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

Basics of wireless communication systems

Marco Luise, Giacomo Bacci
{marco.luise, giacomo.bacci}@unipi.it

Master's Degree in Cybersecurity [WCY-LM]

What are large scale and small scale models in wireless channels?

In wireless communications, **large-scale** and **small-scale** models describe the characteristics of radio signal propagation over different spatial and temporal scales:

Large-Scale Models

These models describe the average signal power behavior over long distances, typically several wavelengths or beyond. They focus on the overall trend of signal attenuation and account for factors such as:

- **Path Loss**: The reduction in signal power as a function of the distance between the transmitter and receiver.
- **Shadowing (or Slow Fading)**: Signal variations caused by large obstacles like buildings or hills that block or scatter the signal.

Large-scale models are used to predict signal strength over a wide area and are crucial for tasks like network planning and cell coverage estimation.

Small-Scale Models

These models describe rapid fluctuations of the signal over short distances (comparable to a few wavelengths) or short time intervals. These fluctuations arise from:

- **Multipath Propagation**: Multiple copies of the transmitted signal arrive at the receiver via different paths, causing interference (constructive or destructive).
- **Doppler Effect**: Frequency shifts due to relative motion between the transmitter and receiver.

Small-scale models are important for understanding and predicting signal variations in real-time, especially in dynamic environments like urban areas or when users are mobile.

Relationship Between the Two

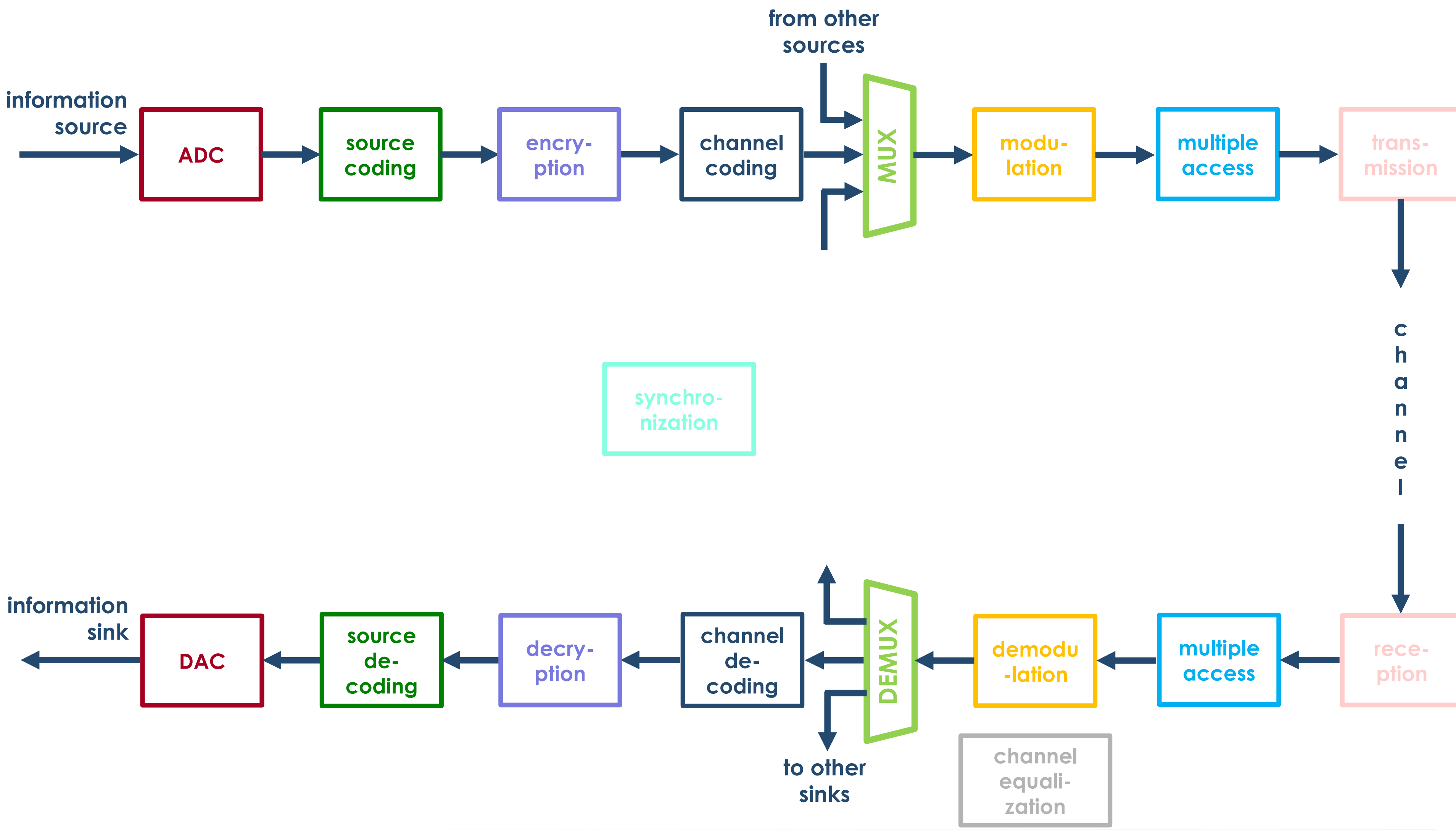
- **Large-scale effects** give the general trend of signal strength over large areas or distances.
- **Small-scale effects** overlay rapid, local variations onto the large-scale trend.

Together, these models provide a comprehensive understanding of wireless channel behavior.

Message

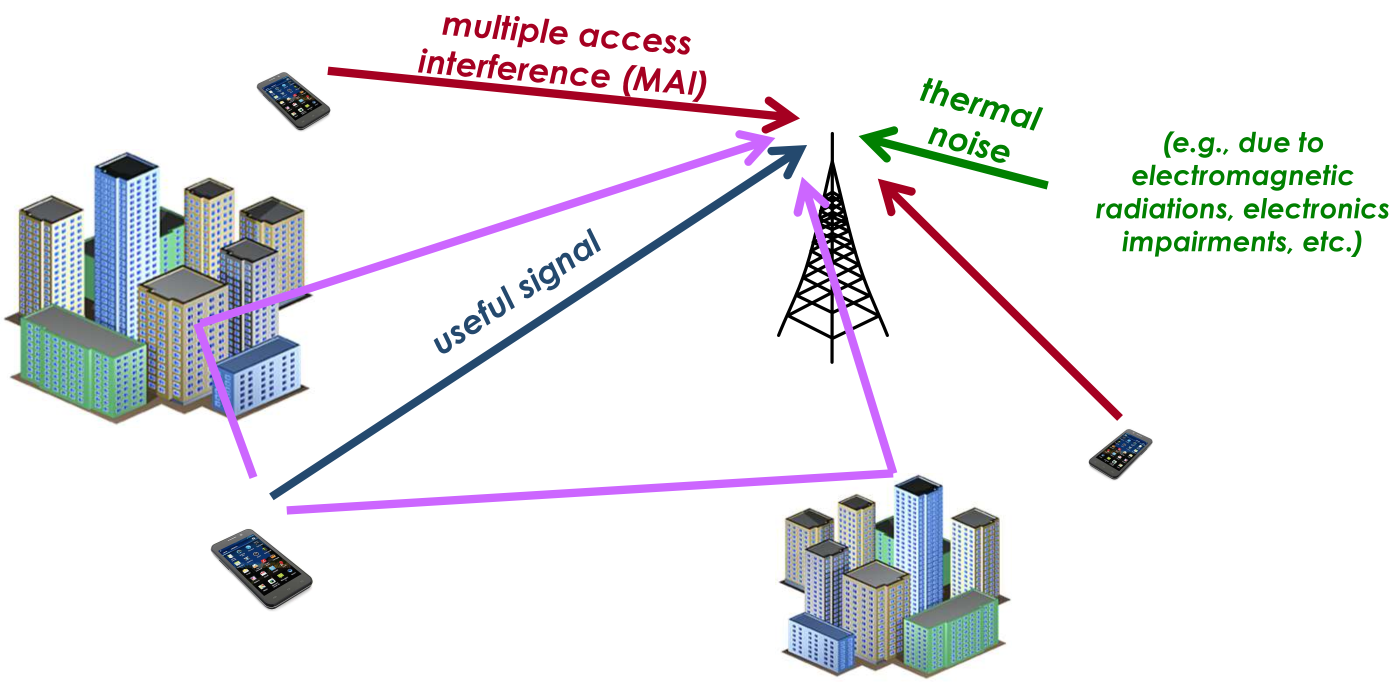
Basics of wireless propagation

Elements of a digital communication system



The wireless propagation channel

Received contributions at the receiver (uplink):



The wireless channel between the transmitter and the receiver fluctuates **randomly** for a number of causes

Large- and small-scale models (1/3)

A better suited propagation model is composed by:

- **large-scale models**, that predict the average energy received in a wireless system as a function of the distance between the transmitter and the receiver
- **small-scale models**, that account for the instantaneous variations in the propagation conditions

Large- and small-scale models (2/3)

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

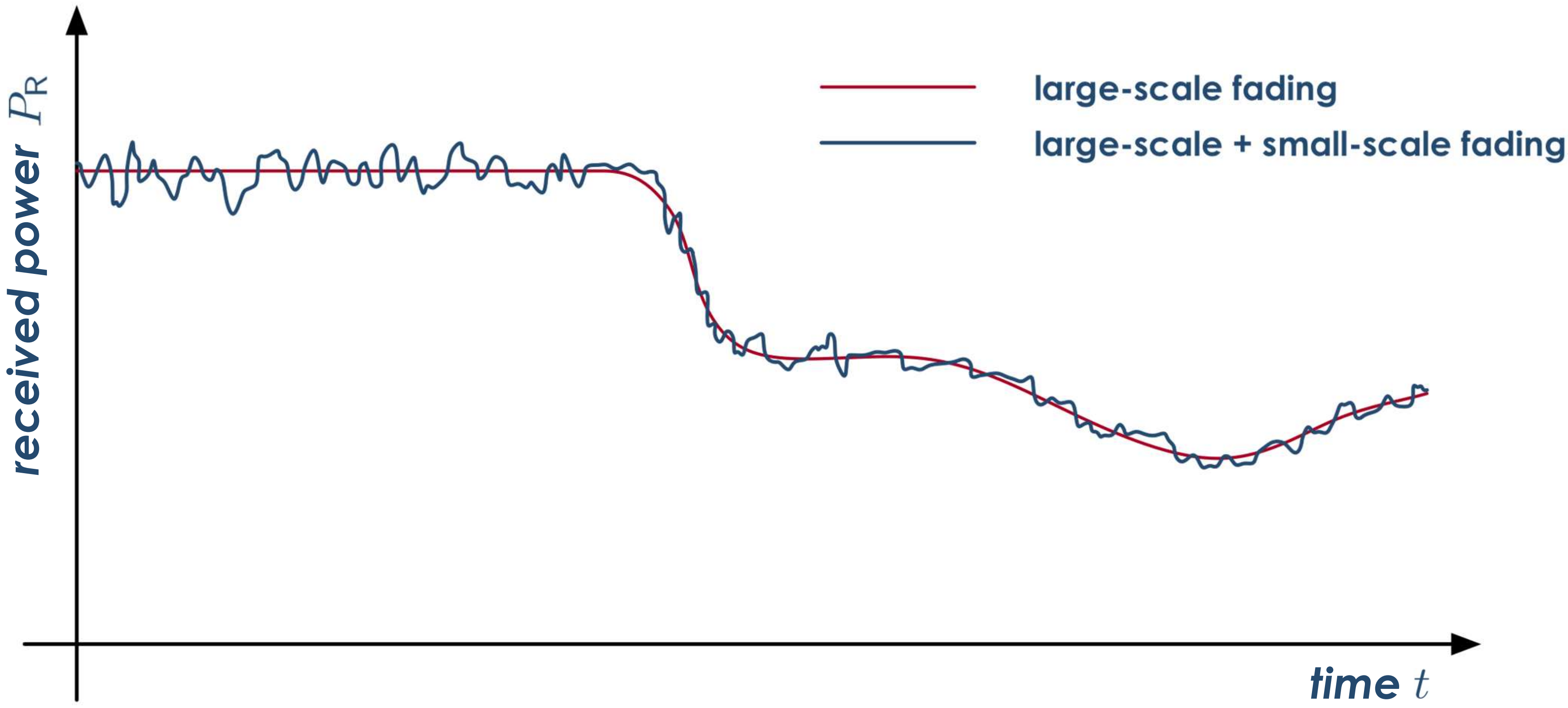
$$P_{\mathsf{Rx}}(d) = G_{\mathsf{Tx}} G_{\mathsf{Rx}} P_{\mathsf{Tx}} \left(\frac{\lambda}{4\pi d} \right)^n$$

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

How the average power behaves depending on the distance from Tx and Rx

This describes attenuation a bit more, but what's the root cause for distortion? Because of the multiple paths that connect Tx and Rx.

Large- and small-scale models (3/3)



Small scale fading

Wavelengths and frequencies in wireless systems (1/2)

Wireless radio spectrum:

Names given to wave ranges: *

High frequencies, Very HF, Ultra HF, Super, Extremely

* Ratio between upper bound and lower bound is constant.

Carrier wavelengths:

speed of light, $3 \cdot 10^8\,\mathrm{m/s}$

$$\lambda = \frac{c}{f_0} = 1\,\mathrm{cm} \div 1\,\mathrm{m} \;*$$

carrier frequency

With wireless communication we work in Ultra and Super high frequencies,

* Why did we choose to use these frequencies?
1. We discovered that the path loss $L(d) = \left(\frac{\lambda}{4\pi d}\right)^m$, if we increase f, λ becomes smaller.

Assume $m=2$, for example. $f_0 = 300\,MHz \Rightarrow \lambda_0 = 1m$ $d = 1Km$

$$L(d) = \left(\frac{\lambda}{4\pi d}\right)^m = \left(\frac{1\cancel{m}}{4\pi \cdot 1000\cancel{m}}\right)^2 = \frac{1}{16 \cdot 10^6 \pi} = 2 \cdot 10^{-8}$$

Imagine now you move to higher frequencies, we get an even bigger loss.
That's why we have an upper bound.
I could decrease the frequency but then I have problem with antennas!
I have to find the right trade off.
Another point: we saw that with FDMA we assign a specific bandwidth assigned to users. And in general $B/f_0 \leq 0,1$ * so smaller frequencies call for smaller bands for users so lower bitrates. Because given a budget we have a band that needs to be divided for users. * This is a reasonable number. Otherwise the system is not sustainable, expensive, inefficient.

When you increase frequency, we have a weaker penetration power for our waves: light can't do that, but our cellular signal can.

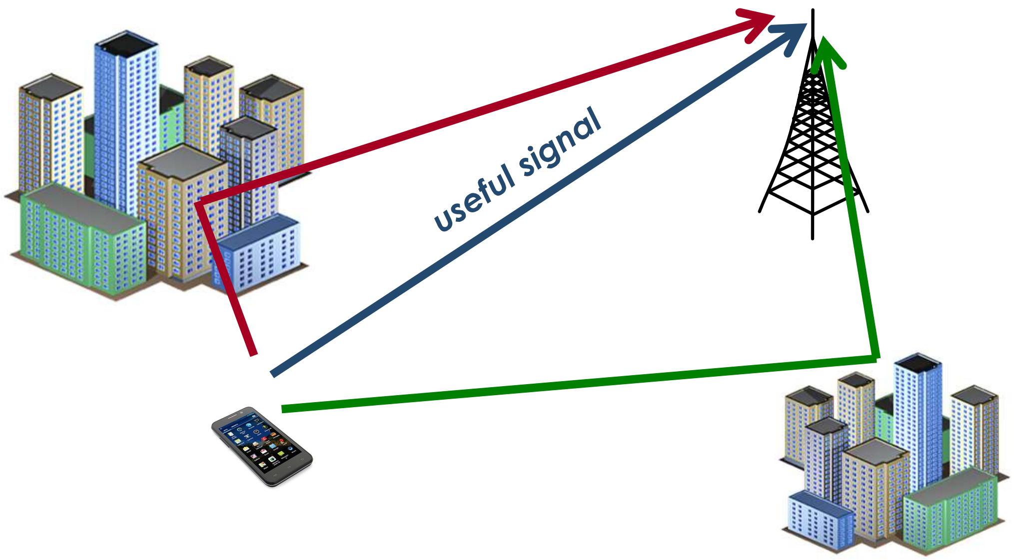
Wavelengths and frequencies in wireless systems (2/2)

Why are such frequencies particularly **attractive**?

