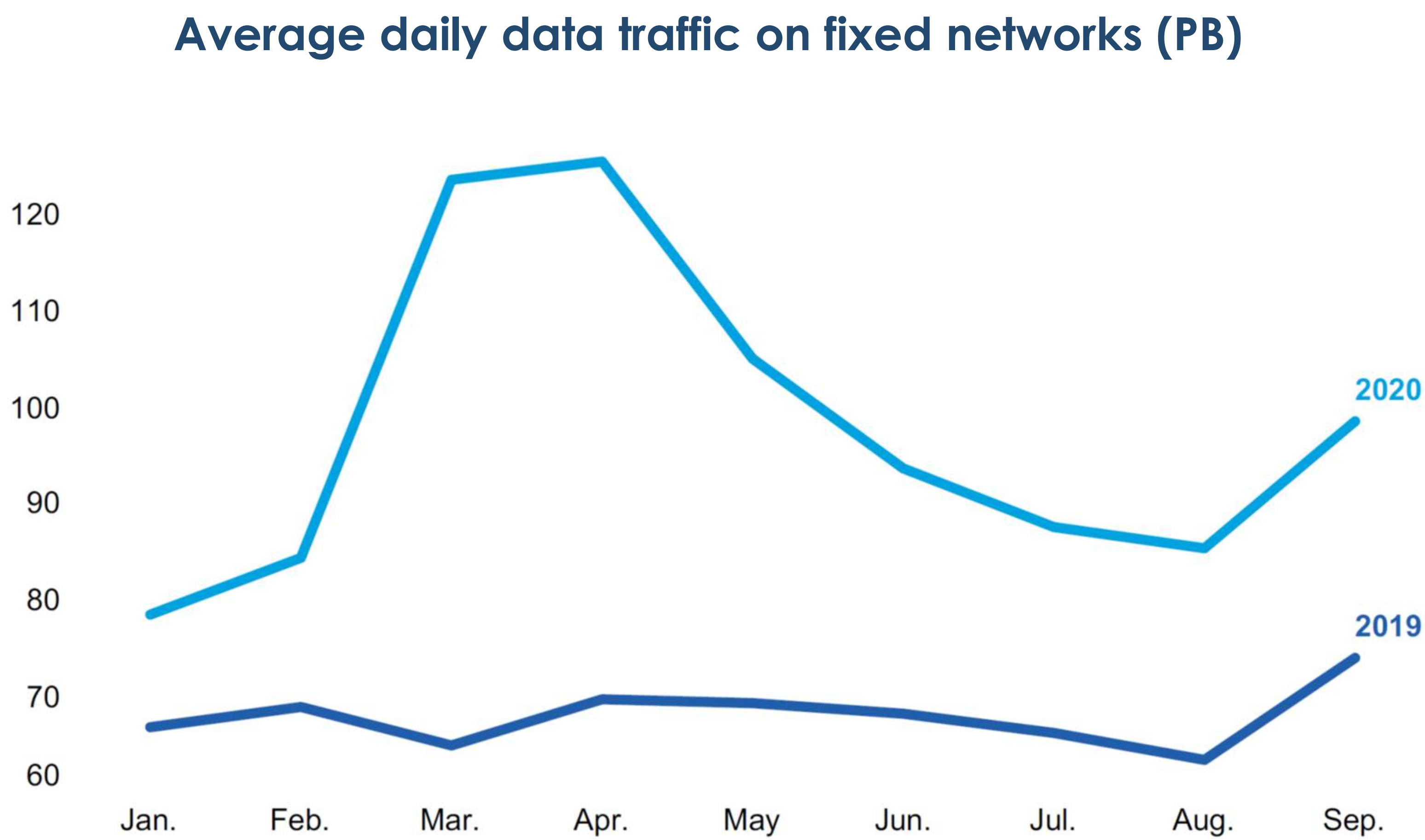
- The number of people with access to mobile communications is higher than those with access to working toilets (around 4.5 billions)



- The number of people that owns a mobile phone is larger than the one that owns/uses a toothbrush (around 4 billions)

