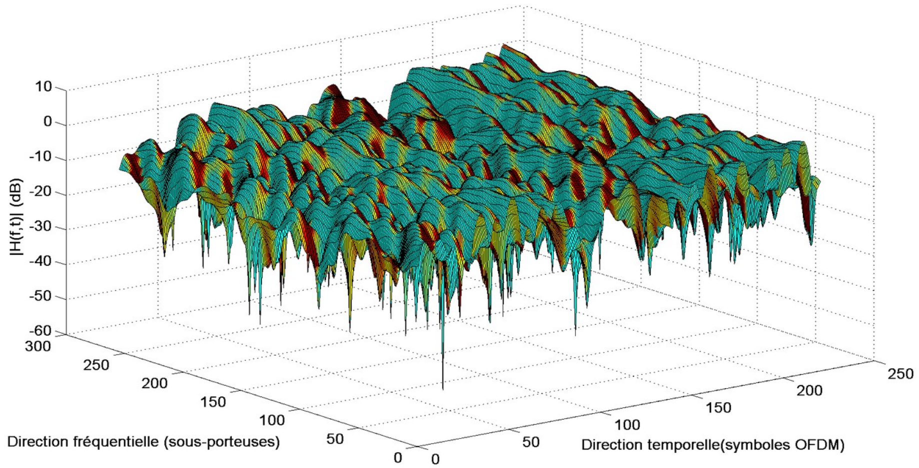
The mobile radio channel: a review



Hervé Boeglen F4JET – SDRA 2022

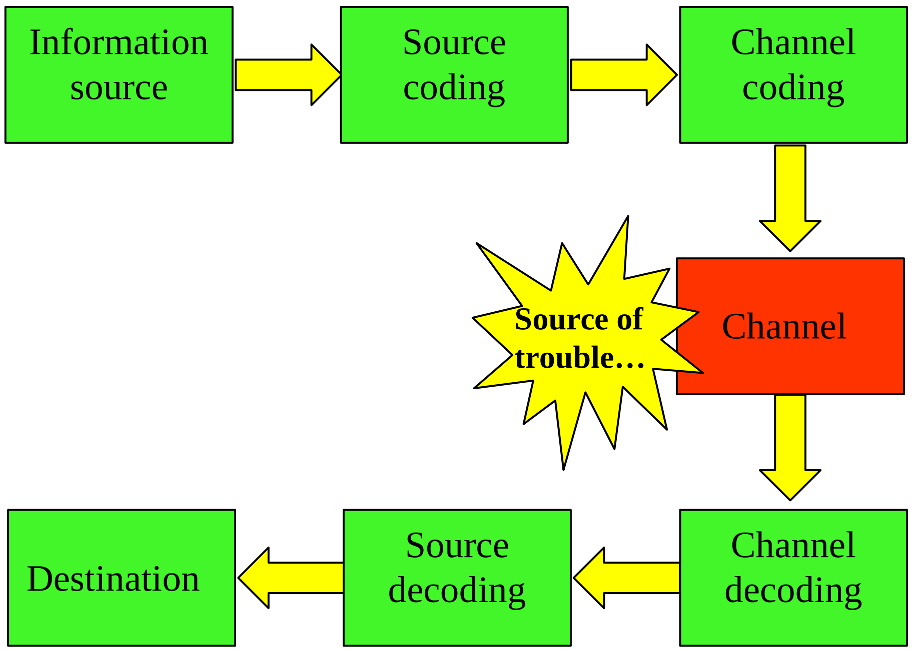
L'Europe s'engage en Nouvelle-Aquitaine avec le Fonds européen de développement régional

Outline

- 1. Introduction
- 2. Modeling the mobile radio channel
- 3. Simulation techniques
- 4. Conclusion

1. Introduction

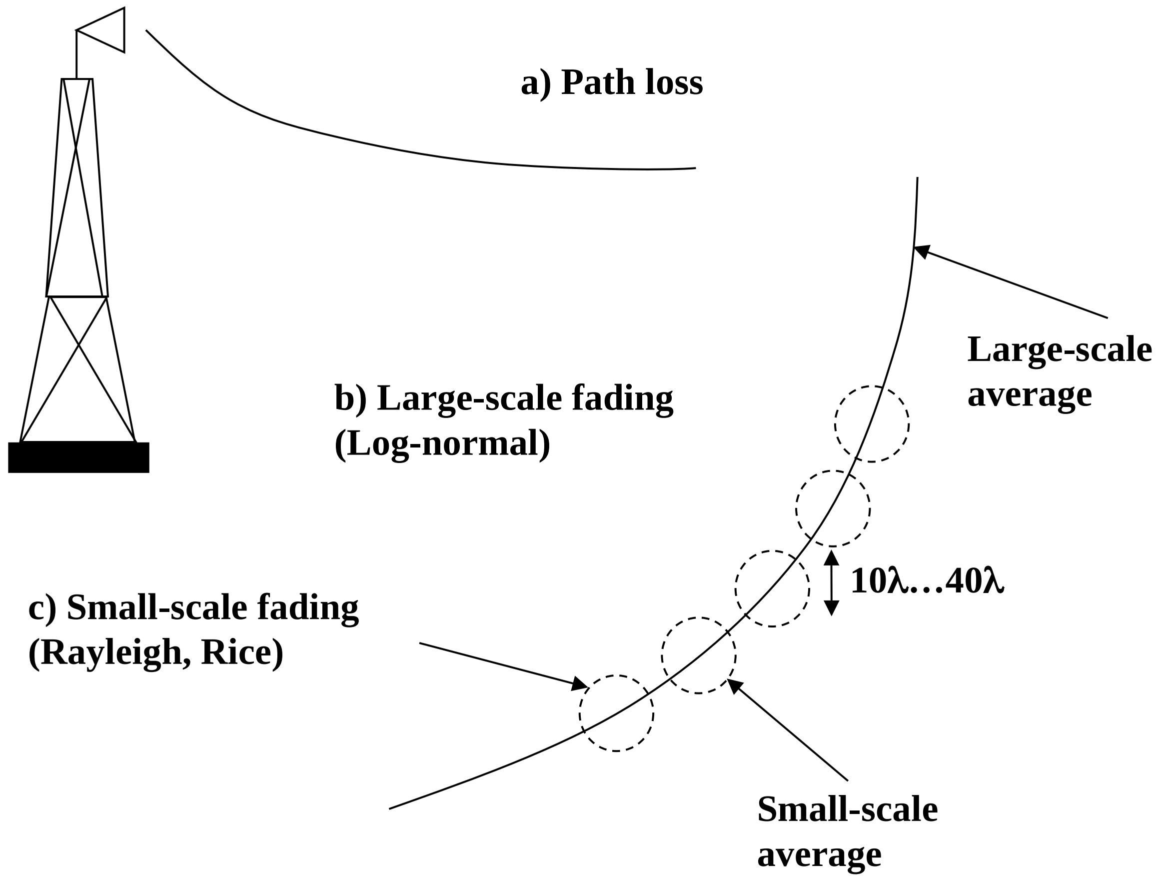
- 1948 C. Shannon « *A Mathematical Theory of Communication* » :



- Channel coding techniques (e.g. OFDM) depend on channel behaviour (e.g. to fight against frequency selectivity).

1. Introduction

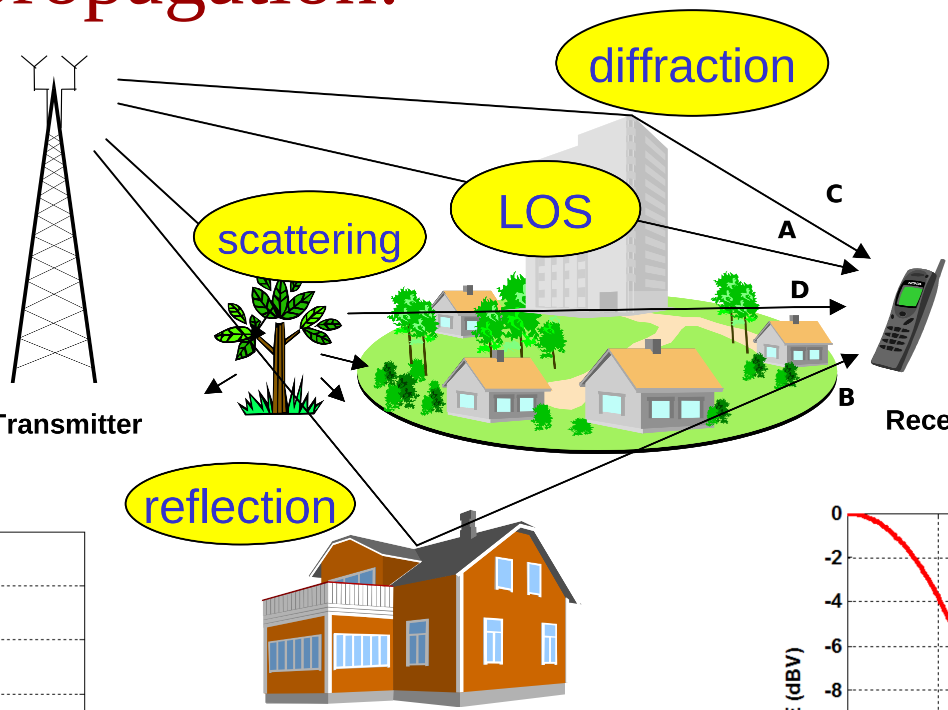
- Types of receive power variations:



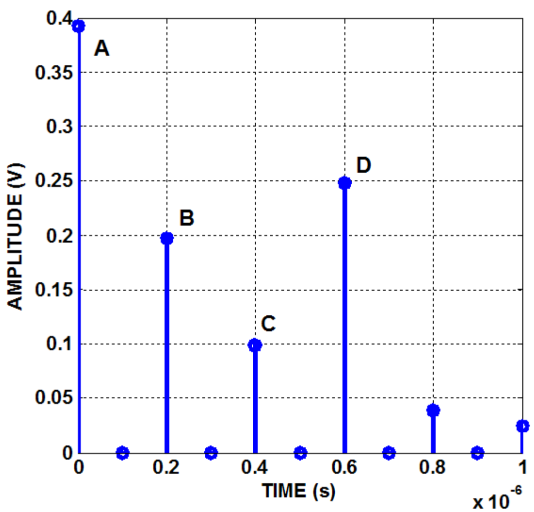
- We are interested in the small-scale behaviour

2. Modeling the mobile radio channel

➢ Multipath propagation:

