patrice.pajusco@imt-atlantique.fr
1462
C02-142A

TAF STAR & OPE
UE Cœur 1

2. Radio propagation Channel
2.2 RF Propagation

Patrice Pajusco
Microwave Department

September 2025

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

INTRODUCTION

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

INTRODUCTION

Wireless systems

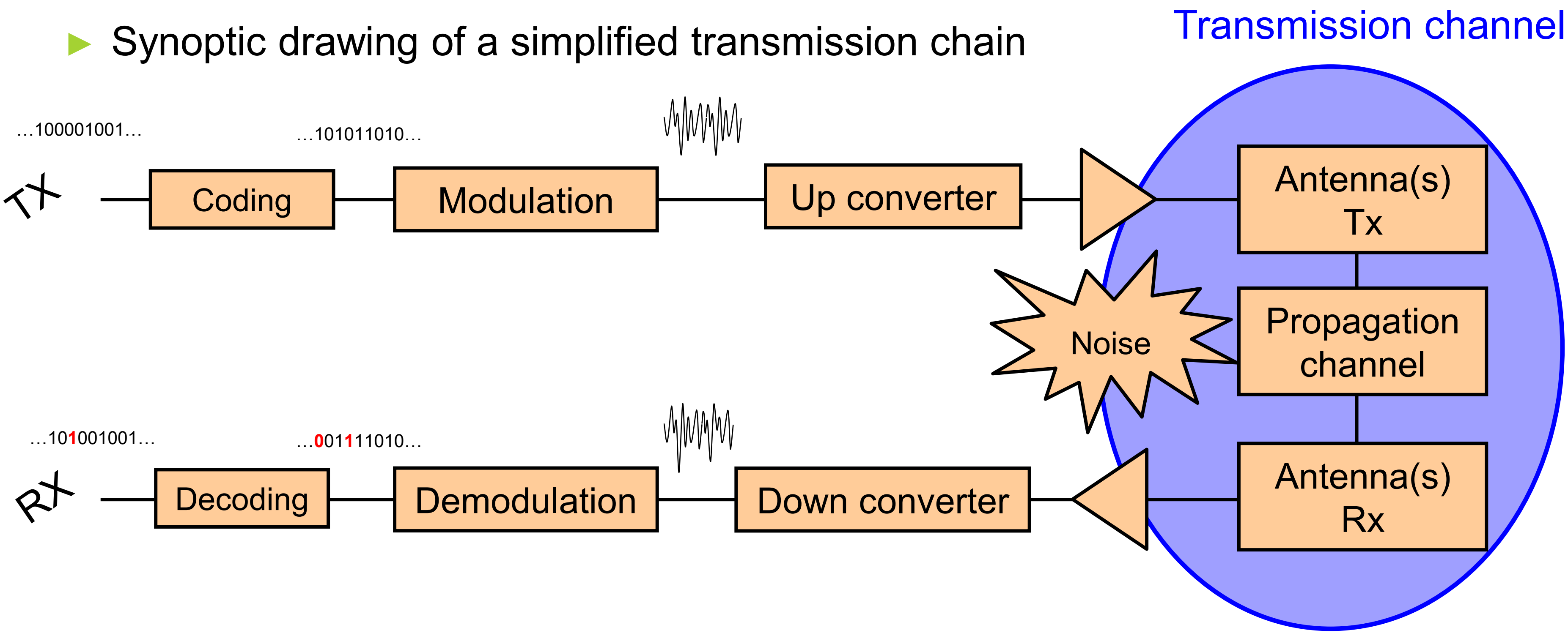
- Many telecommunication standards

- Different air interfaces
  - Carrier frequency
  - Bandwidth
  - Data throughput
  - Modulation
  - …

trade-off

Transmission constraints
versus
Radio channel limitation

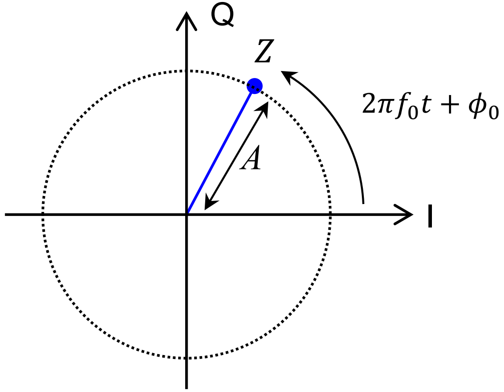
- Synoptic drawing of a simplified transmission chain