- Every second, more than eight hours of videos is uploaded to Youtube

# Some (whopping) facts on communications* (3/3)



# Spot the intruder*

# History of wireless communications

# A brief history of wireless communications* (1/3)

- **1864:** Maxwell proves the existence of electromagnetic waves
- **1887:** Hertz sends and receives wireless waves, using a spark transmitter and a resonator receiver
- **1895:** Guglielmo Marconi sends a radio signal over more than a mile, from the Isle of Wight to a tugboat 18 miles away
- **1904:** Fleming patents the diode
- **1906:** DeForest patents the triode amplifier; first speech wireless transmission, by Fessenden
- **WW I:** Rapid development of communications intelligence, intercept technology, cryptography
- **1920:** Marconi discovers short-wave radio, with wavelengths between 10 and 100 meters
- **1935:** Armstrong invents the frequency modulation (FM)

# A brief history of wireless communications* (2/3)

Mobile wireless systems ensure the communications between mobile nodes

NODES CAN MOVE

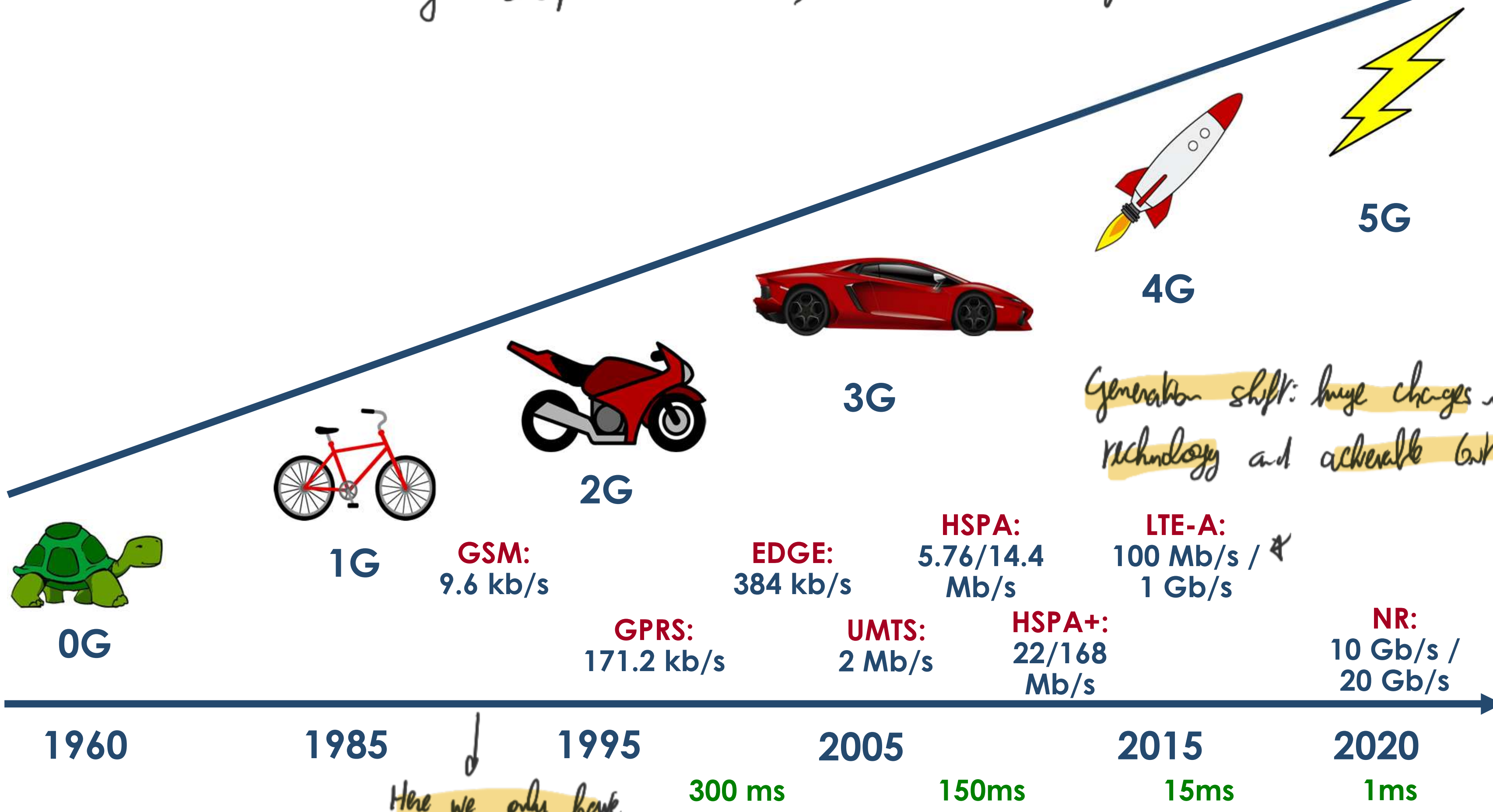
Challenges:

In the last eighty years, wireless technology has evolved over many aspects:

- increased coverage distance
- increased quality (throughput, error rate performance, spectral efficiency)
  applications: voice, images, data, files exc.
- improved availability of services (broadband communications)
- decreased energy consumption (energy efficiency)
- reduced costs (for both service providers and subscribers/users)
- reduced device sizes and costs

# A brief history of wireless communications (3/3)

Limited coverage area; with cellular systems we have many access points.