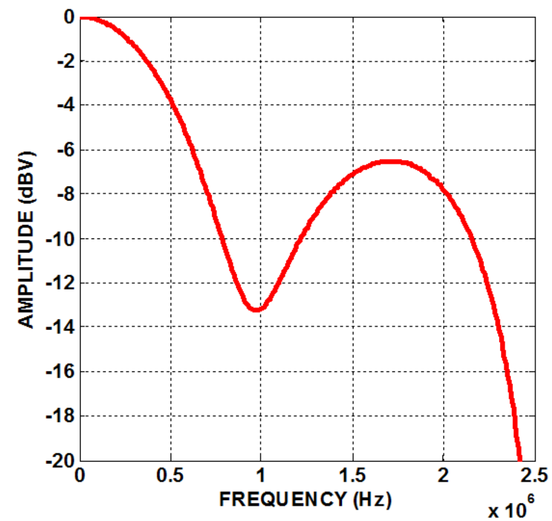


CIR = h(τ)



FT

TF = H(f)



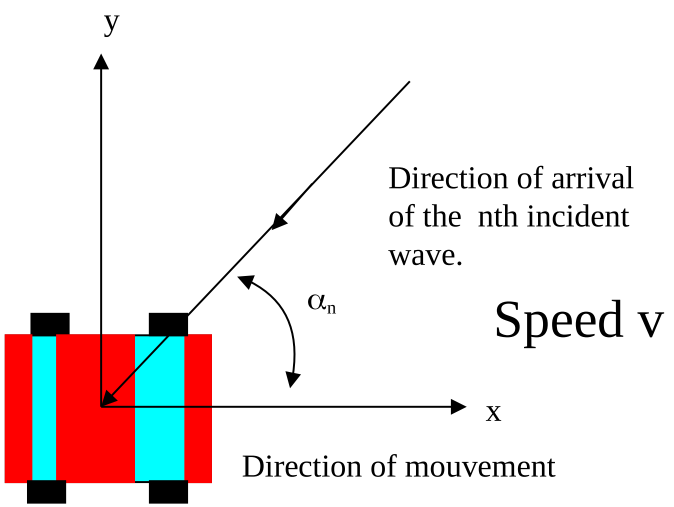
➔ Spectrum distorsion of the transmitted signal

2. Modeling the mobile radio channel

➤ Doppler effect (T and/or R are moving) :

$$f_n = f_{max}.\cos(\alpha_n)$$

$$f_{max} = \frac{v}{c_0} \cdot f_0$$



f_0 = carrier frequency

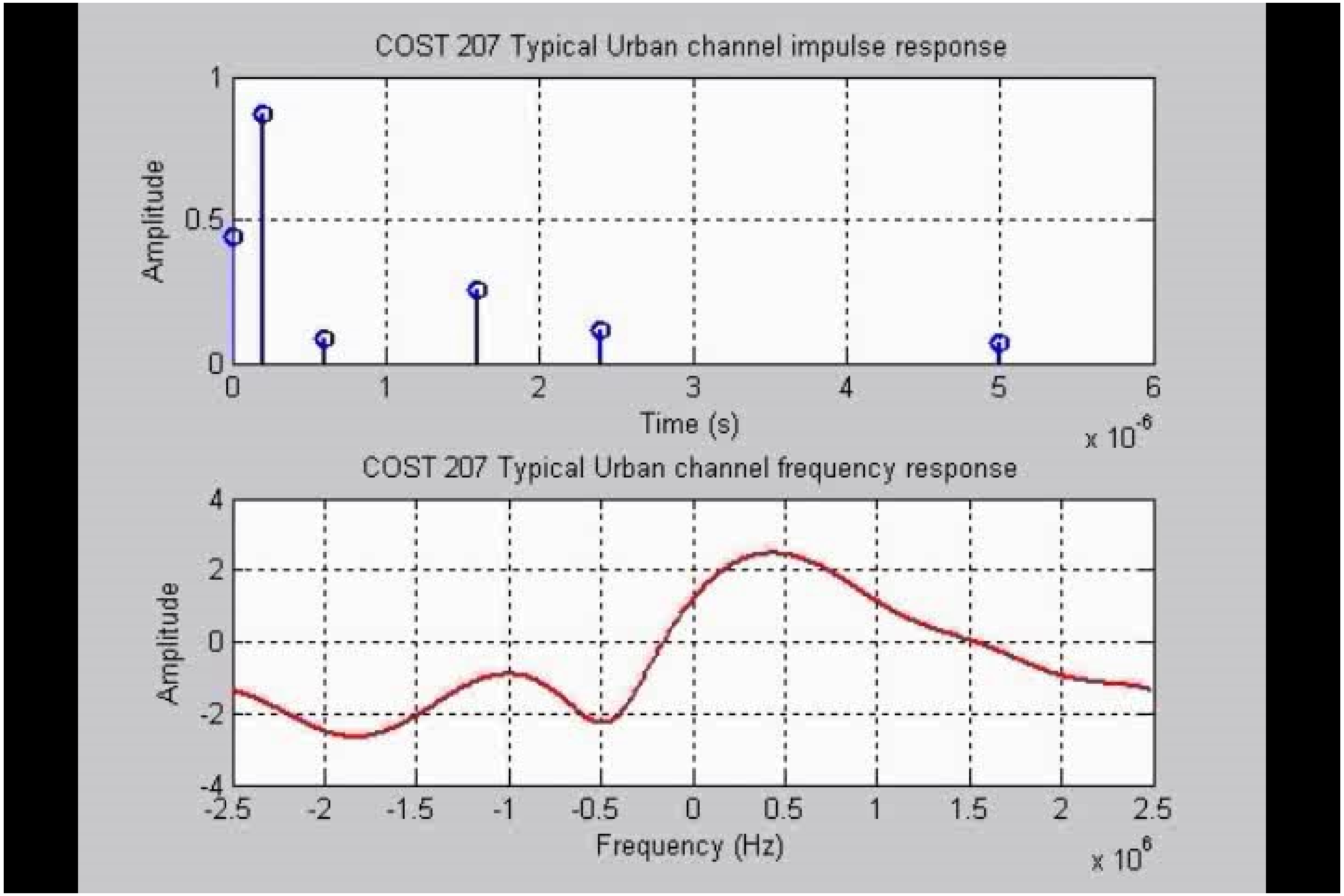
The transmitted signal spectrum undergoes a frequency expansion

➡

The CIR becomes time dependant

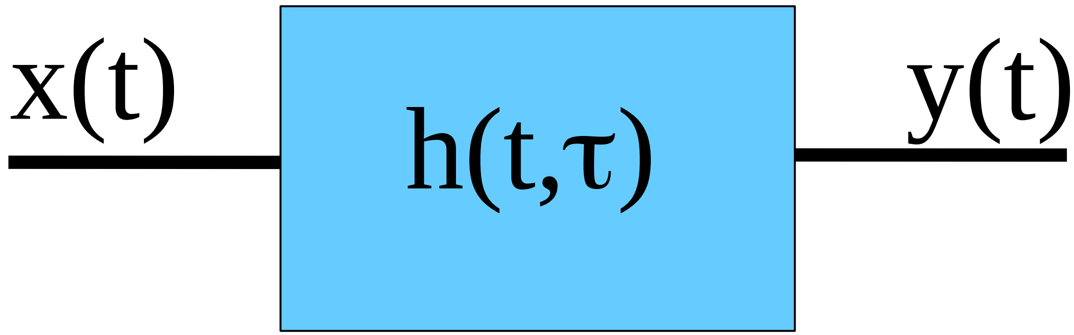
2. Modeling the mobile radio channel

- Doppler effect (T and/or R are moving) :



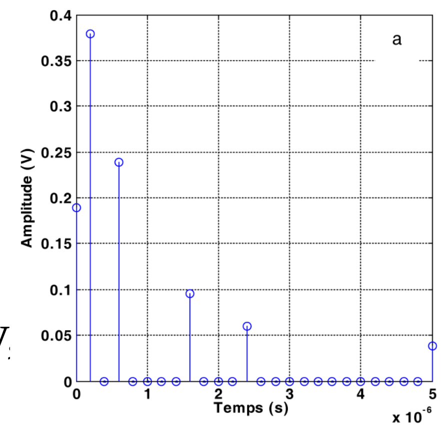
2. Modeling the mobile radio channel

- Mobile radio channel = linear system:



- Channel Impulse Response (CIR) :

$$h(\tau,t)=\sum_{n=0}^{N}\alpha_n(t)e^{-j\varphi_n(t)}\delta(\tau-\tau_n(t))$$



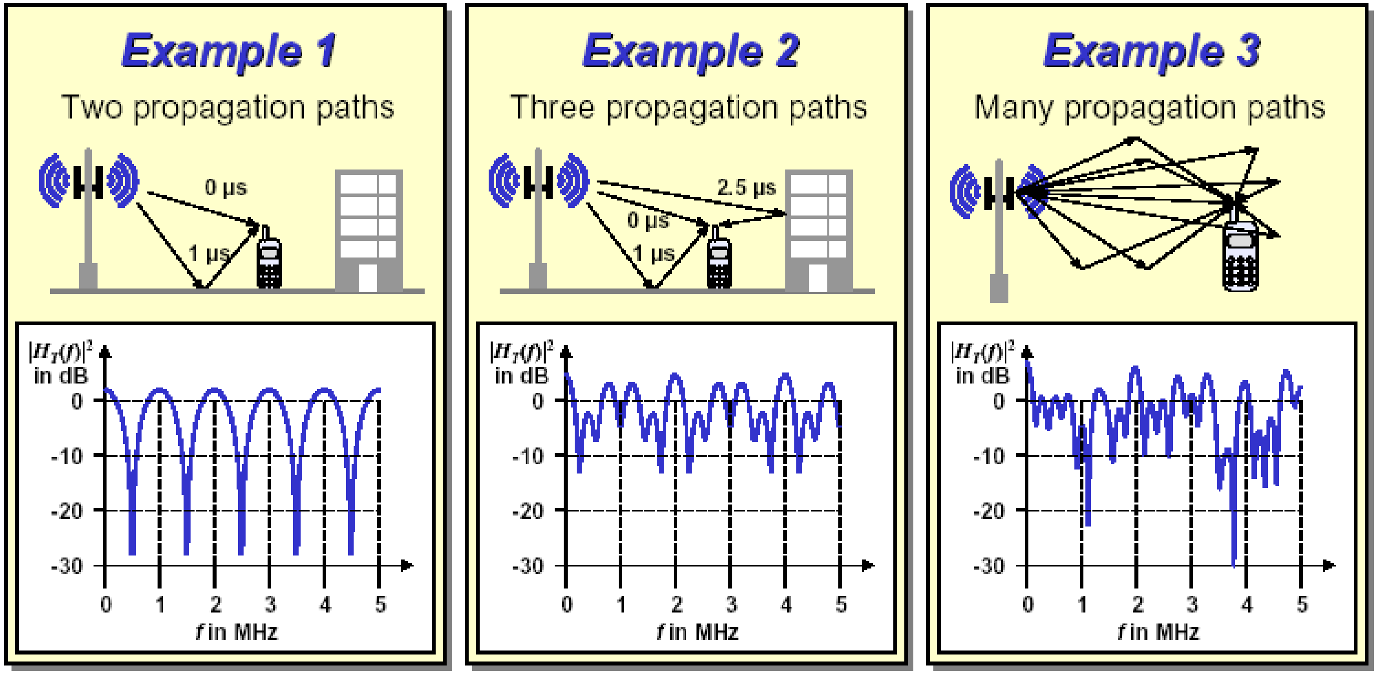
  - With N = number of paths, $\tau_n(t) = r_n(t)/c$ = n_{th} path delay, ϕ_n = n_{th} path phase shift (Doppler)and $\alpha_n(t)$ n_{th} path amplitude.