- larger f_0's yield **larger** path losses: $L(d) \propto \frac{1}{\lambda^n}$
- smaller f_0's call for **larger** antennas (with size comparable with λ)
- smaller f_0's show favorable conditions for over-the-horizon (OTH) propagation, thus **reducing** the potential for frequency reuse
- such f_0's can accommodate **large** enough channel spacing and provide room for **large** user multiplexing and multiple access
- such f_0's have good **indoor** propagation

Multipath propagation

In this frequency spectrum, the wireless signal experiences a **multipath propagation**: the received signal is a **linear combination** of multiple paths



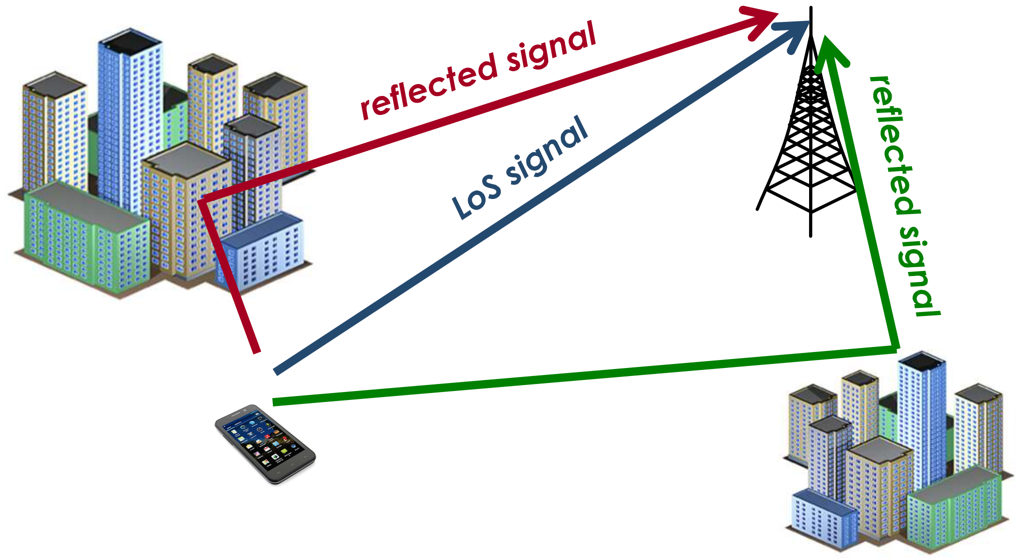
In addition to the direct path (a.k.a. line of sight (LoS) path), the wireless signal can propagate due to:

- **reflection:** ① $S \gg \lambda$ higher order of magnitude
- **shadowing:** $S \simeq \lambda$ same order of magnitude
- **scattering:** $S \ll \lambda$ lower order of magnitude

① When the dimension of the obstacle is much larger than the wavelength. This causes reflection.

Channel modelling we are talking about now works for the bands we are working in.

Reflection*



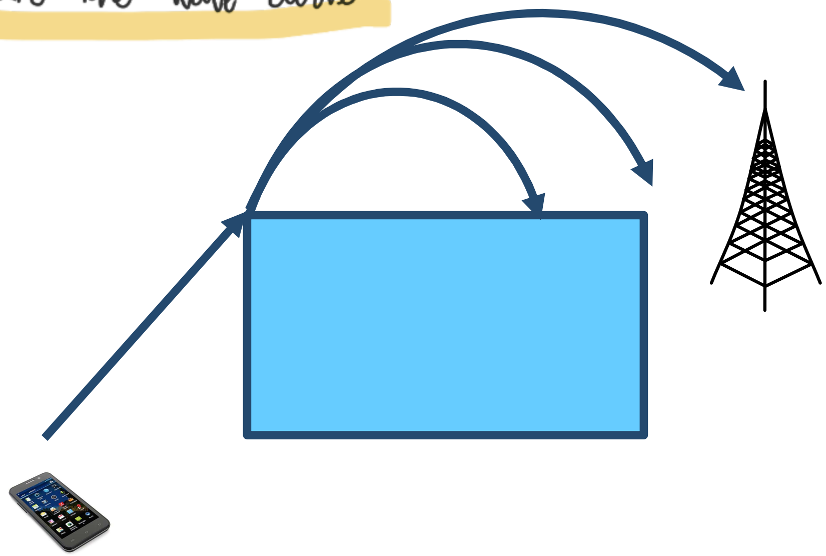
Due to the different propagation lengths, for each path the reflection introduces:

- **amplitude attenuation**: cammino più lungo e potenza assorbita dalla riflessione.
- **time shift (a.k.a. group delay)**
- **phase shift (a.k.a. phase delay)**

Delay: length of the path is longer and we can have phase shift when bouncing

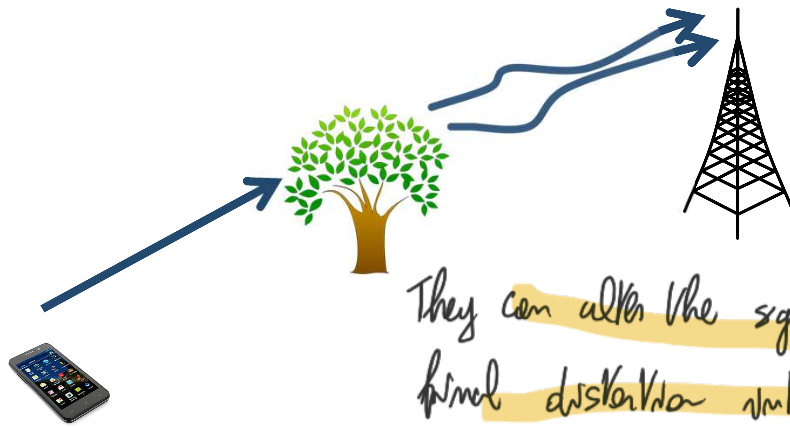
Shadowing*

Edges can make the wave curve



Shadowing introduces **additional** paths when the transmitter and the receiver are **not** in visibility, thus affecting the statistics of the channel

Scattering*



They can alter the signal and contribute to the final distortion introduced by the channel

Similarly, scattering introduced a disordered reflection of the electro-magnetic waves, thus impacting on attenuations and phase delays

Multipath propagation: frequency selectivity

Multipath propagation model*

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

attenuation ($\rho \leq 1$). Then we have delays (signal arrives later than when transmitted)

Received signal.

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

Ideally $y(t) = x(t)$.

Phase distortion too (phase delay) (root delay)

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

due to reflection, shadowing, scattering we have multiple paths.

$L(t)$: number of propagation paths

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

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

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

All these quantities are function of time.

$$y(t) = \rho e^{j\theta} x(t-\tau) + n(t)$$ → additive white gaussian noise

ρ attenuation; $e^{j\theta}$ phase rotation; τ delay

We need to simplify this formula. 1. For the time being let's remove the time dependency.

The easiest multiple path channel is 2, so let's look at it.

(Preliminary) classification of the wireless channel*

Time domain:

- **static** (time-invariant): its statistics change very slowly wrt signaling time
- **time-varying**: its statistics are a function of time

Frequency domain:

- **frequency-flat**: its behavior is similar across the frequency components of the signal
- **frequency-selective**: each frequency component of the signal is distorted in a different way by the wireless channel

Static frequency-flat channels* (1/3)

A **static** channel means: the random processes $L(t), \{\rho_\ell(t)\}, \{\theta_\ell(t)\}$, and $\{\tau_\ell(t)\}$ are **not** functions of time (i.e., they are just **random variables**):

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

Let us suppose that the standard deviation $\sigma_\tau = \sqrt{\mathbb{E}\{|\tau_\ell - \overline{\tau}|^2\}}$ is **much smaller** than the **signaling interval** T, where $\overline{\tau} = \mathbb{E}\{\tau_\ell\}$:

$$\sigma_\tau \ll T$$

With good accuracy, we can approximate

$$\boxed{\tau_\ell \approxeq \overline{\tau} \quad \forall \ell}$$

Static frequency-flat channels* (2/3)

Hence,

$$y(t) = \sum_{\ell=1}^{L} \rho_\ell e^{j\theta_\ell} x(t - \tau_\ell) \approxeq x(t - \overline{\tau}) \cdot \sum_{\ell=1}^{L} \rho_\ell e^{j\theta_\ell}$$

$$= \overline{\rho} e^{j\overline{\theta}} x(t - \overline{\tau})$$

where

$$\overline{\rho} = \left| \sum_{\ell=1}^{L} \rho_\ell e^{j\theta_\ell} \right|, \qquad \overline{\theta} = \angle \left(\sum_{\ell=1}^{L} \rho_\ell e^{j\theta_\ell} \right)$$

In practice, the received signal is just a scaled copy of the transmitted signal $x(t)$, delayed by $\overline{\tau}$, attenuated by $\overline{\rho}$, and rotated by $\overline{\theta}$

Static frequency-flat channels* (3/3)