INTRODUCTION
Basics about modulation

- Adaptation of the signal to the transmission support

- Possible parameter changes of the carrier wave



$$s(t) = A\cos\left(2\pi f_0 t + \phi_0\right)$$

Amplitude Frequency Phase

- Changes can be continuous (analogue transmission) or discrete (digital transmission)

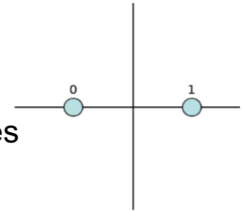
- Demodulation step is the inverse operation

INTRODUCTION

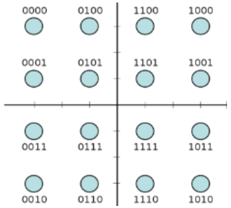
Numerical modulation examples

- ASK : Amplitude Shift Keying

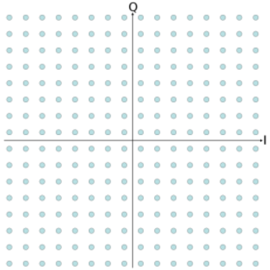
2 states



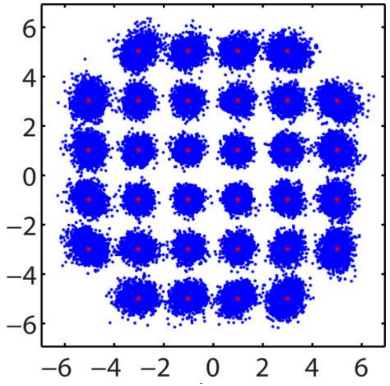
16 QAM



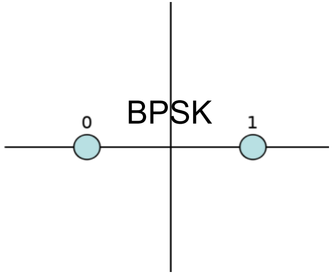
256 QAM

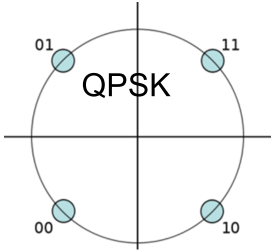


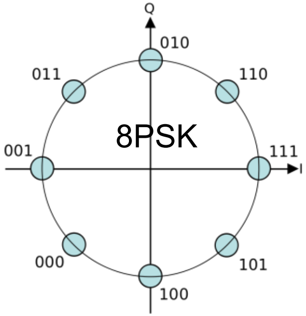
Noise influence
32 QAM



- PSK : Phase Shift Keying







INTRODUCTION

Radio channel model ?

- Channel models are required for any wireless system

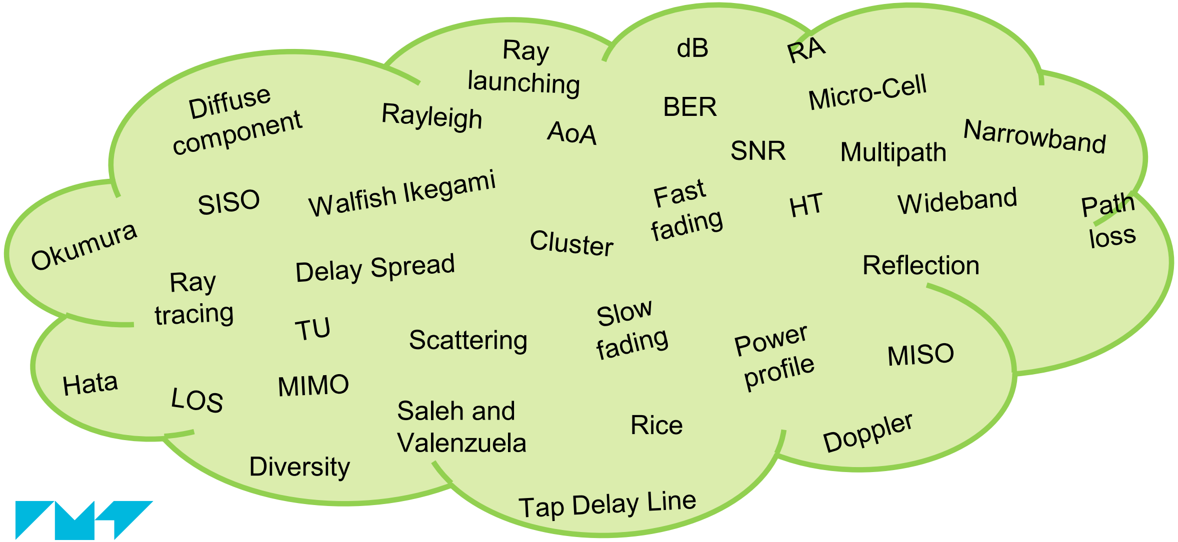
- Channel models are used during the whole life cycle of a system
  - Standardization : Fair comparison between air interface candidates
  - Dimensioning : Rough coverage, cost estimation
  - Deployment : Site specific engineering
  - Optimization : New release, densification