2. Modeling the mobile radio channel

- Two parameters can vary: τ and t
  - h(t, τ) does not depend on t:

$$h(\tau,t)=h(\tau)=\sum_{n=0}^{N}\alpha_n e^{-j\varphi_n}\delta(\tau-\tau_n)$$

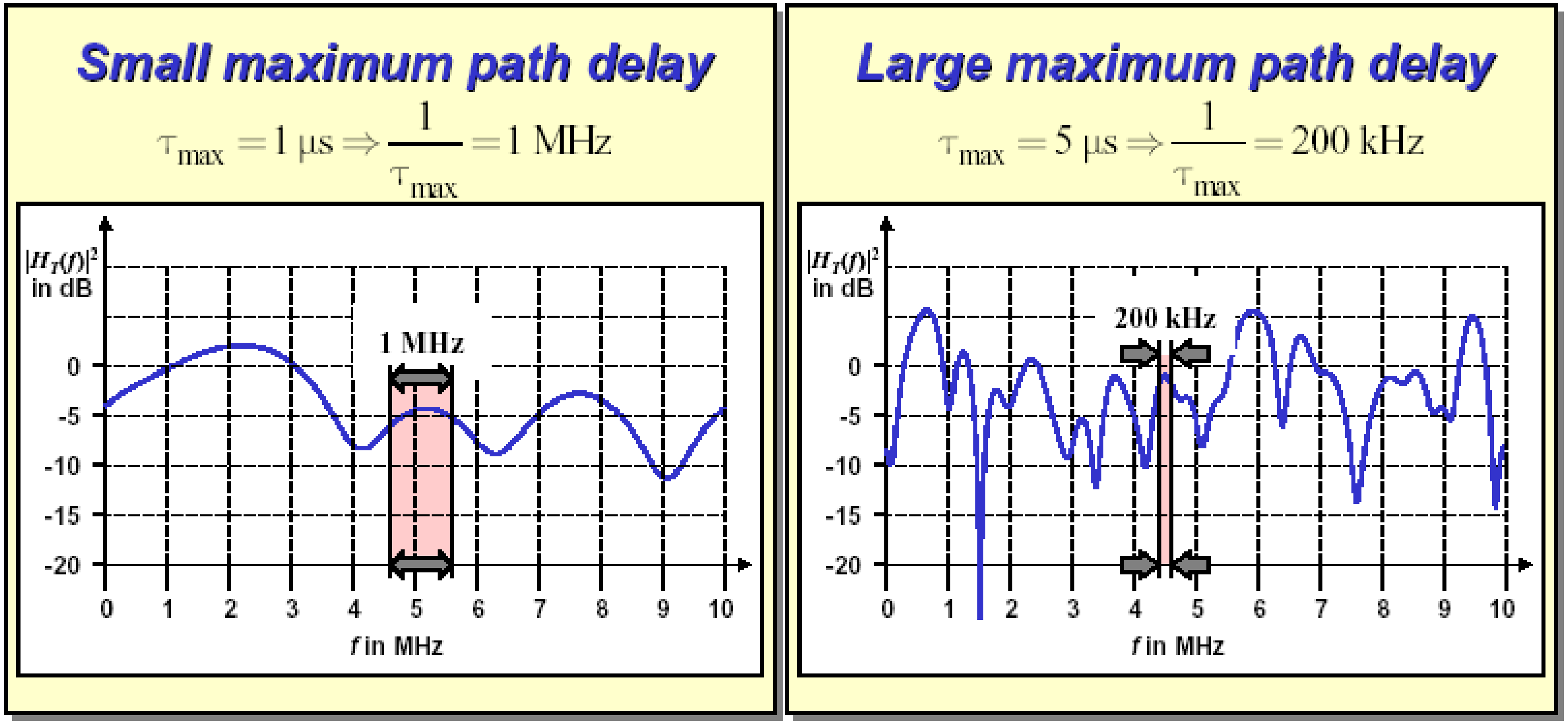
➔ Time invariant channel.



The signals coming from different paths interfere either constructively or destructively ➔ FREQUENCY SELECTIVITY.

2. Modeling the mobile radio channel

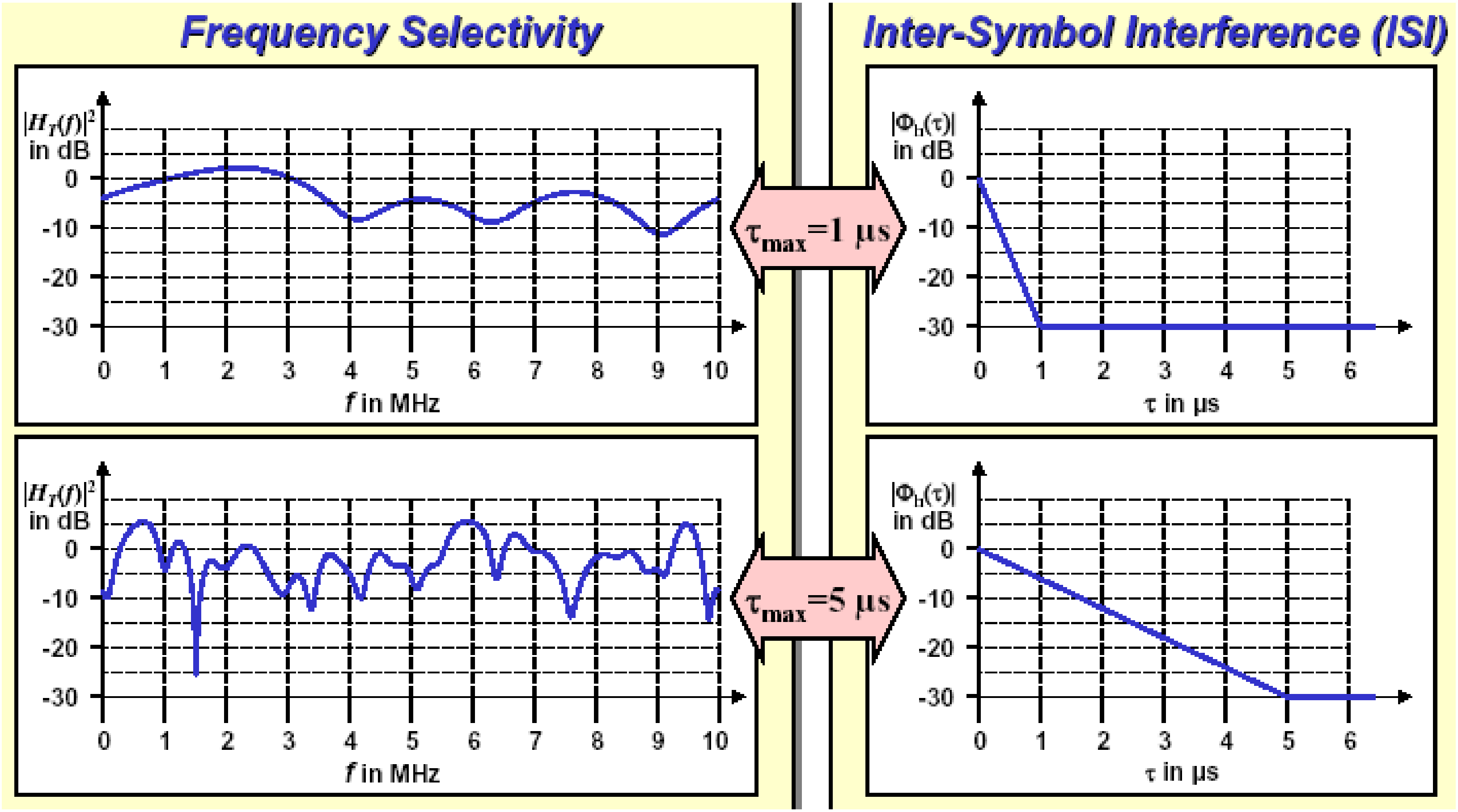
- Influence of the delays duration on the channel transfer function:



$\Rightarrow$ The larger τ_{max} the more selective the channel.

2. Modeling the mobile radio channel

- Frequency selectivity = ISI:



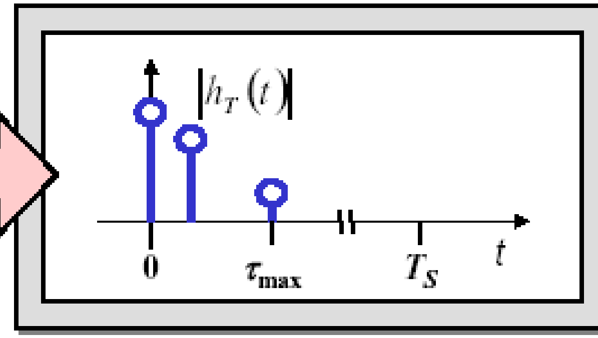
➔The more frequency selectivity, the more ISI.