Generation shift: huge changes in technology and achievable bit rate.

Here we only have voice. (1)

Latency is reduced

* Distinction between uplink and downlink.

(and was analog)

① 1st gen was supporting only voice, but with 2nd gen we also support data. We have now a digital systems. One shift between the 2 different standards we have the possibility of assigning multiple slots to a user.

The design of the 3rd gen started with internet communication in mind. In between we had more patches to the standard to have higher throughput. Then, with short latency we can also think of other applications like remote driving or remote surgery.

The most succesful gens are the even one. 1st gen was defined independently with different standards. With GSM in Europe we had the same standard at least.

3G has the same standard in EU and JAP.

↳ But the tech wasn't very succesful (CDMA didn't scale well with the bandwidth)

4G introduced slicing the bandwidth.

5G is a bit weird, not very much different than 4G in terms of speed.

Biggest novelty of 5G is go beyond 30GHz limit up to 78GHz.

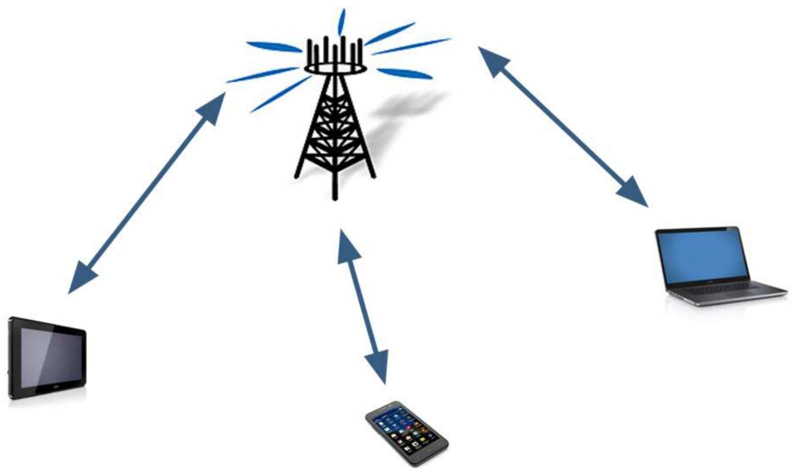
We want $\frac{B}{f_0} \approx 5\%$, so with higher $f_0$ we can increase the throughput, but we have a higher path loss.

Odd gens introduce new tech, which is then refined by even gens.

# Basic concepts

# Wireless communication systems

## infrastructure networks

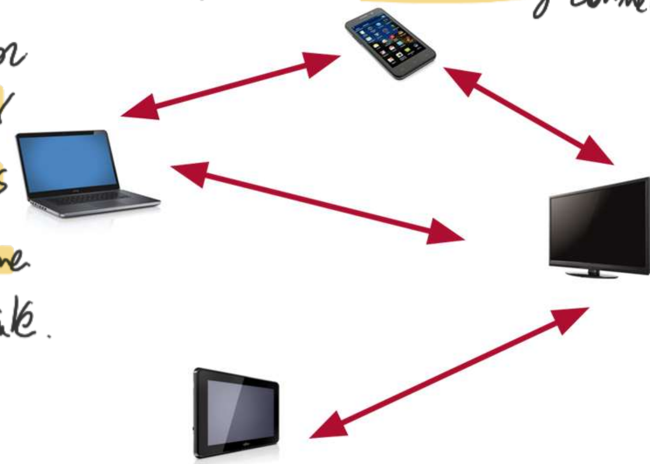


- higher rates
- lower latencies

Only a part of the network: transport or core network that acts as a backbone to communicate.

## ad-hoc networks

We can have directly connected points



- lower deployment costs
- useful in impaired environments

↓ hostile environment.