- Two main families
  - Path loss models : Dimensioning and engineering
  - Wideband models : Performance system simulation

INTRODUCTION

Many reference documents

- Reference document are available for each standard
- Similar model approaches in each document
- Dedicated vocabulary to understand



IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

INTRODUCTION
Main objective of this very short course

- Understanding basic propagation phenomena's
- Understanding of channel impact characteristics on wireless transmission
- Discovering dedicated vocabulary of this research field
- Understanding some main channel modeling concepts

GENERALITIES

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

GENERALITIES

Radio channel classification

- Need to simplify the problem
  - Channel models proposed in typical configurations
  - Type of environment
  - Visibility condition
  - Cell configuration

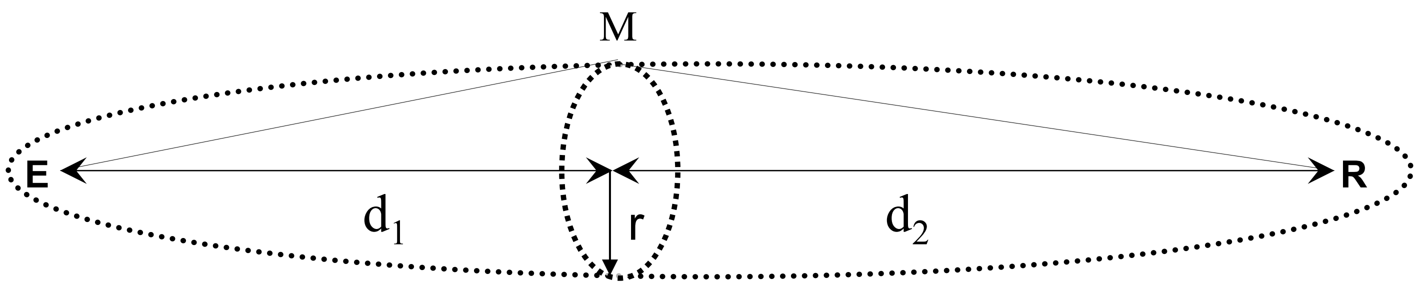
LOS : Line-of-sight
NLOS : Non-line-of-sight

- Outdoor environment classification
  - Dense urban
  - Urban
  - Sub urban
  - Residential
  - Rural
  - Hilly

- Indoor environment classification
  - Residential
  - Office
  - Commercial center
  - Industrial
  - Corridor