2. Modeling the mobile radio channel

- At this point, we can distinguish two types of channels:
  - The narrowband channel:

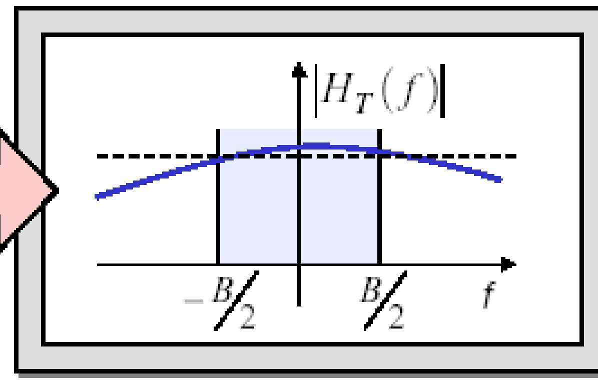
Symbol duration T_S is much larger than the maximum channel tap delay:

$$T_S \gg \tau_{\max}$$



Channel Transfer Function is assumed to be **constant** over the Signal Bandwidth *B*

$$\Rightarrow |H_T(f)| \approx const \text{ for } |f| \leq B \approx \frac{1}{T_S}$$



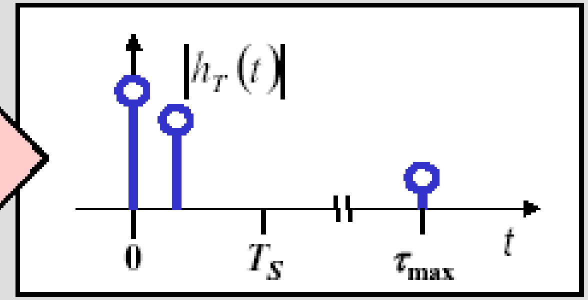
➔ Low frequency selectivity and therefore not much ISI.

2. Modeling the mobile radio channel

- The broadband channel:

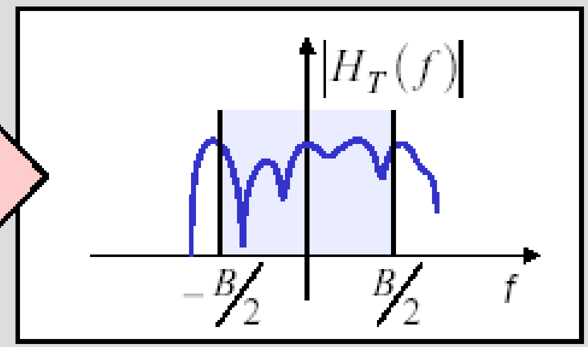
Symbol duration T_S is much smaller than the maximum channel tap delay:

$$\boxed{T_S \ll \tau_{max}}$$



Channel Transfer Function **fluctuates** over the Signal Bandwidth B

$$\Rightarrow |H_T(f)| \neq const \text{ for } |f| \leq B \approx \frac{1}{T_S}$$

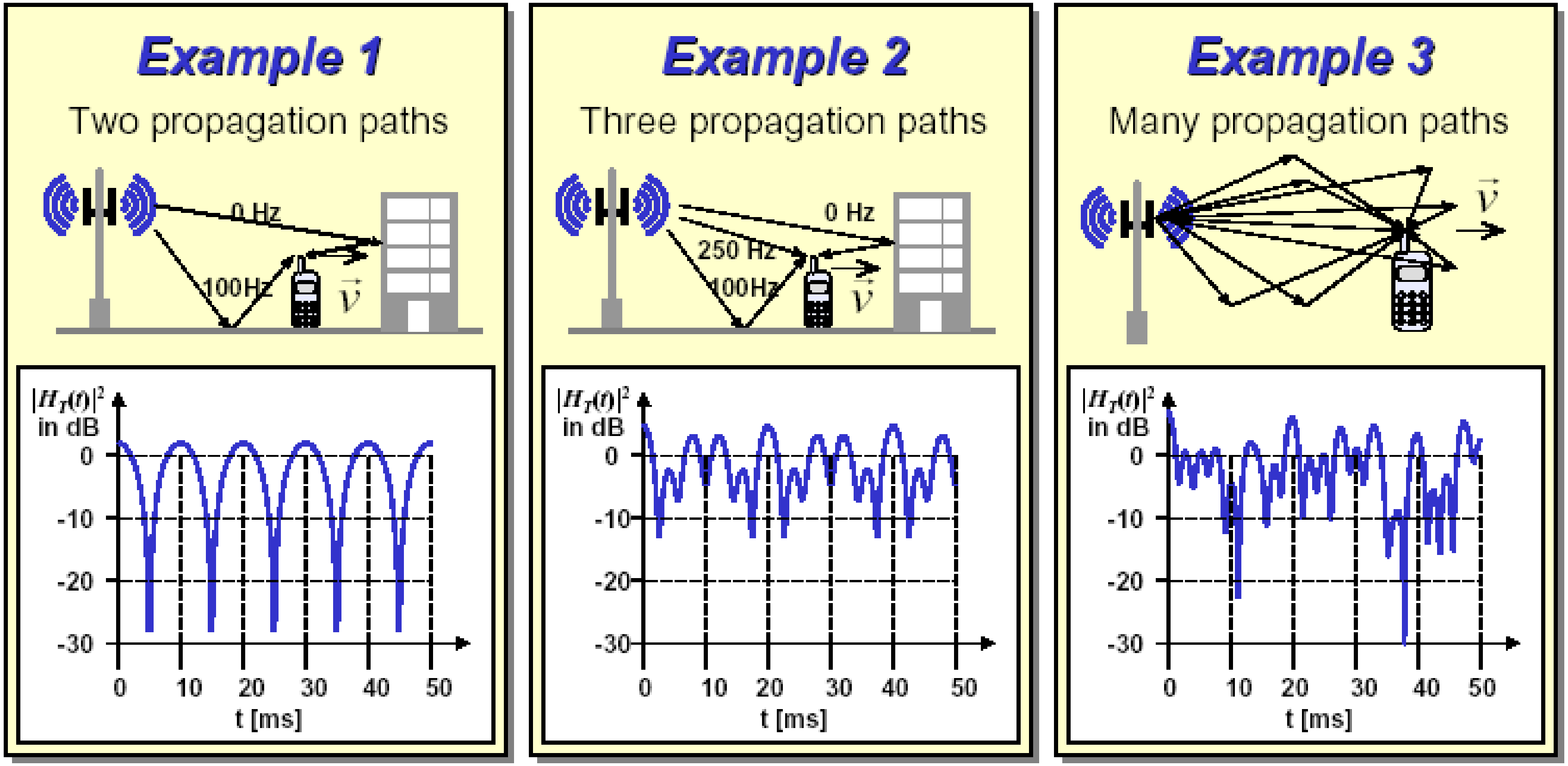


➔ Frequency selectivity, high ISI.

2. Modeling the mobile radio channel

❖ Let's consider t (E and/or R are moving):

$$h(\tau,t)=\sum_{n=0}^{N}\alpha_n(t)e^{-j\varphi_n(t)}\delta(\tau-\tau_n(t))$$



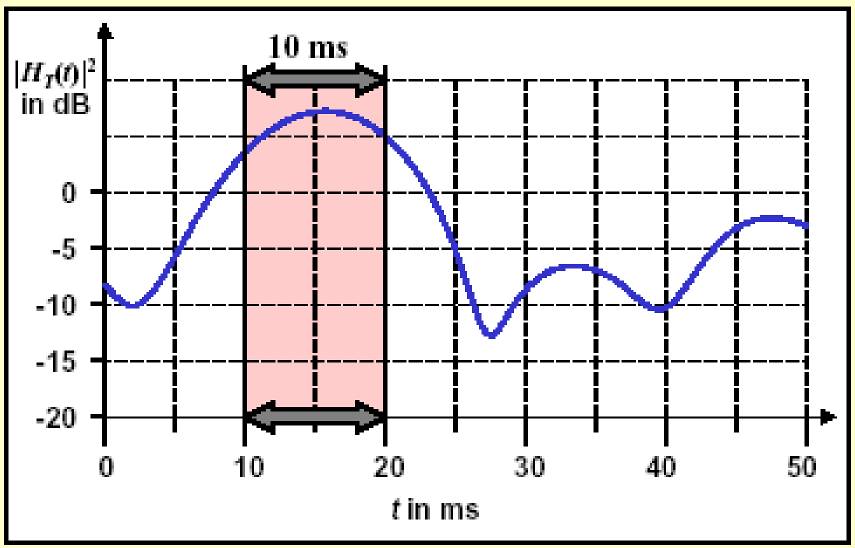
2. Modeling the mobile radio channel

- Influence of the max Doppler frequency:

time-variant narrowband channel

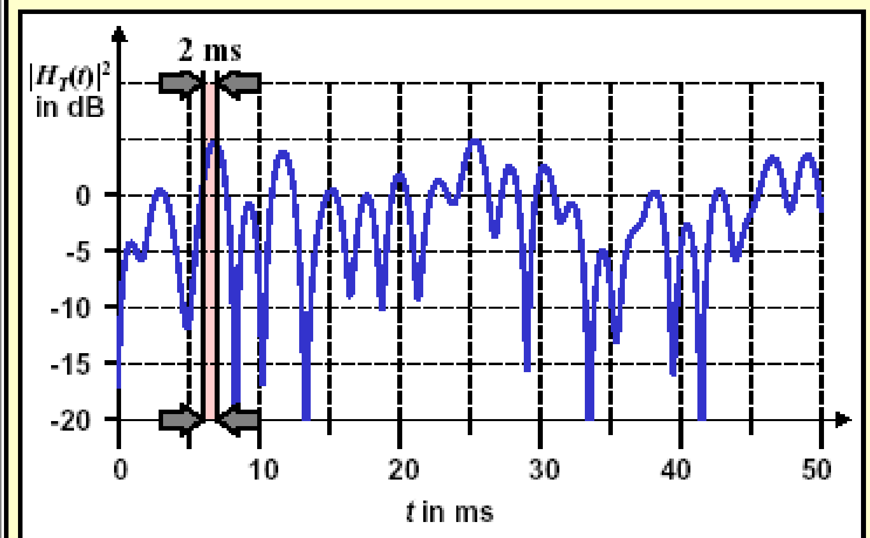
Example 1

$$f_{D,\max} = 100\ \text{Hz} \Rightarrow \frac{1}{f_{D,\max}} = 10\ \text{ms}$$



Example 2

$$f_{D,\max} = 500\ \text{Hz} \Rightarrow \frac{1}{f_{D,\max}} = 2\ \text{ms}$$



Time-variance increases with higher Doppler frequency (=higher mobility)