*Examples:*

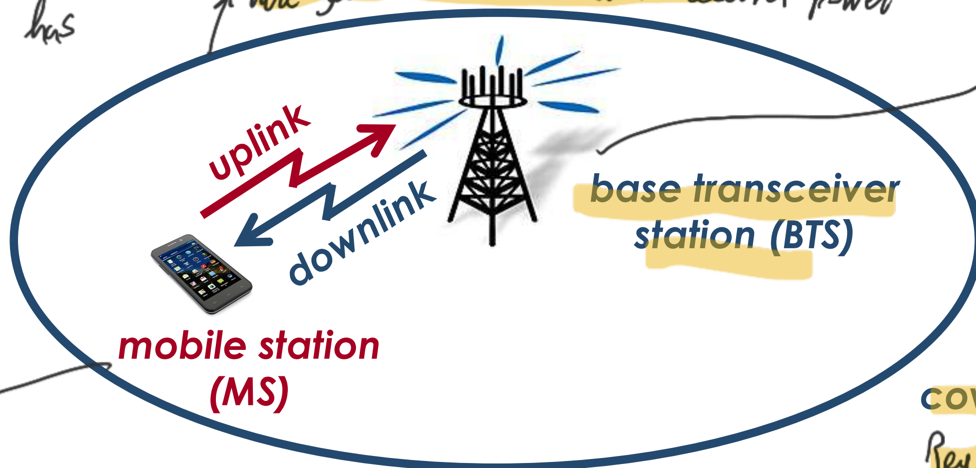
- *cellular networks*
- *WLANs*
- *paging systems*: old fashion network. One way system in which access point sends a message to the paging systems.

We want to build a mobile wireless comm. system. 1 option: ①. Network with a very solid hierarchy, you have an access point. Every time the nodes need to communicate, they have to contact the access point. "Higher rates": you don't need to do any routing!

# An elementary wireless system

Elementary Wireless system has a coverage area

here you have minimum received power




interface between users and core network.

Users

coverage area

Regulated by the minimum Received power required by your system

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

↳ Example: police station with cars.

**Constraints:**

- limited frequency range (due to licensed spectrum) 1
- limited coverage area (due to power masks)

↳ What if I increase the transmit power? You cannot transmit whatever you want: in the uplink you have batteries so you have more battery consumption. Then, it would also interfere with other systems, ...

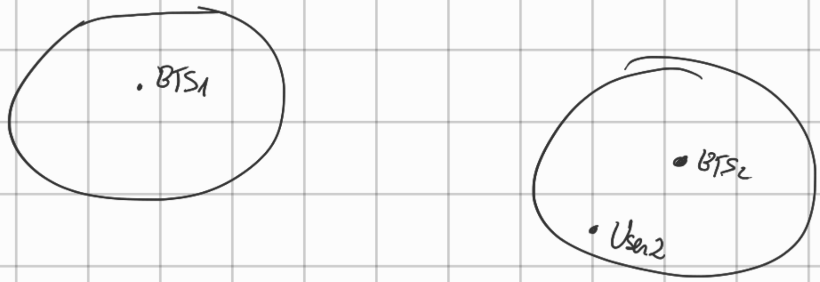
**Features:**

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

① We need multiple access scheme (easiest is FDMA). Even if you have unlimited power, your frequency range limits you: if you want N users you need a certain bandwidth B to give to each user.
Let $\Delta f = B_{user}$, $B$ = bandwidth you have available, $N = \frac{B}{\Delta f}$, so even with increased coverage you have a limitation in terms of users and frequency! You do not solve the issue by increasing the power. B is subject to licences.

So this system doesn't scale.

NOTE: if you had 2 BTS: The interference generated by BTS1 for User2 is negligeable.
So this is good.