Définition

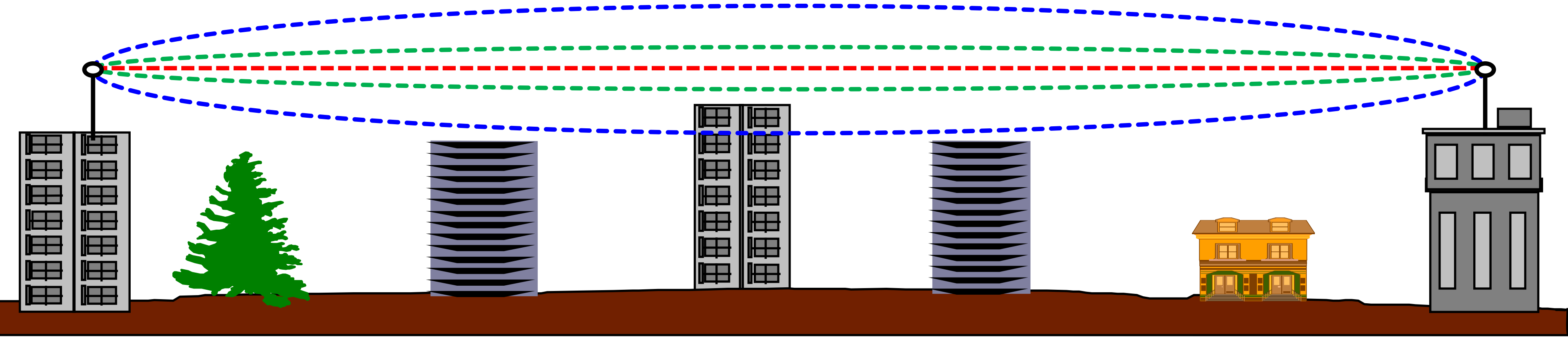
- E (Emetteur) et R (Récepteur) les foyers des ellipsoïdes
- Famille d'ellipsoïdes définie par EM+MR=ER+nλ/2 où λ est la longueur d'onde et n l'ordre entier de l'ellipsoïde
- Condition de propagation en visibilité directe : Pas d'obstacle à l'intérieur du premier ellipsoïde



$$r(d_1, d_2) = \sqrt{n\lambda d_1 d_2 / (d_1 + d_2)} \qquad r_{\max}(d) = \frac{1}{2}\sqrt{n\lambda d}$$

- Condition de visibilité ou LOS (Line Of Sight)
  - Lumière → Ok
  - 10 GHz → Ok
  - 1 GHz → No (début de « masquage » par l'immeuble central)

$$r_{\max}(d) = \frac{1}{2}\sqrt{n\lambda d}$$



GENERALITIES
Radio channel classification

- **Macro cell configuration**
  - Clear view over the surrounding terrain
  - Large area covering
  - High output power
  - Rural and sub-urban area
  - ~ several tens km cell radius
- **Small cell configuration**
  - Antenna above roof top level
  - Dense urban area
  - ~ a few km cell radius

GENERALITIES

Radio channel classification

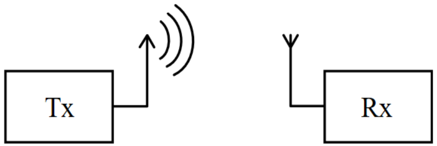
- **Micro cell configuration**
  - Antenna below rooftop level
  - High traffic area
  - Low output power
  - Street guided propagation
  - < 100 meters cell radius

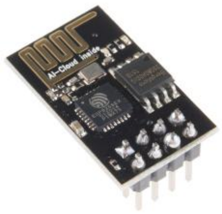
- **Pico/femto cell configuration**
  - Indoor environment (Usually)
  - Low power
  - High traffic area « Hot spot »
  - ~a few tens meters cell radius

GENERALITIES

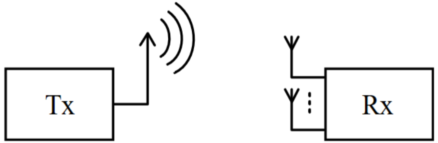
Transmission channel type

- SISO : Single-Input Single-Output

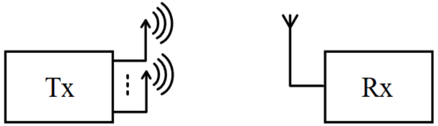




- SIMO : Single-Input Multiple-Output
  - Diversity
  - Beamforming



- MISO : Multiple-Input Single-Output
  - Diversity
  - Beamforming



- MIMO : Multiple-Input Multiple-Output
  - Dual diversity or beamforming
  - Spatial multiplexing

Figures : https://en.wikipedia.org/wiki/Single-input_single-output_system

GENERALITIES
Channel metrics

- Data throughput
  - Rate of data transmission
  - In bit/s or samples/s

- Signal to Noise Ratio (SNR)
  - Power ratio between the useful signal and the noise
  - Good indication of the quality of the transmission link
  - No dimension, usually in dB

- Bit Error Rate (BER)
  - Number of bit errors divided by the total number of transferred bits
  - No dimension, usually in %
  - Worse value 50%