2. Modeling the mobile radio channel

Summary:

	narrowband channel	broadband channel
time-invariant	***Time-invariant narrowband channel*** • Frequency non-selective • no Inter Symbol Interference occurs • CTF is a constant: $\boxed{\Rightarrow H_T(f,t) = \text{const}}$	***Time-invariant broadband channel*** • Frequency-selective • Inter Symbol Interference occurs • CTF is constant over time, but frequency-selective $\boxed{\Rightarrow H_T(f,t) = H_T(f)}$
time-variant	***Time-variant narrowband channel*** • Frequency non-selective • no Inter Symbol Interference occurs • CTF is constant over the considered bandwidth, but time-variant $\boxed{\Rightarrow H_T(f,t) = H_T(t)}$	***Time-variant broadband channel*** • Frequency-selective • Inter Symbol Interference occurs • CTF is time-variant and frequency-selective $\boxed{\Rightarrow H_T(f,t) = H_T(f,t)}$

2. Modeling the mobile radio channel

- **Mobile fading channels modeling**
- **Rayleigh channel:**
  - The max delay duration << Ts (narrowband)
  - The received signal is a superposition of a large number of subpaths WITHOUT a LOS path
  - I (real) et Q (imag) received components follow a Gaussian distribution
  - In this case, we have:

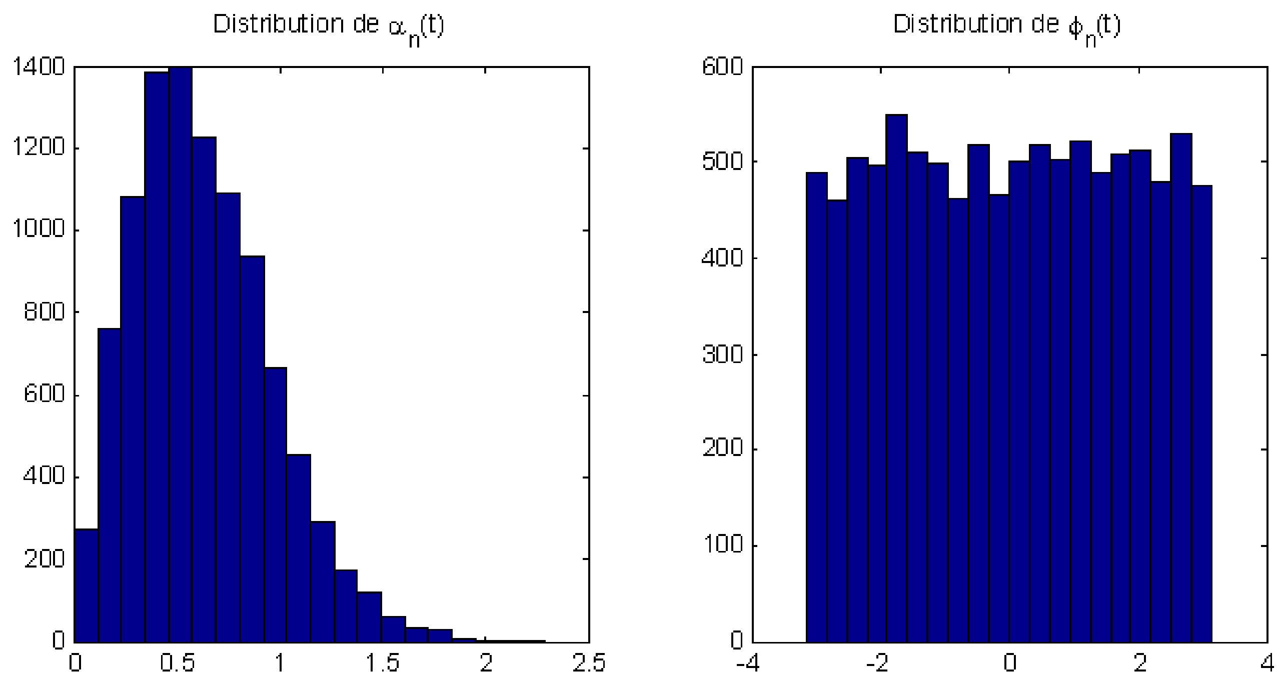
$$z(t)=|r(t)|=\sqrt{r_I^2(t)+r_Q^2(t)}$$

and z(t) follows a Rayleigh distribution:

$$p_z(z)=\frac{2z}{\Pr}\exp\left(-z^2/\Pr\right)=\frac{z}{\sigma^2}\exp\left(-z^2/\left(2\sigma^2\right)\right), z\geq 0$$

2. Modeling the mobile radio channel

- Rayleigh channel (cont'd) :
  - $\phi(t)$ the phase of r(t) follows a uniform distribution

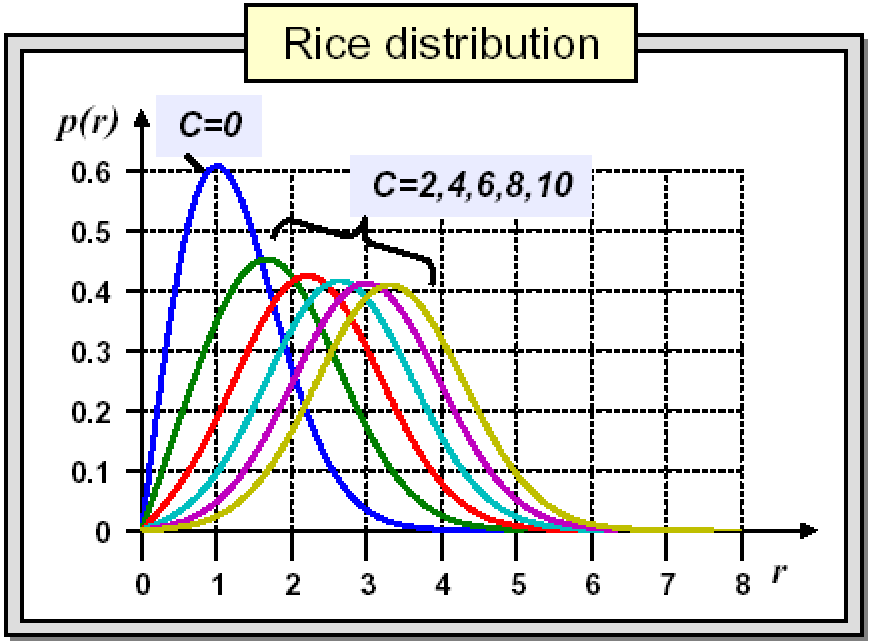


2. Modeling the mobile radio channel

Rice channel:

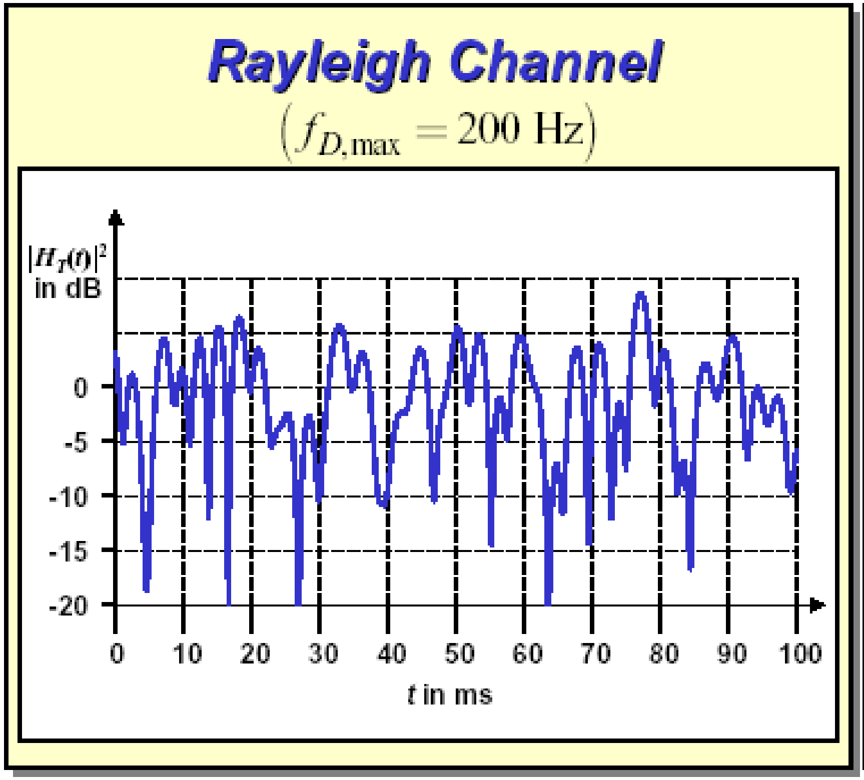
- The received signal is a superposition of many reflected paths and one LOS path
- The Rice K factor (or C) is the power of the LOS path s^2 over the power of the NLOS paths:

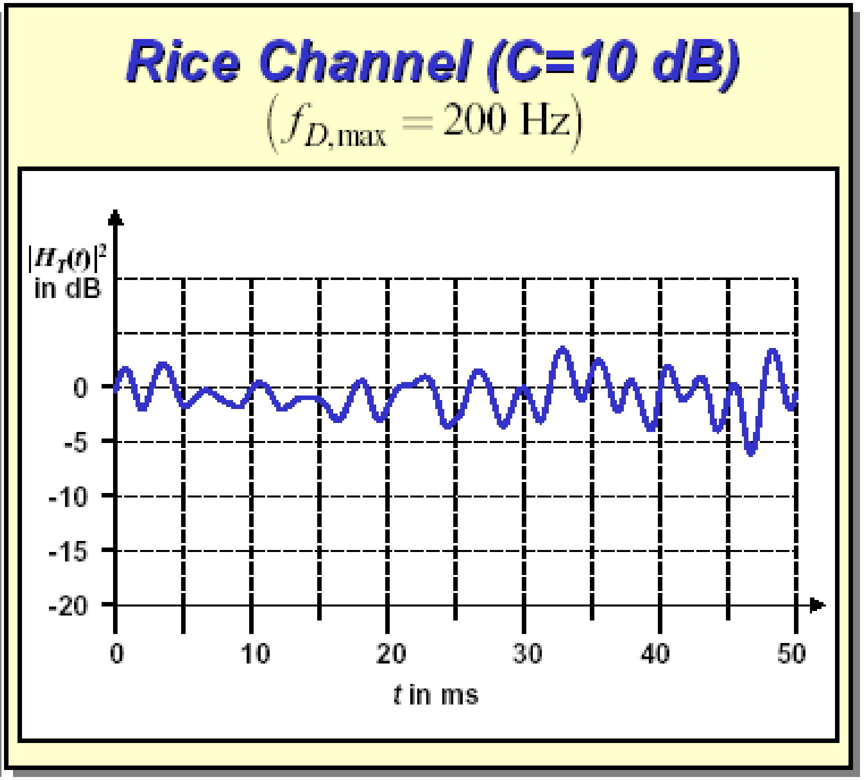
$$K = \frac{s^2}{2\sigma^2}$$



2. Modeling the mobile radio channel

➢ Rayleigh and Rice comparison:





In comparison to a ***Rayleigh channel***, the power fluctuations of a ***Rice channel*** are considerably smaller

2. Modeling the mobile radio channel

Statistical channel models and the WSSUS model:

- The CIR h(τ,t) is a stochastic process and is characterized by its **autocorrelation function**:

$$\varphi_h(\tau_1,\tau_2;t_1,t_2)=E\left\{h(\tau_1,t_1)\cdot h^*(\tau_2,t_2)\right\}$$

- In the case of the WSSUS approximation, one suppose that:
  - The stochastic process is Wide Sense Stationnary (WSS), which means the autocorrelation function does not depend on t:

$$\varphi_h(\tau_1,\tau_2;\Delta t)=E\left\{h(\tau_1,t)\cdot h^*(\tau_2,t+\Delta t)\right\} \quad with \quad \Delta t=t_2-t_1$$

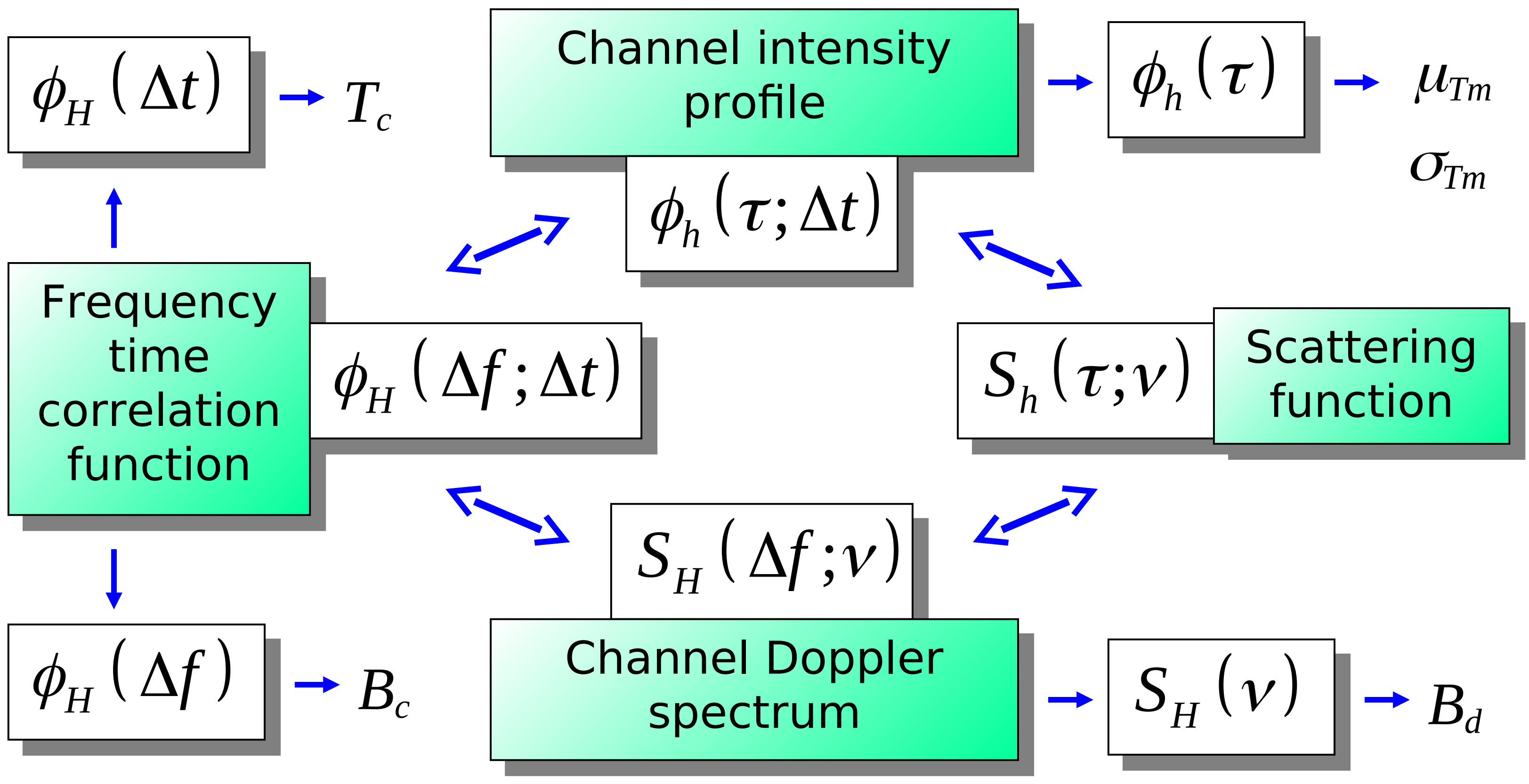
  - The different paths are not correlated (Uncorrelated Scattering US):

$$\varphi_h(\tau_1,\tau_2;\Delta t)=0 \quad \forall\ \tau_1\neq\tau_2$$

$$\boxed{\varphi_h(\tau;\Delta t)=E\left\{h(\tau,t)\cdot h^*(\tau,t+\Delta t)\right\}}$$

2. Modeling the mobile radio channel

WSSUS characterization:



2. Modeling the mobile radio channel

The power delay profile:

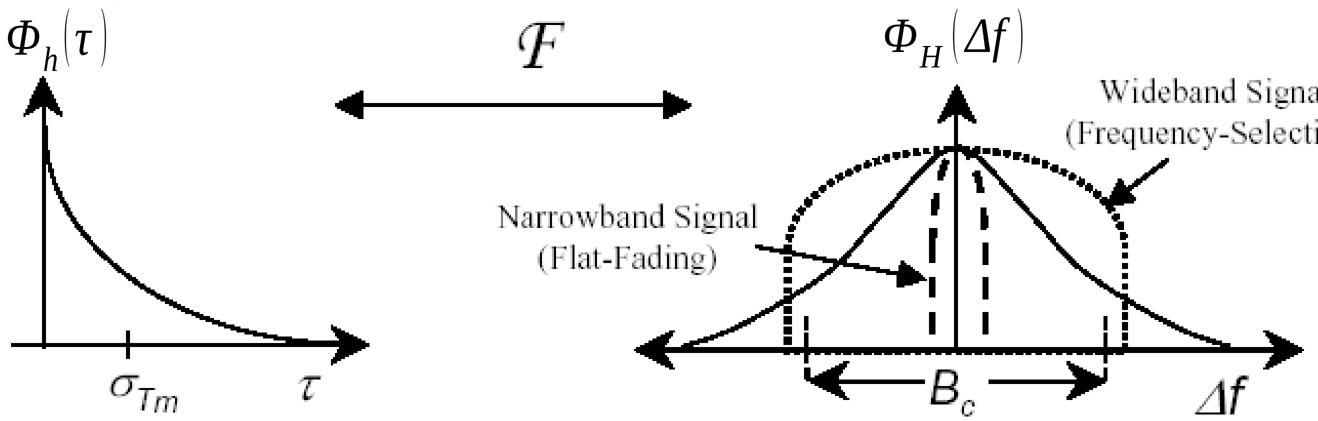
$$\Phi_h(\tau,0)=\Phi_h(\tau)$$

- Represents the mean power associated to a path with a given multipath delay. Easily measured empirically.
- The mean delay spread and the RMS delay spread are defined by:

$$\mu_{T_m}=\frac{\int_0^{\infty}\tau\cdot\Phi_h(\tau)\,d\tau}{\int_0^{\infty}\Phi_h(\tau)\,d\tau} \qquad \sigma_{T_m}=\sqrt{\frac{\int_0^{\infty}\left(\tau-\mu_{T_m}\right)^2.\Phi_h(\tau)\,d\tau}{\int_0^{\infty}\Phi_h(\tau)\,d\tau}}$$

2. Modeling the mobile radio channel

➢ The coherence bandwidth Bc:



✦ A commonly used approximation is:

$$\boxed{B_c \approx 1/\sigma_{Tm}}$$

2. Modeling the mobile radio channel

- Doppler spectrum and coherence time:
  - Doppler effect can be characterized by taking the FT of the frequency-time correlation function $\Phi_H(\Delta f,\Delta t)$ relative to Δt.
  - To characterize Doppler at a single frequency, we set $\Delta f = 0$. We then get the power Doppler spectrum (FT of an autocorrelation function):

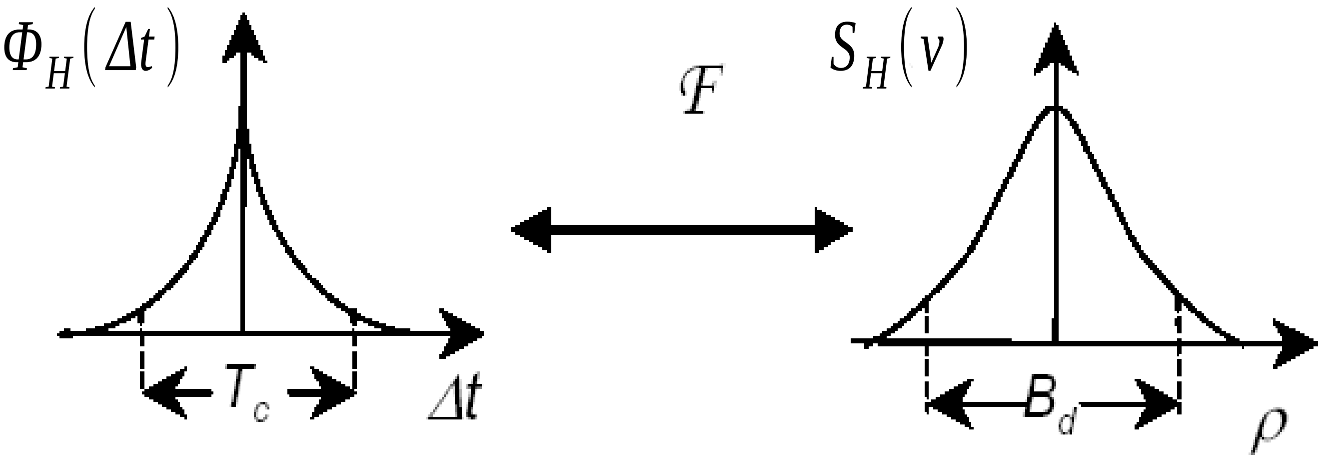
$$S_H(\nu) = \int_{-\infty}^{+\infty} \Phi_H(\Delta t)\, e^{-j2\pi\nu\Delta t}\, d\Delta t$$

  - The maximal value ν for which $S_H(\nu)$ is nonzero is called the ***Doppler spread*** and is denoted Bd.