This happens for **each frequency component** of the input signal $x(t)$:

$$Y(f) \triangleq \mathcal{F}\{y(t)\} = \mathcal{F}\left\{\bar{\rho}e^{j\bar{\theta}}x(t-\bar{\tau})\right\}$$
$$= \bar{\rho}e^{j\bar{\theta}}e^{-j2\pi f\bar{\tau}}X(f)$$

where

$$X(f) \triangleq \mathcal{F}\{x(t)\} = \int_{-\infty}^{+\infty} x(t)\,e^{-j2\pi ft}dt$$

is the **Fourier transform** of the signal $x(t)$

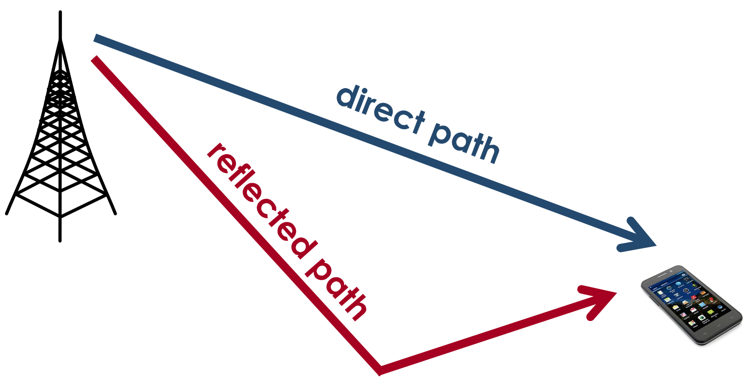
If $\sigma_\tau \ll T$, the channel is **frequency-flat**: $H(f) = \dfrac{Y(f)}{X(f)} = \bar{\rho}e^{j\left(\bar{\theta}-2\pi f\bar{\tau}\right)}$

Static frequency-selective channels (1/4)

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

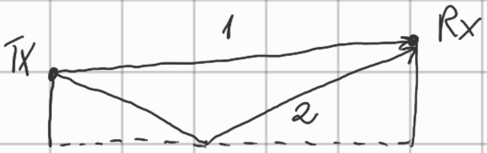
$$y(t) = \sum_{\ell=1}^{L} \rho_\ell e^{j\theta_\ell} x\left(t - \tau_\ell\right)$$

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



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

Two-ray channel:



$$y(t) = \underbrace{\rho_1 e^{j\theta_1} x(t-\tau_1)}_{\text{① Line of sight (because there is no obstacle)}} + \overbrace{\rho_2 e^{j\theta_2} x(t-\tau_2)}^{\text{2-ray channel}}$$

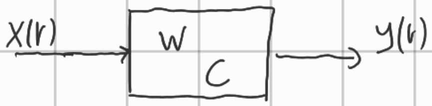
Easiest case, $\rho_1 = 1$, $\theta_1 = 0$, $\tau_1 = 0$. Best case

So $y(t) = x(t) + \rho e^{j\theta} x(t-\tau)$

↳ scaled, delayed and rotated.

Move to the frequency domain:

You can imagine channel as a system that takes an input and generates an output:



$y(t) = h(t) \otimes x(t)$

↳ impulse response of the system

$Y(f) = H(f)\,X(f)$

↳ fourier transform of the impulse domain. It's easier to study.

Let's try to find the relationship between $Y(f)$ and $X(f)$.

$$Y(f) = X(f) + \mathcal{F}\{\rho e^{j\theta} x(t-\tau)\} = X(f) + \rho e^{j\theta} e^{-2\pi j f \tau} X(f)$$

$$\int_{-\infty}^{+\infty} \rho e^{j\theta} x(t-\tau) e^{-2\pi j f t}\, dt = \rho e^{j\theta} \int_{-\infty}^{+\infty} x(t-\tau) e^{-2\pi j f t}\, dt = \rho e^{j\theta} e^{-2\pi j f \tau} X(f)$$

$t-\tau = y$, $t = (y+\tau)$

So, $$Y(f) = X(f)\underbrace{\left[1 + \rho e^{j\theta} e^{-j2\pi f \tau}\right]}_{H(f)\text{, Fourier transform of the 2-ray channel}}$$

So $H(f) = 1 + p e^{j\theta} e^{-j2\pi f \tau} = 1 - p e^{j\pi} e^{j\theta} e^{-j2\pi f \tau} =$

$= 1 - p e^{-j2\pi\left(f - \frac{1}{2\tau} - \frac{\theta}{2\pi\tau}\right)\tau}$ $\underline{\underline{f_N = \frac{1}{2\tau} + \frac{\theta}{2\pi\tau}}}$ notch frequency

$1 - p e^{-j2\pi(f - f_N)\tau}$

So let's compute $|H(f)|$: $\left(|1 + a e^{jb}| = \sqrt{1 + a^2 + 2a\cos(b)} \right)$

$= \sqrt{1 + p^2 - 2p\cos(2\pi(f - f_N)\tau)}$

$\cos(-\alpha) = \cos(\alpha)$

If $p = 0$, then $|H(f)| = 1$: so what you put in the input is exactly what you get in the output!

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

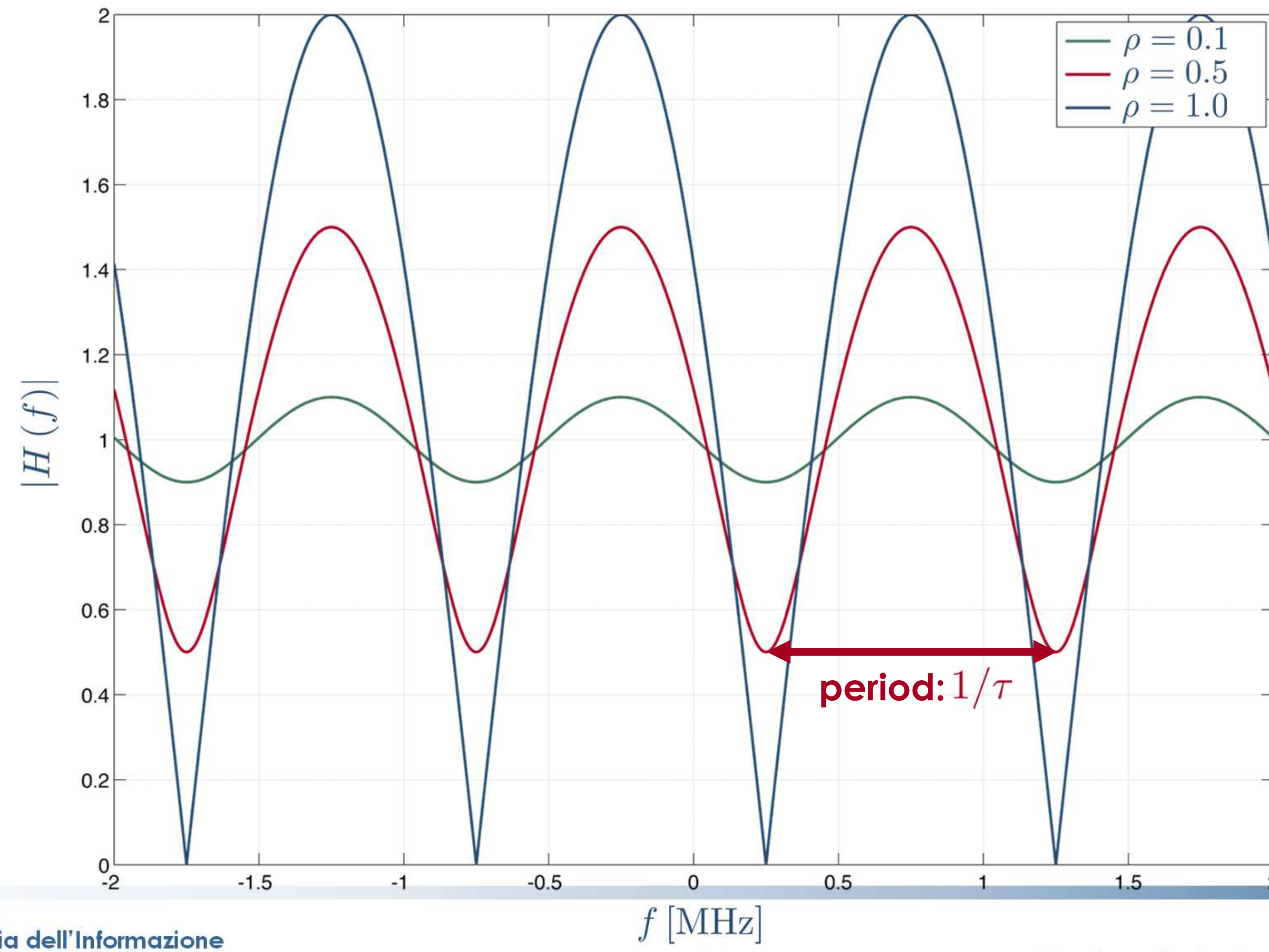
$$H(f) = \frac{Y(f)}{X(f)} = 1 - \rho e^{-j2\pi (f - f_{\mathrm{N}})\tau}$$