GENERALITIES

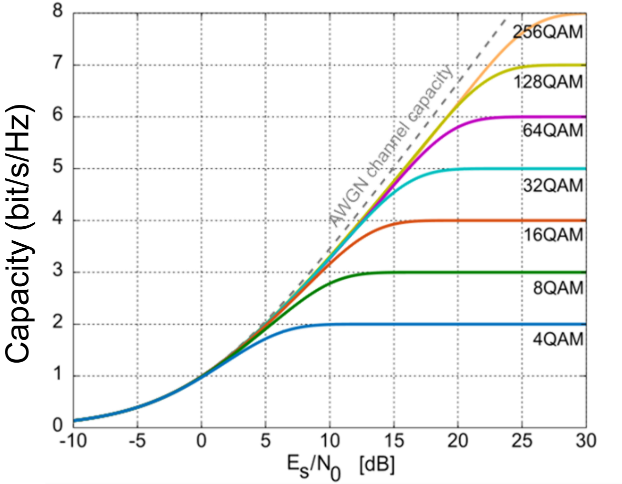
Channel capacity

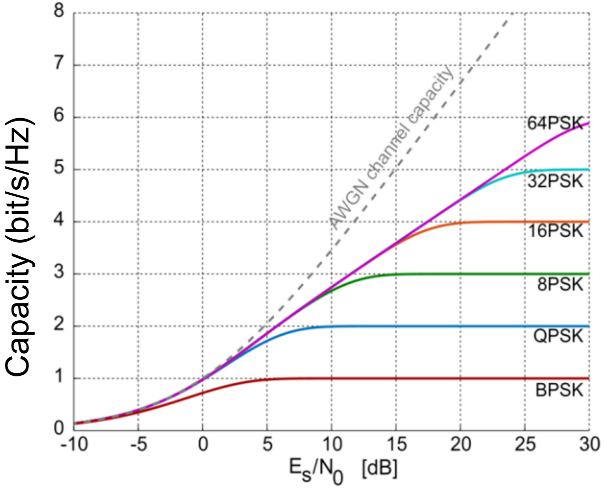
- **Definition**
  - Highest information rate that can be achieved without error
  - Upper bound introduced by C. Shannon in 1948

$$\boxed{\begin{array}{c} C(bit/s/Hz) = \log_2(1+\rho) \\ \text{with } \rho \text{ the signal to noise ratio} \end{array}}$$

- **Numerical application :**
  - $\rho = 0$ C ?
  - $\rho = 1$ C ?
  - $\rho = 100$ C ?
  - Maximum throughput for a Wi-Fi (20 MHz bandwidth) with 6 dB SNR?

- Influence of modulation

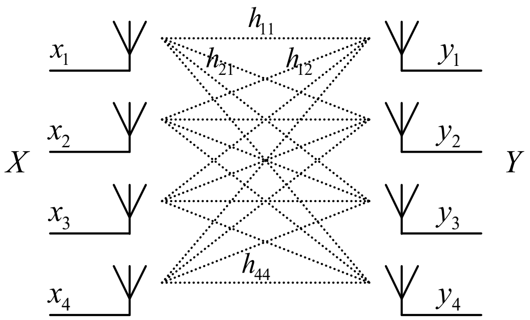




☞ Need to adjust the modulation to the channel state

Crédit figures : en.wikipedia.org/wiki/Phase-shift_keying, en.wikipedia.org/wiki/Quadrature_amplitude_modulation