2. Modeling the mobile radio channel

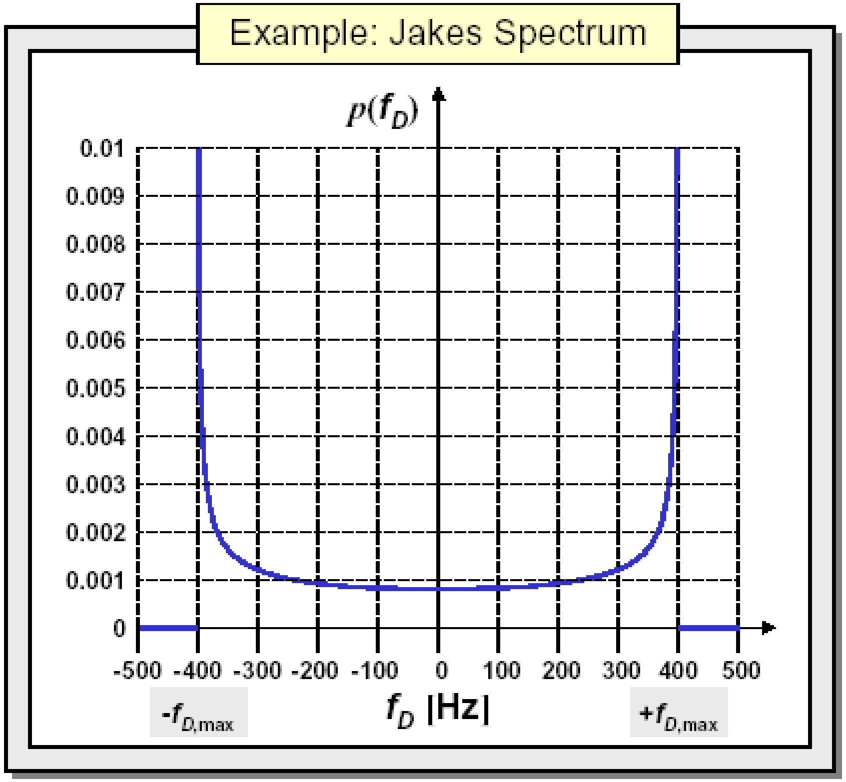
- Doppler spectrum and coherence time (cont'd):
  - The time during which $\Phi_H(\Delta t)$ is nonzero, is called the channel ***coherence time*** Tc.
  - A commonly used approximation is:

$$Bd \approx 1/Tc$$



2. Modeling the mobile radio channel

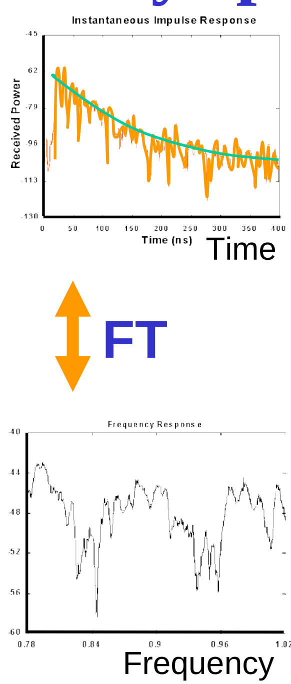
- Doppler spectrum and coherence time (cont'd):
  - A common Doppler spectrum shape, the Jakes spectrum:

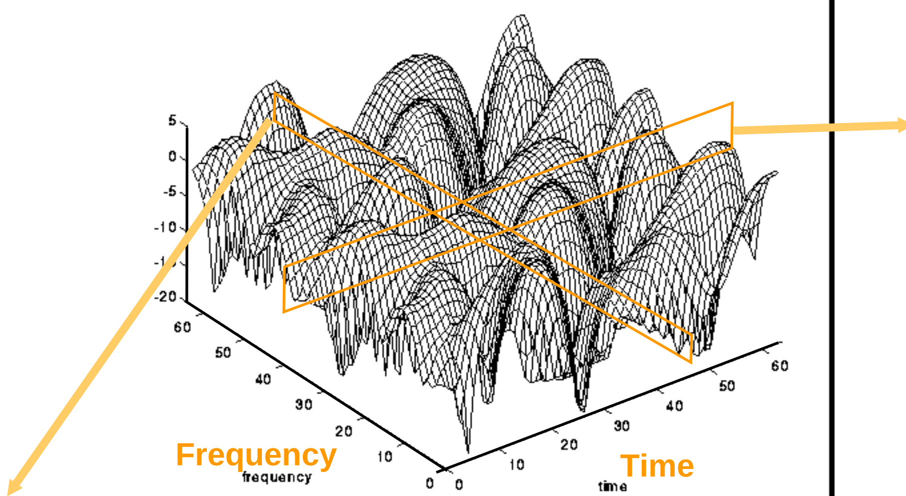


2. Modeling the mobile radio channel

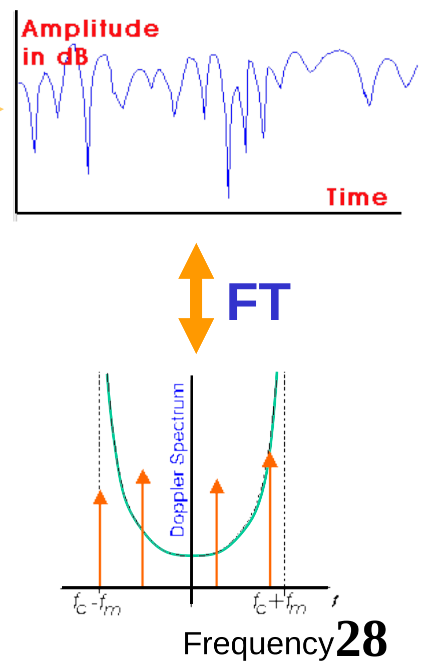
- In Summary:
  - The mobile radio channel is a ***stochastic process***.
  - It can be analyzed and modeled using statistical tools.
  - It has to be analyzed in the **time and frequency** domains.

Delay spread



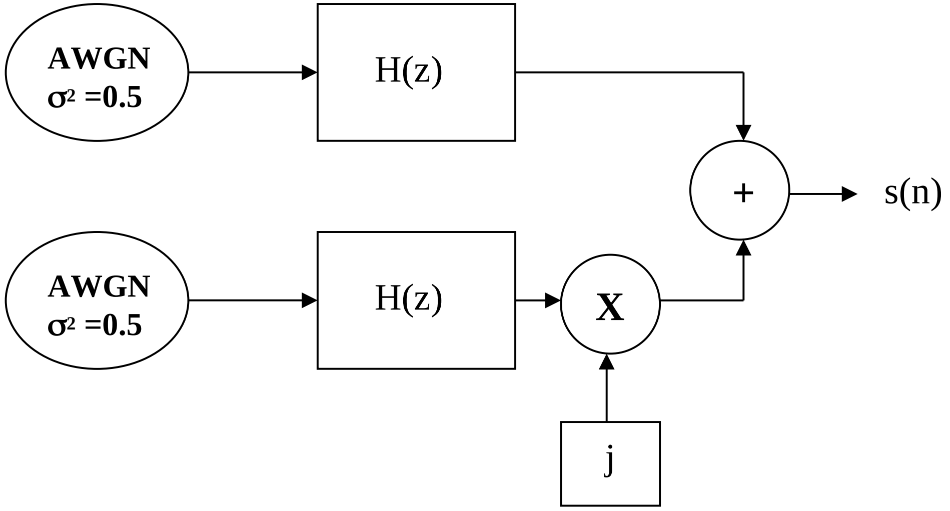


Doppler shift



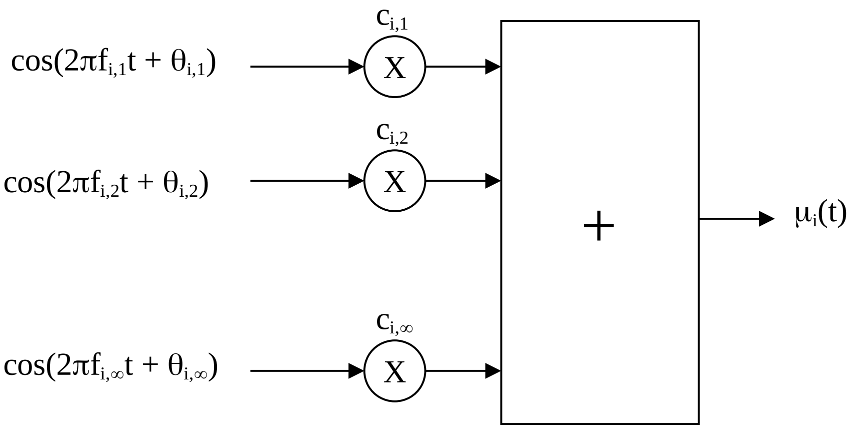
3. Simulation techniques

- Techniques for simulating mobile radio channels:
  - To be able to design efficiently digital communication systems, it is important to have tools to simulate communication channels.
  - There are two main techniques:
    - The filter method:



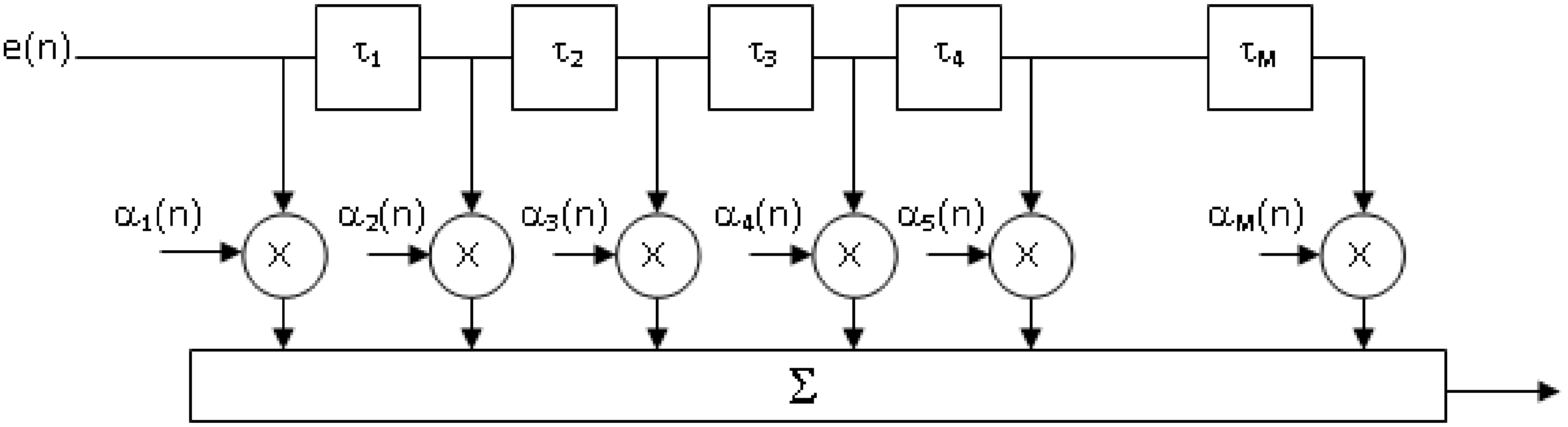
3. Simulation techniques

- Techniques for simulating mobile radio channels (cont'd):
  - The Rice Sum of Sine (SoS) method:



3. Simulation techniques

- Techniques for simulating mobile radio channels (cont’d):
  - More than one path leads to a tapped delay line structure:



3. Simulation techniques

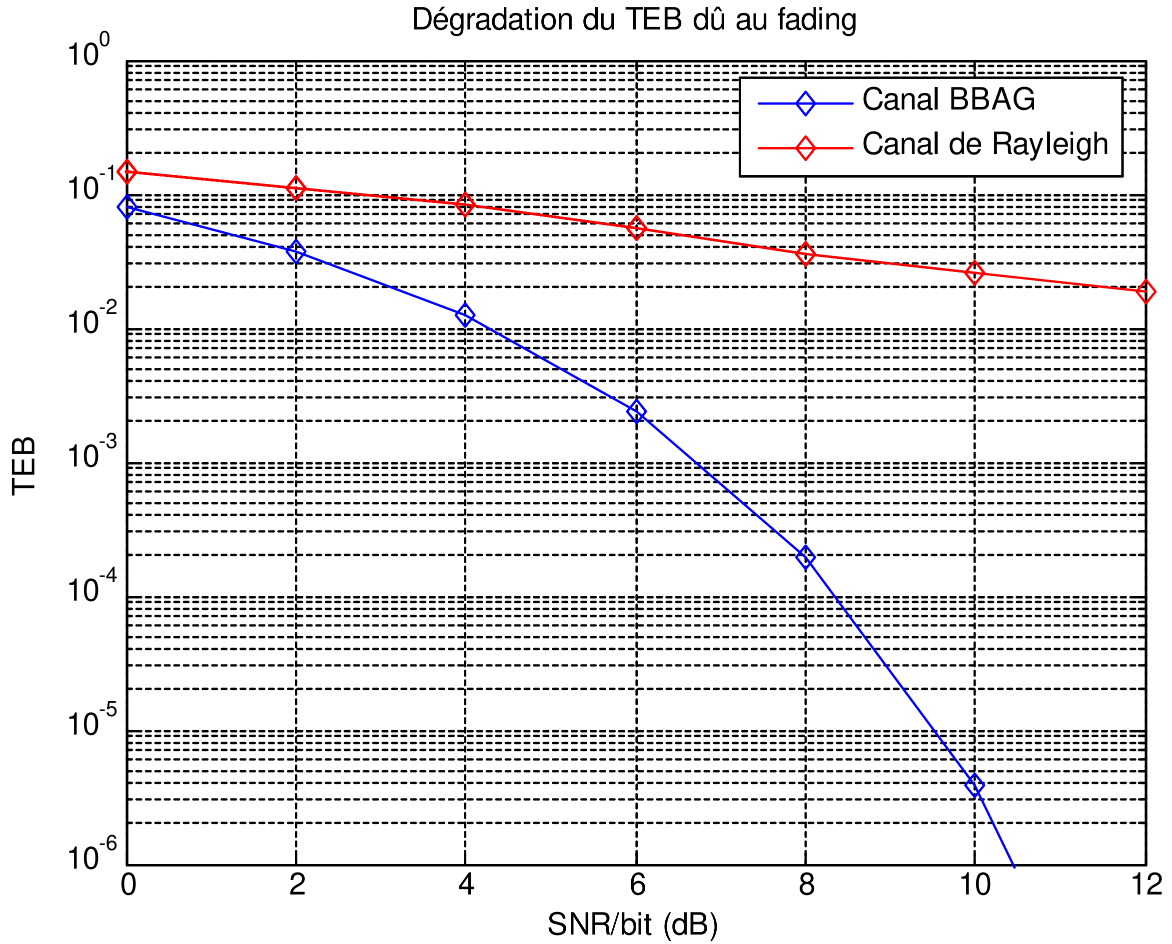
- Normalized mobile radio channels models:
  - COST207: an example of a WSSUS channel model:

Path no. ℓ	Propagation delay τ'_ℓ	Path power (lin.)	Path power (dB)	Category of the Doppler PSD	Delay spread $B^{(2)}_{\tau'\tau'}$
(iii) Typical Urban: 6-path channel model (alternative)					
0	0.0 μs	0.5	-3	"Jakes"	1.0 μs
1	0.2 μs	1	0	"Jakes"	
2	0.5 μs	0.63	-2	"Jakes"	
3	1.6 μs	0.25	-6	"Gauss I"	
4	2.3 μs	0.16	-8	"Gauss II"	
5	5.0 μs	0.1	-10	"Gauss II"	

  - Modern signal generators integrate these models.

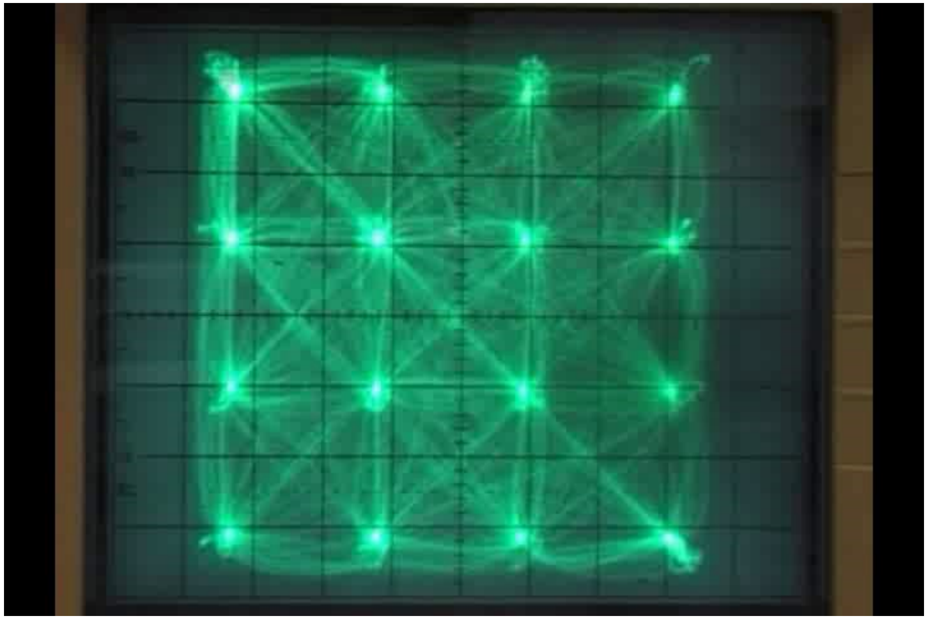
3. Simulation techniques

BER degradation (Rayleigh channel):

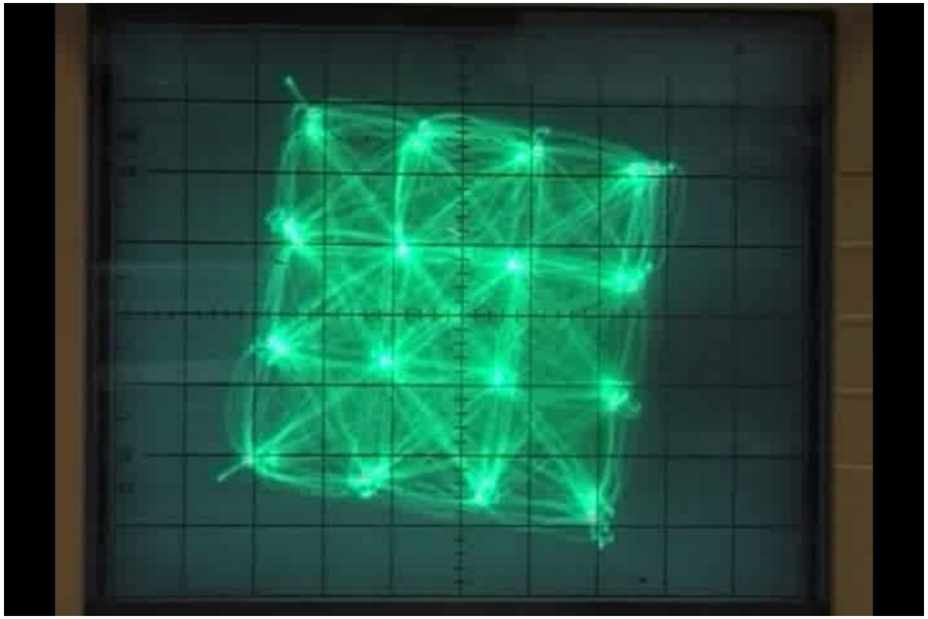


3. Simulation techniques

- Illustration of the BER degradation:



16QAM AWGN channel



16QAM Rayleigh channel

3. Simulation techniques

- **Demonstration:**
  - Generation of Rayleigh channel samples using the filter method + BER curve (Octave).
  - COST207TU channel model and the resolvable paths concept (Matlab).
  - Digital communication system with Rayleigh channel (GNU Radio).
  - Digital communication system with COST207TU frequency selective fading channel (GNU Radio).

  ⇒ Files available on my github :

  https://github.com/hboeglen/Mobile_Fading_Channel_Tutorial_SDRA_2022

4. Conclusion

- The mobile fading channel is the real world!
- Worst case: time and frequency selectivity.
- The expected BER is very high

➔ Need for sophisticated digital communication techniques (e.g. OFDM, interleaving, spread spectrum etc.).

Bibliography

- Books:
  - Digital Communications: A Discrete-Time Approach, M. Rice, Prentice Hall, 2008.
  - Wireless Communications, A. Goldsmith, Cambridge University Press, 2005.
  - Principles of Mobile Communication, G. Stuber, Springer, 2011.
  - Mobile radio channels, M. Pätzold, Wiley, 2011.