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

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



$\tau = 1\ \mu\text{s}$

$f_{\mathrm{N}} = 0.25\ \text{MHz}$

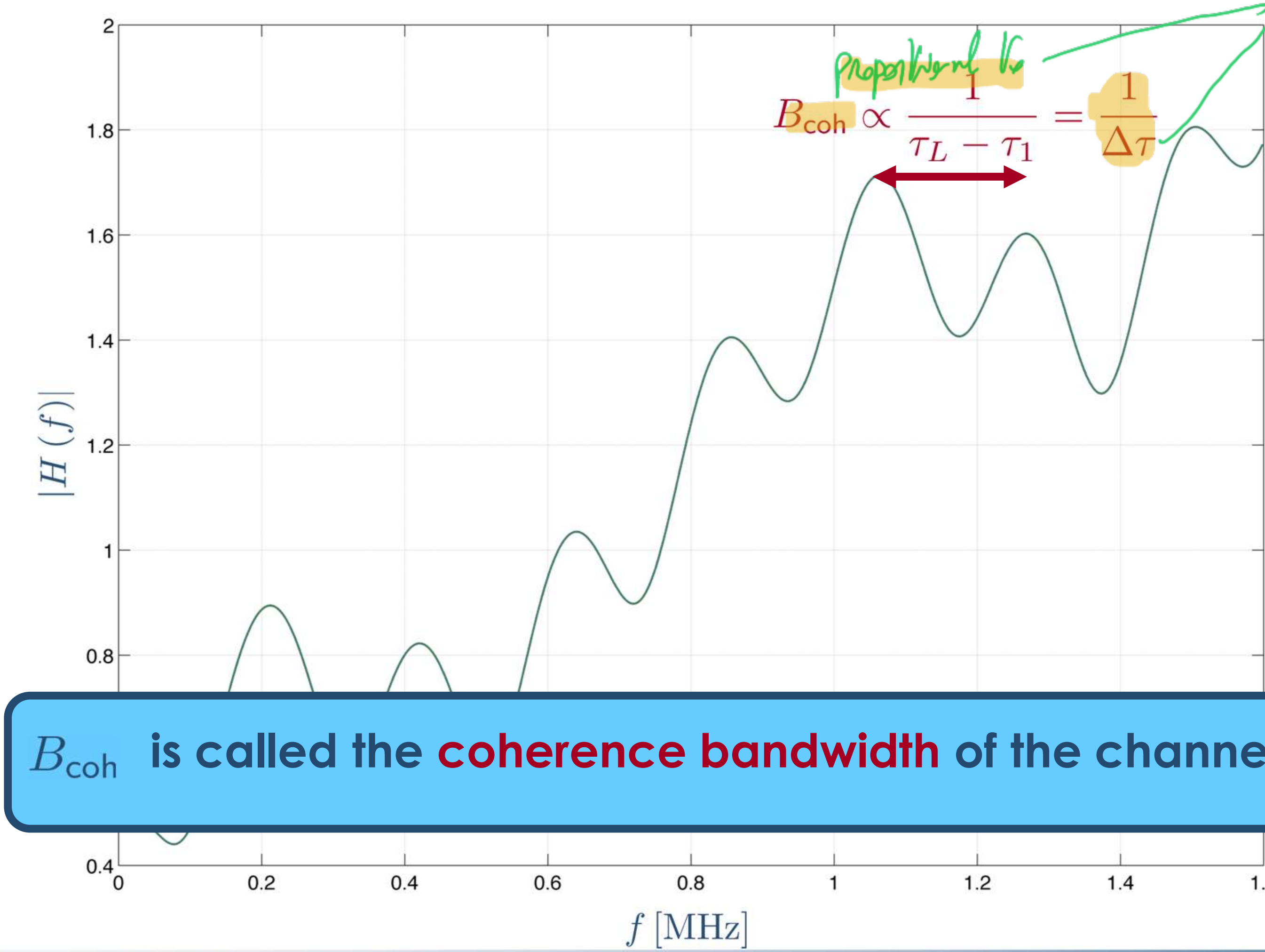
$\theta = -\pi/2$

When p is close to 0, the channel is close to 1 and it's not too much of a problem. If p gets bigger, with small variations of frequencies you have the channel changing a lot. But the damage depends on your signal: if my bandwidth is narrow with respect to the "speed" of the spectrum.

If band is narrow, $Y(f) = H(f)X(f) \approx Y(f) = H(f_0)X(f_0)$

Static frequency-selective channels (4/4)

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



proportional to

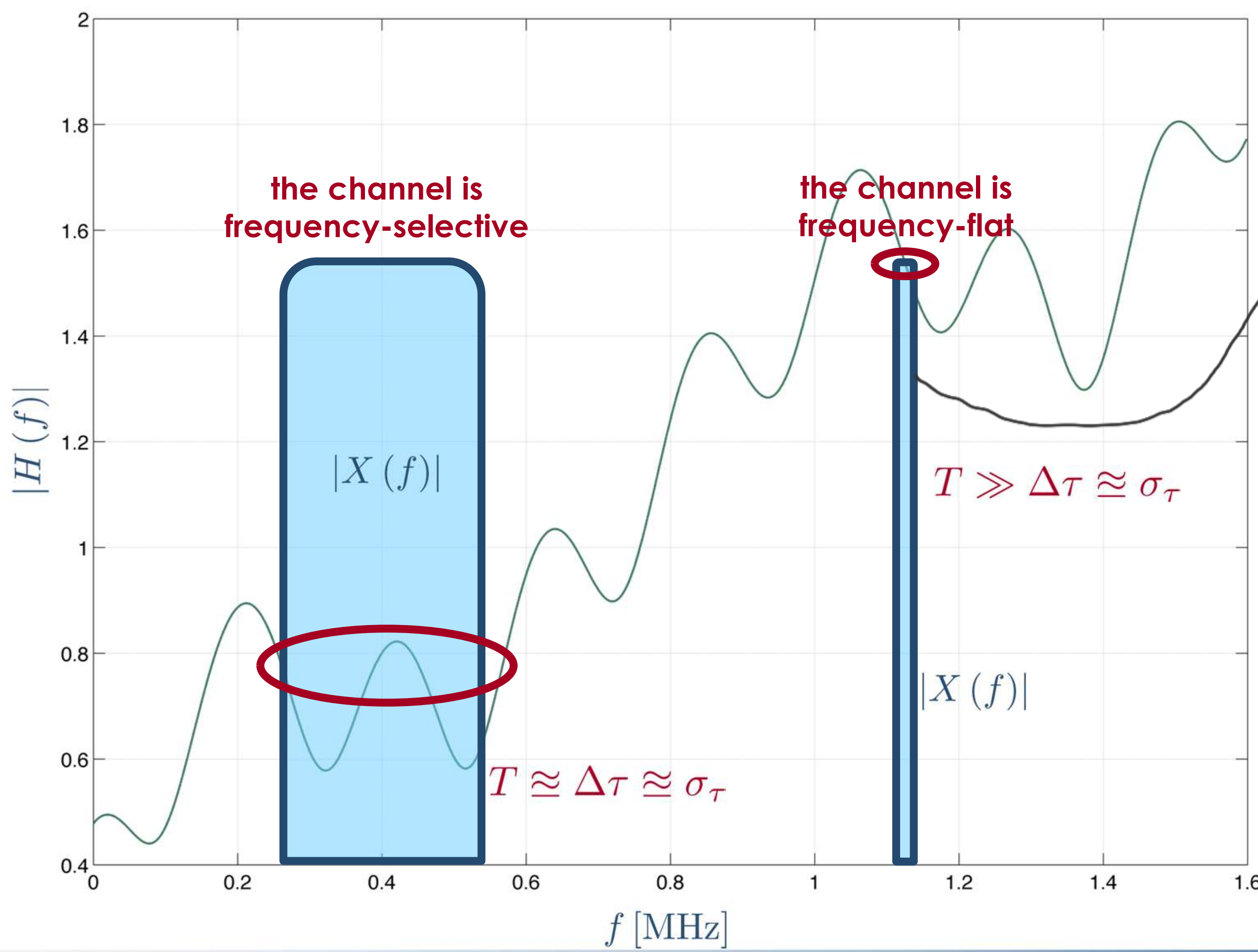
$$B_{\text{coh}} \propto \frac{1}{\tau_L - \tau_1} = \frac{1}{\Delta\tau}$$

difference between shortest and longest delay. Then you compare this with the bandwidth of the signal.

B_{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 $B \propto 1/T$



my channel is almost flat.

Communication Technologies (24/25) WCY-LM M.Sc. Cybersecurity

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:

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

if the B of my signal is much smaller than the coherence bandwidth (inverse of the difference between the slowest path and the fastest path) (delay of 0 vs delay of τ)

Example:

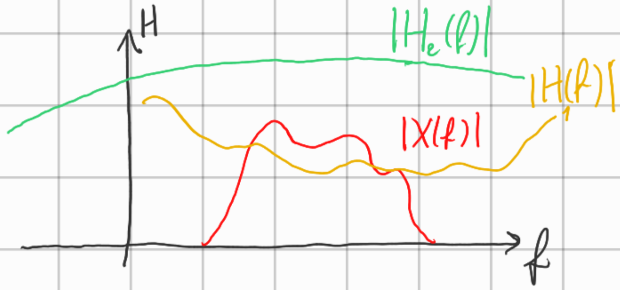
- **urban scenarios:** $\sigma_\tau \approxeq 1\,\mu\text{s} \Rightarrow B_{\text{coh}} \approxeq 1\,\text{MHz}$ which is the period of $|H(f)|$.
- **4G and 5G signals:** $B \geq 1.5\,\text{MHz}$

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

LEZIONE 12 END

If $B \ll B_{coh}$, the rays arrive so close that I consider them one signal.