► MIMO transmission channel



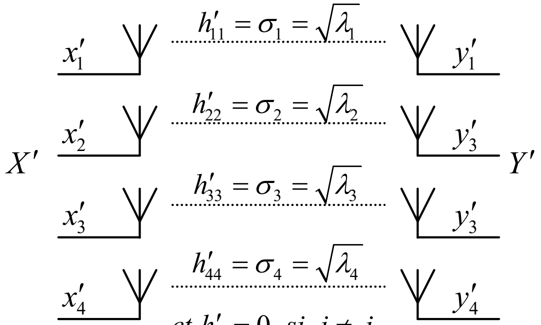
$$Y = HX + N$$

Spatial multiplexing

↓

Spatial channel number depends on H

$$H = U\Sigma V^H$$



$et\ h'_{ij} = 0\ si\ i \neq j$

$$Y' = \Sigma X' + N'$$

☞ The capacity gain is **LINEAR** to the smallest number of antenna at TX & RX

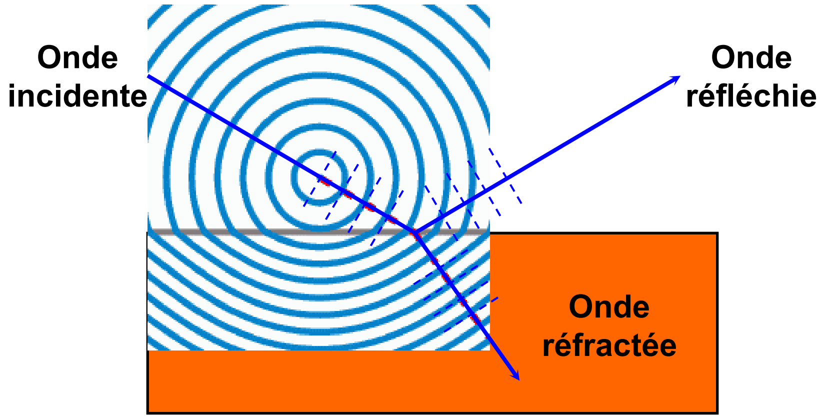
INTERACTION ONDES ENVIRONNEMENT

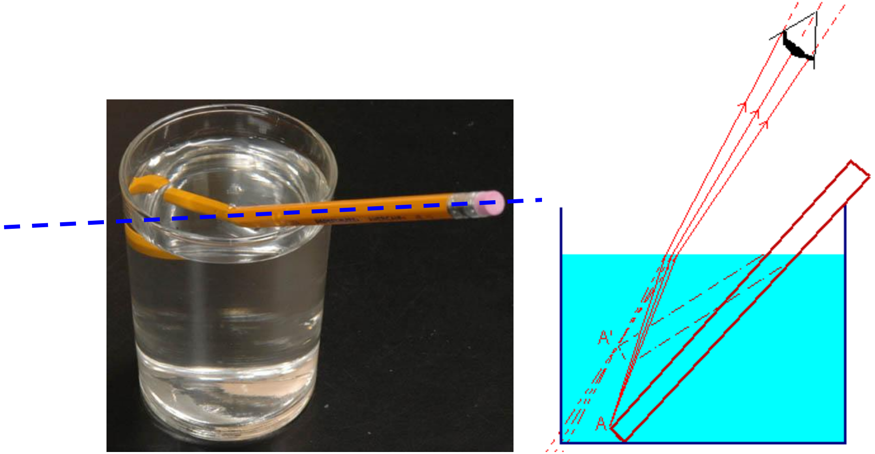
IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

INTERACTIONS ONDE-ENVIRONNEMENT

Réfraction / Réflexion

- Vitesse de propagation dépendant du milieu → Changement de direction de l'onde lorsque le milieu change
- Surface lisse → Réflexion spéculaire





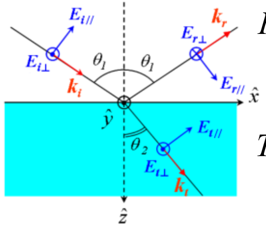
Exemple de réfraction dans la vie courante

- Influence de la polarisation

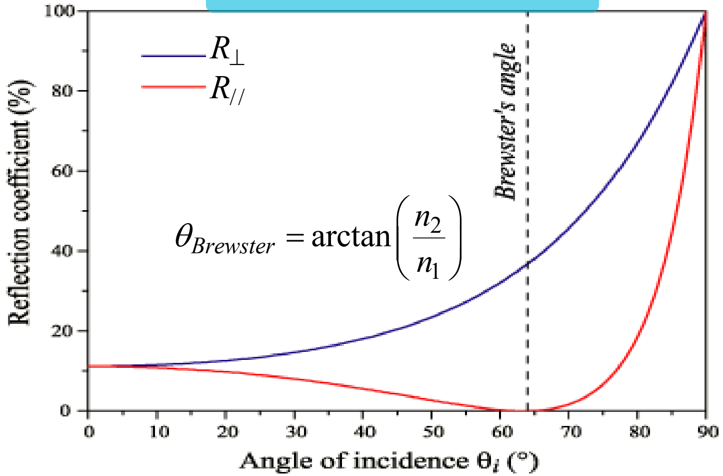
$$R_\perp = \frac{E_{r\perp}}{E_{i\perp}} = \frac{n_1\cos\theta_1 - n_2\cos\theta_2}{n_1\cos\theta_1 + n_2\cos\theta_2} \qquad R_{//} = \frac{E_{r//}}{E_{i//}} = \frac{n_2\cos\theta_1 - n_1\cos\theta_2}{n_2\cos\theta_1 + n_1\cos\theta_2}$$