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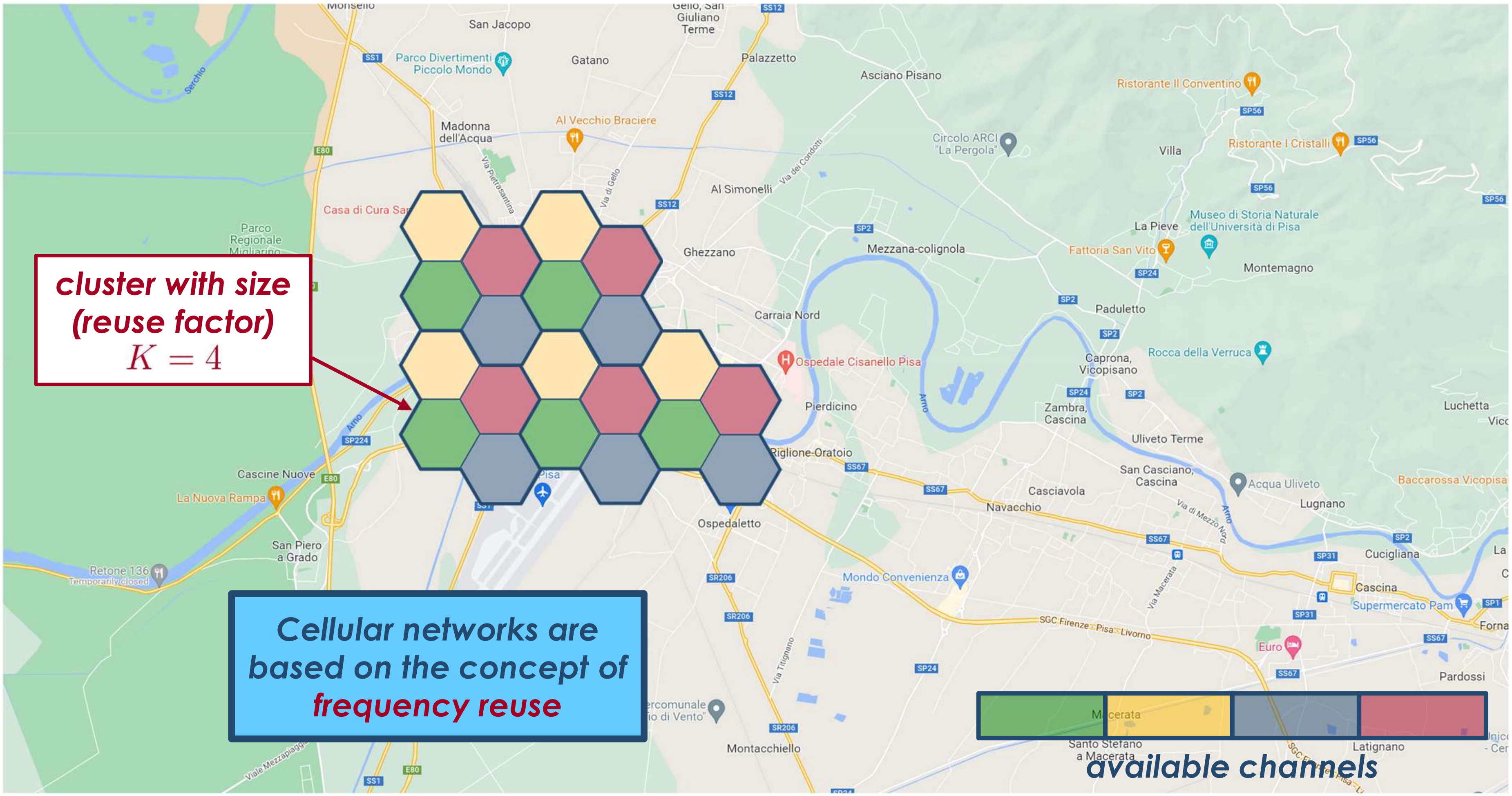
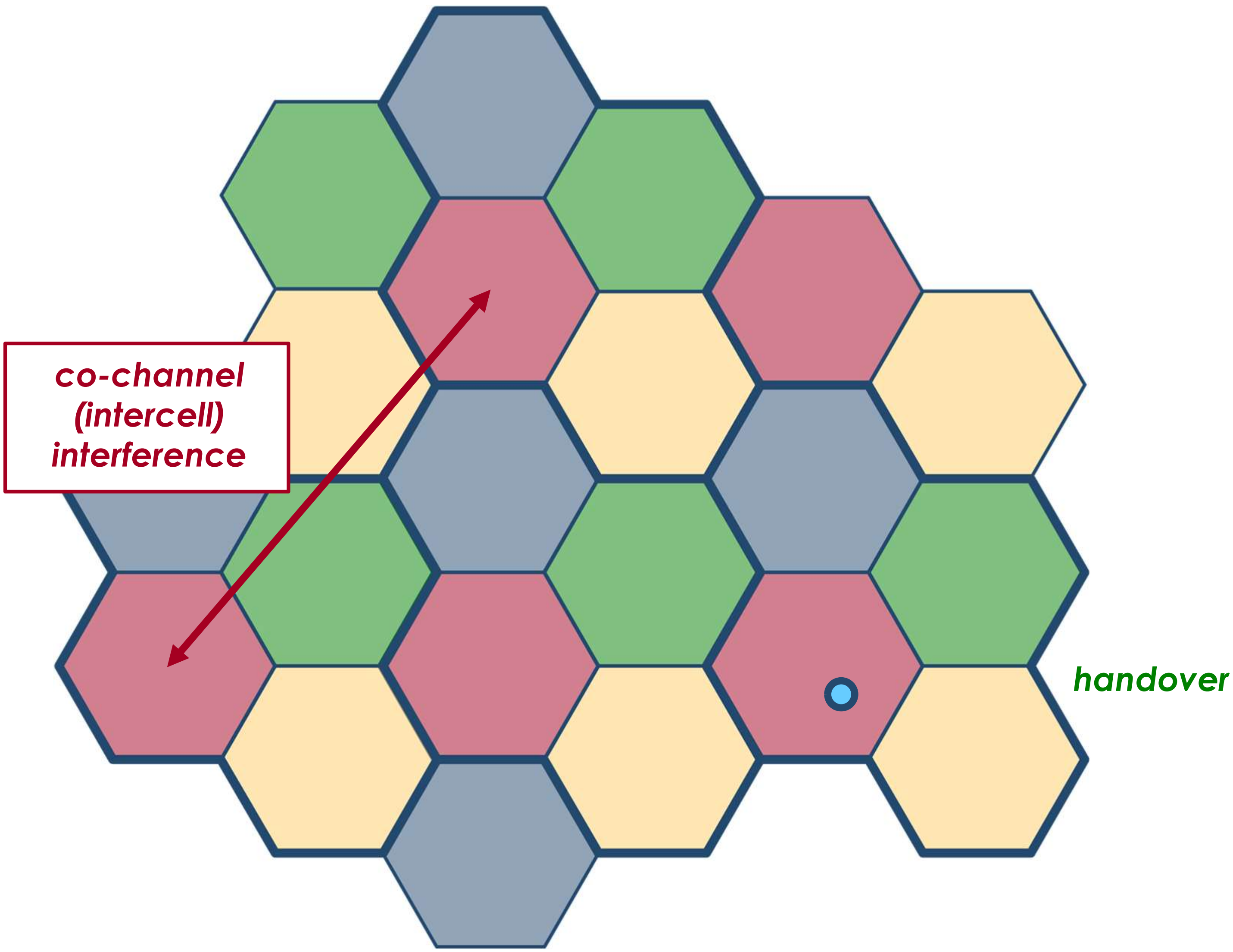
# The concept of a cellular network (1/4)