I don't have distortion for the signal, I only have a multiplication of a value.



$$|Y(f)| = |H(f)| \cdot |X(f)|$$

$H_1(f)$ changes the shape of a signal. The channel introduces a distortion called frequency selectivity because it behaves differently for diff. frequencies.

For $H_2(f)$ the distortion is very weak so I can neglect the distortion.

In an urban scenario $\Delta\tau = 10^{-6}s$, so $\frac{1}{\Delta\tau} = 1\,MHz$

Idea => $Y(f) \approx X(f)\,H(f_0)$, so just a constant to be compensated.

can also pretty much consider it equal.

NOTE: $B_{coh} \stackrel{=}{\propto} \frac{1}{\Delta\tau}$. In case of multiple signals and not just two, $B_{coh} \stackrel{\sim}{\propto} \frac{1}{\Delta\tau}$

$B_{coh} \gg B$

Channel can be frequency-flat or frequency selective based on the input signal.

NOTE: ideally you'd want to increase the bandwidth! But then we have more frequency selectivity in channels.

In general, when dealing with fs*, you have $Y(f) = X(f)H(f)$. If you could estimate $H(f)$, you can get $X(f)$ back. This is what CHANNEL EQUALIZATION DOES.
1st issue, you need $H(f)$ but all you get is an estimation. This because all systems today are frequency selective.

Multipath propagation: time selectivity

The transmitter and receiver might change their position or the surrounding environment might change. You cannot get rid of 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 ℓ-th path

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

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

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:

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

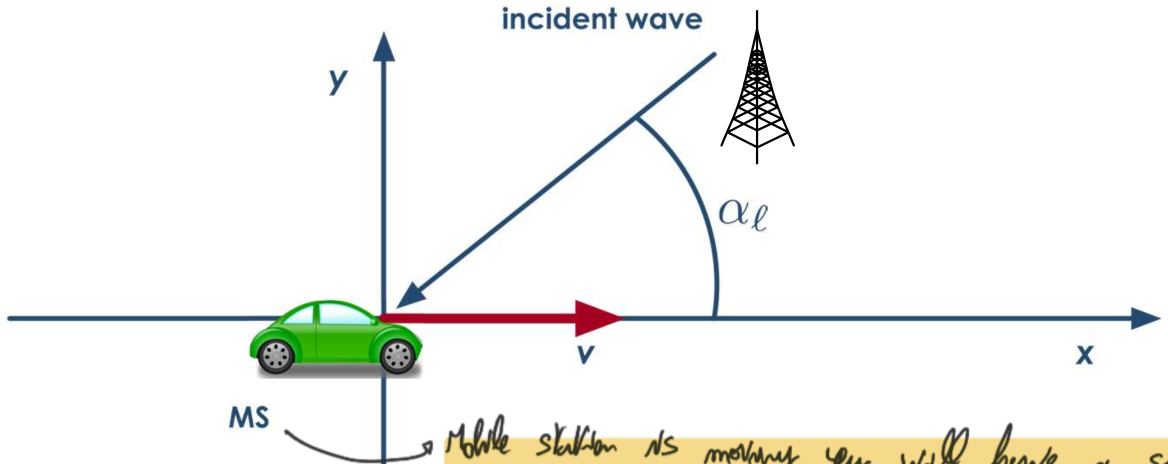
For simplicity, let's assume a frequency-flat channel: $\sigma_\tau \ll T \Rightarrow \tau_\ell(t) \approxeq \overline{\tau} \quad \forall \ell$

Similarly to the static case,

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

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:



Mobile station is moving, you will have a shift that is function of shift and speed. (Relative speed between T_x, R_x)

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** Δf:

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

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

Giacomo Bacci

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

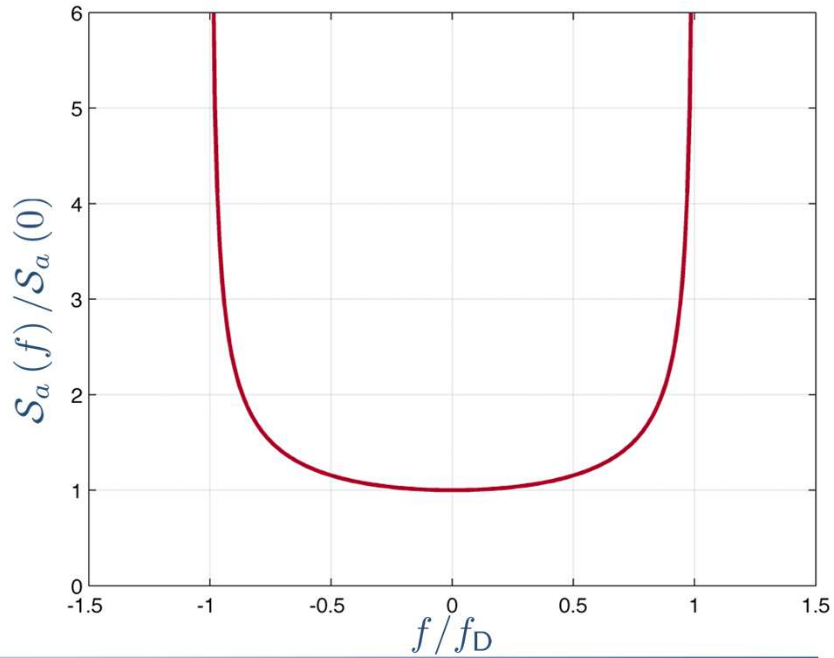
The behavior of $A(t)$ is given by the impact of the Doppler effect over all signal frequency components $f \in \left[f_0 - \frac{B}{2}, f_0 + \frac{B}{2}\right]$

A key parameter is the maximum Doppler shift at the carrier frequency f_0, called the Doppler spread f_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 $A(t)$:

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

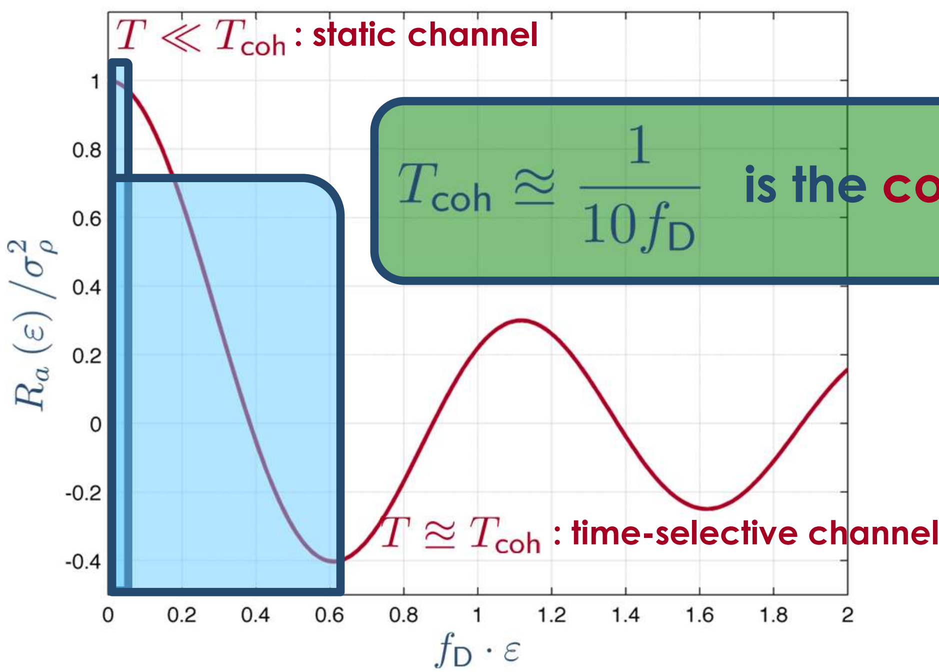


Time-varying frequency-flat channels (4/4)

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,



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

Autocorrelation is a measure of how a signal is similar to itself. This can be done with channel too.
It can be shown that after the coherence time the channel is completely different from itself. It tells you how fast the channel is changing. If the coherence time is big, the channel is not changing much.

How to measure? Inverse of 10 - The doppler spread, which is the maximum shift of the doppler effect. $f_D \triangleq \max_{d_e} |\Delta f| = \frac{V}{c} \cdot f_0 \Rightarrow T_{coh} = \frac{1}{10 f_D} = \frac{1}{10 \cdot \frac{V}{c} f_0}$. So increasing the speed lowers the coherence time. So if my channel is changing very quickly I need to refresh my channel estimation very frequently. In general, I take a max speed and design the channel to work with a minimum T_{coh}, so I know how frequently I need to re-estimate.