$$\vec{E}_i = \begin{bmatrix} E_{i//} \\ E_{i\perp} \end{bmatrix} \quad \vec{E}_r = \begin{bmatrix} R_{//}.E_{i//} \\ R_\perp.E_{i\perp} \end{bmatrix} \quad \vec{E}_t = \begin{bmatrix} T_{//}.E_{i//} \\ T_\perp.E_{i\perp} \end{bmatrix}$$

$$T_\perp = \frac{E_{t\perp}}{E_{i\perp}} = \frac{2n_1\cos\theta_1}{n_1\cos\theta_1 + n_2\cos\theta_2} \qquad T_{//} = \frac{E_{t//}}{E_{i//}} = \frac{2n_1\cos\theta_1}{n_2\cos\theta_1 + n_1\cos\theta_2}$$



$n_1 = 1.0, \quad n_2 = 2.0 \quad (\theta_1 > \theta_2)$



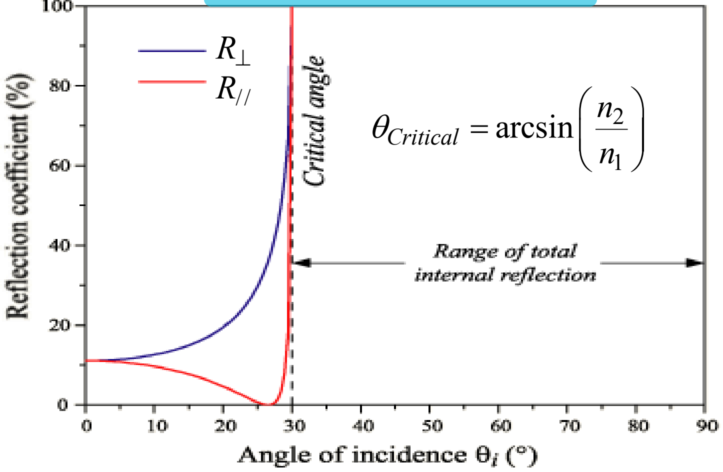
- Influence de la polarisation

$$R_\perp = \frac{E_{r\perp}}{E_{i\perp}} = \frac{n_1\cos\theta_1 - n_2\cos\theta_2}{n_1\cos\theta_1 + n_2\cos\theta_2} \qquad R_{//} = \frac{E_{r//}}{E_{i//}} = \frac{n_2\cos\theta_1 - n_1\cos\theta_2}{n_2\cos\theta_1 + n_1\cos\theta_2}$$

$$\vec{E}_i = \begin{bmatrix} E_{i//} \\ E_{i\perp} \end{bmatrix} \quad \vec{E}_r = \begin{bmatrix} R_{//}.E_{i//} \\ R_\perp.E_{i\perp} \end{bmatrix} \quad \vec{E}_t = \begin{bmatrix} T_{//}.E_{i//} \\ T_\perp.E_{i\perp} \end{bmatrix}$$

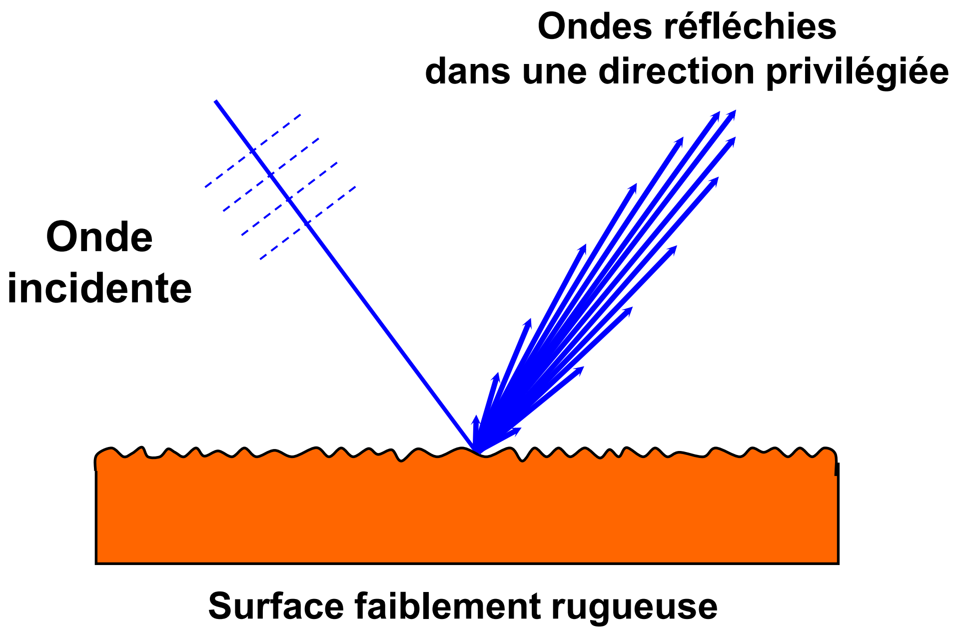
$$T_\perp = \frac{E_{t\perp}}{E_{i\perp}} = \frac{2n_1\cos\theta_1}{n_1\cos\theta_1 + n_2\cos\theta_2} \qquad T_{//} = \frac{E_{t//}}{E_{i//}} = \frac{2n_1\cos\theta_1}{n_2\cos\theta_1 + n_1\cos\theta_2}$$