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



# The concept of a cellular network (2/4)



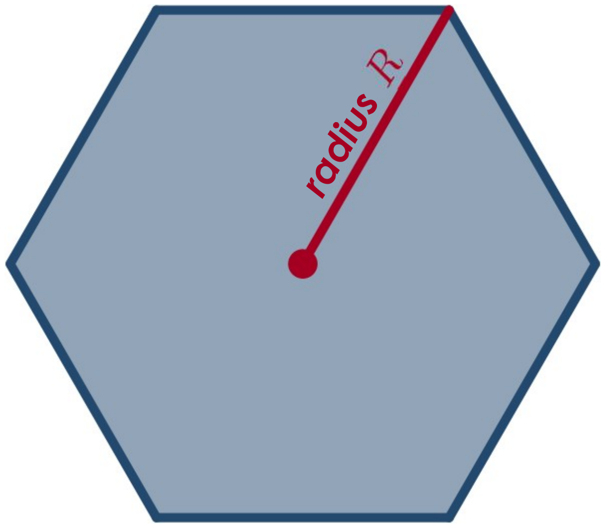
## The concept of a cellular network* (3/4)

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

## 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 $P_\mathsf{T}$
- Handoff rate $\mu_\mathsf{H}$
- User density $u$
- Minimum SIR $\underline{\xi}$

| **KPI** | $R \uparrow$ | $K \uparrow$ |
| --- | --- | --- |
| $P_\mathsf{T}$ | $\uparrow$ (✗) | $\leftrightarrow$ |
| $\mu_\mathsf{H}$ | $\downarrow$ (✓) | $\uparrow$ (✗) |
| $u$ | $\downarrow$ (✗) | $\downarrow$ (✗) |
| $\underline{\xi}$ | | |

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