EX: $V = 300\ km/h$, $f_0 = 3GHz$ $\quad T_{coh} = \frac{3 \cdot 10^8\ m/s}{10 \cdot 300\ km/h \cdot 3 \cdot 10^9\ Hz} = \frac{3.6 \cdot 10^8}{3000 \cdot 10^8} = \frac{10^{-2} \cdot 3.6}{3 \cdot 10^2} =$

$= 1.2 \cdot 10^{-4} s = 0.12\ ms$

So, if the time interval $T \ll T_{coh}$, then the channel is static.
If $B \gg f_D \Leftrightarrow T \ll T_{coh}$: Channel is STATIC
If $B \simeq f_D \Leftrightarrow T \simeq T_{coh}$: time-selective 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)

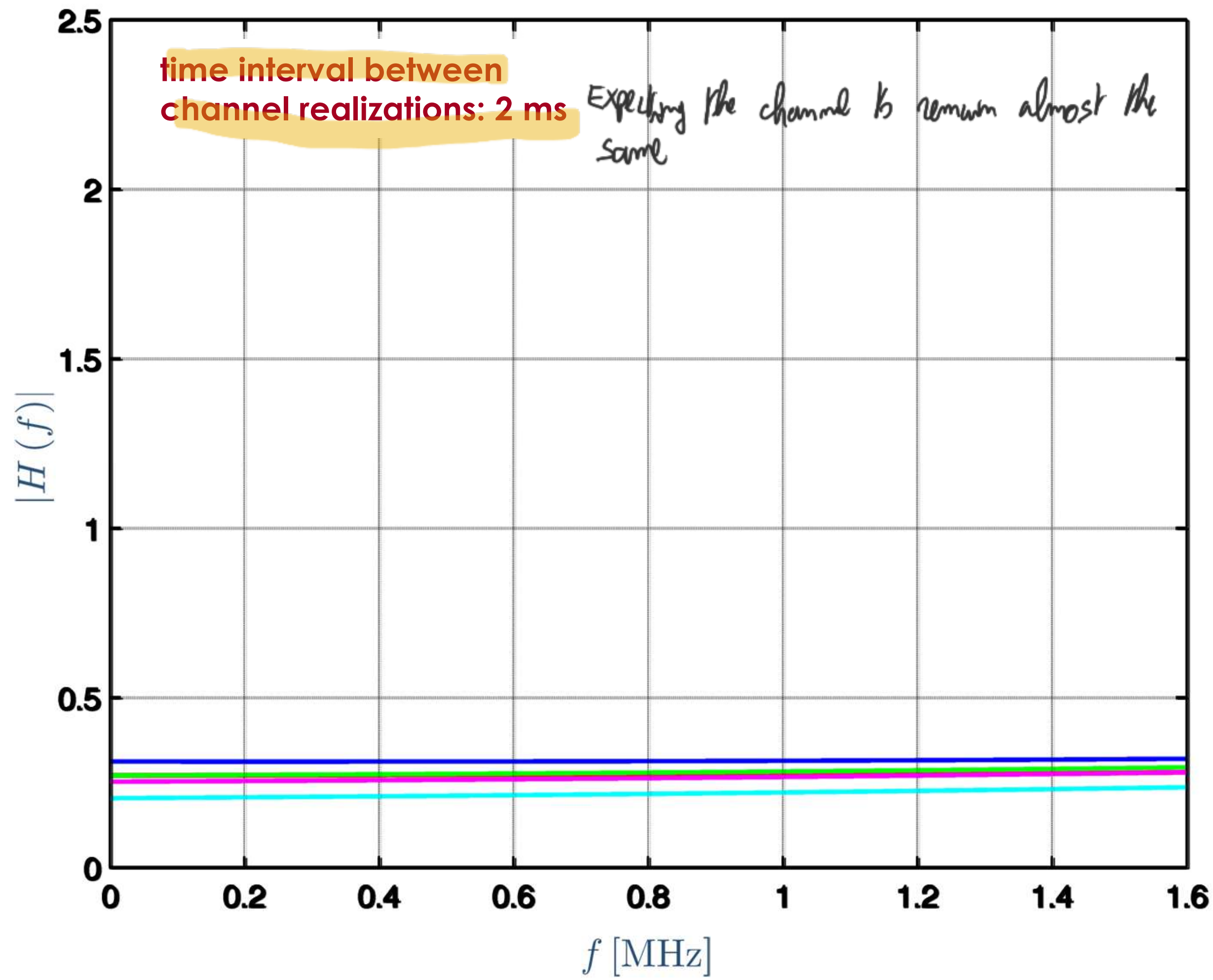
Both time- and frequency-selectivity are functions of **both** the channel and the input signal properties:

	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!

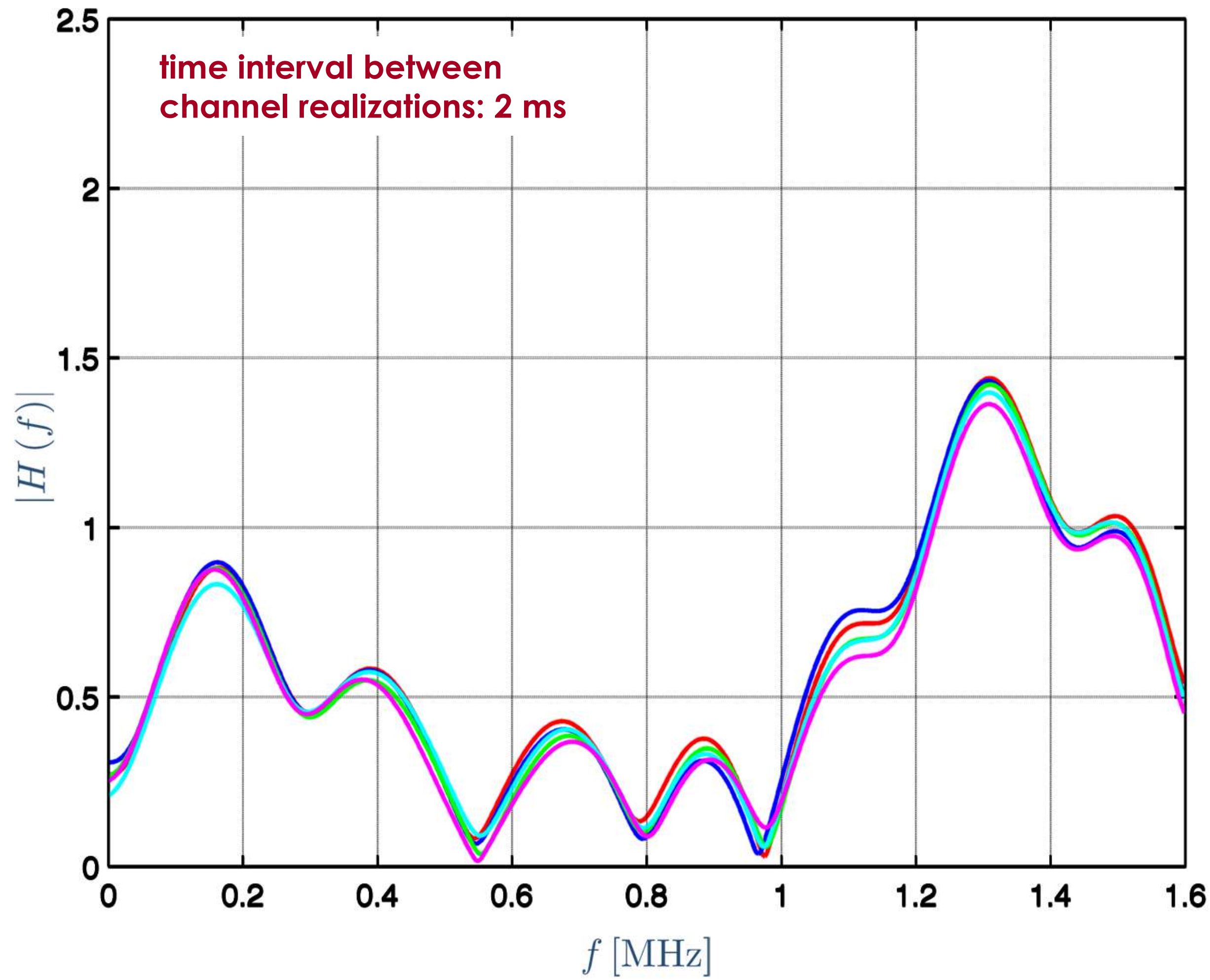
Frequency and time selectivity: A summary (2/5)

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



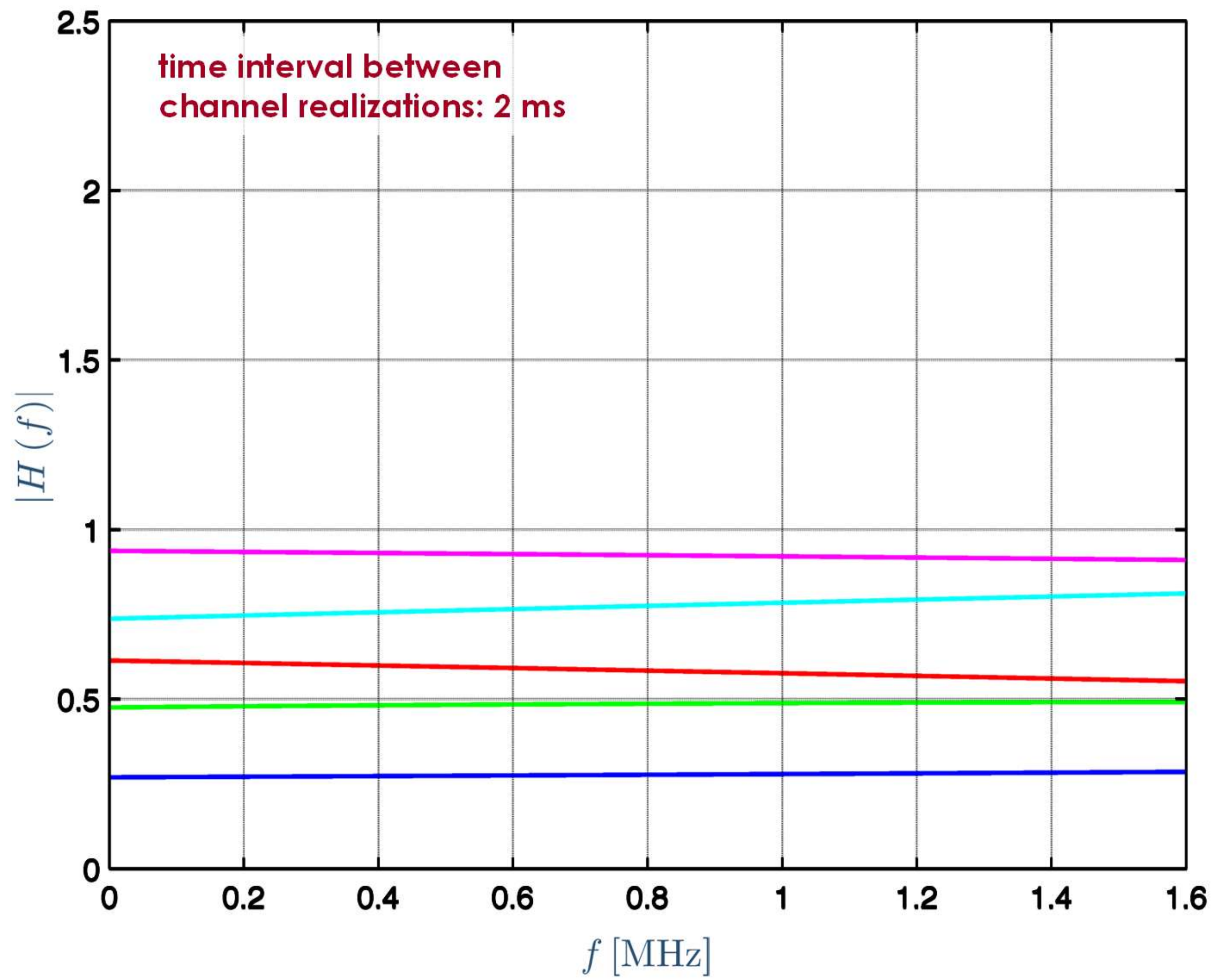
Frequency and time selectivity: A summary (3/5)

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



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

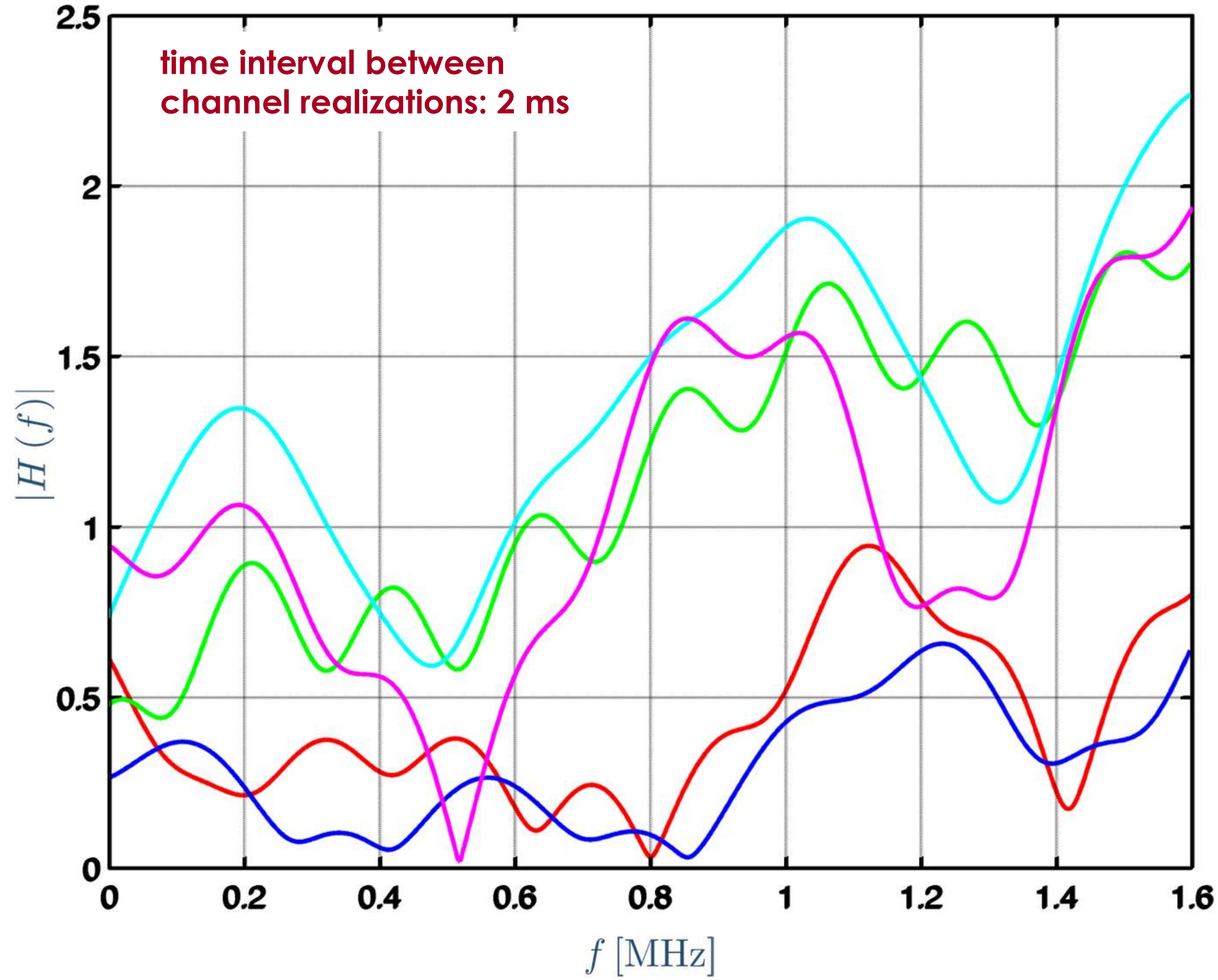
A time-selective frequency-flat channel ($T_{\text{coh}} = 1\,\text{ms}, B_{\text{coh}} = 10\,\text{MHz}$):



Communication Technologies (24/25) WCY-LM M.Sc. Cybersecurity

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

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



Bibliography

[01] B. Sklar and F. Harris, *Digital Communications* , 3rd ed. Upper Saddle River, NJ, US: Prentice Hall, 2021.

[02] J.G. Proakis and M. Salehi, *Digital Communications,* 5th ed. New York, NY: McGraw-Hill, 2007.

[03] M. Luise, *The wireless communications engineer's toolkit*. Pisa, Italy, Oct. 2021. [Online] http://www.iet.unipi.it/m.luise/Signals_Systems.pdf

[04] T.S. Rappaport, *Wireless Communications: Principles and Practice,* 2nd ed. Upper Saddle River, NJ: Prentice-Hall, 2002.

[05] A.J. Goldsmith, *Wireless Communications*. Cambridge, UK: Cambridge Univ. Press, 2005.

[06] A.F. Molisch, *Wireless Communications*. West Sussex, UK: J. Wiley & Sons, 2005.

[07] J.D. Parsons, *The Mobile Radio Propagation Channel.* Chichester, UK: J. Wiley & Sons, 2000.

[08] M. Pätzold, *Mobile Fading Channels.* Chichester, UK: J. Wiley & Sons, 2002

CONTINUE