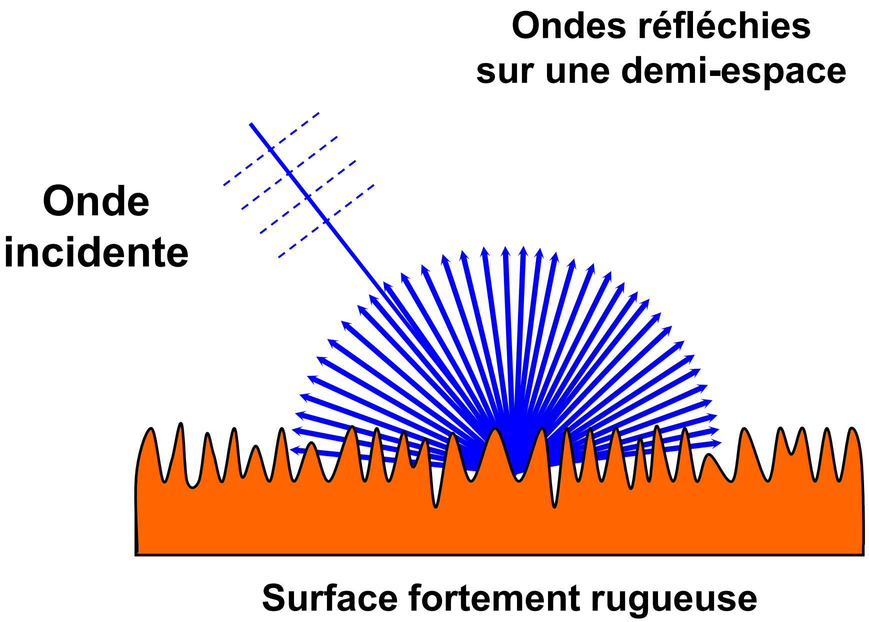
$n_1 = 2.0, \quad n_2 = 1.0 \quad (\theta_1 < \theta_2)$



Réflexion diffuse

- Surface rugueuse → réflexion diffuse voir diffusion totale



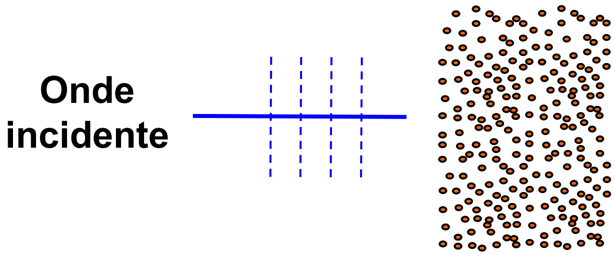


- Exemple en fonction de l'état de mer

INTERACTIONS ONDE-ENVIRONNEMENT

La diffusion

- Interaction avec un milieu aléatoire
- Influence de la longueur d'onde et de l'angle d'observation (non isotrope)
- Différents modèles de diffusion : Rayleigh, Mie



Ex : Diffusion de la lumière dans l'atmosphère
Rayleigh : Molécules – Ciel bleu
Mie : Goutelettes d'eau – Nuages blancs

- Des effets variables en fonction de la fréquence / longueur d’onde

Liaison optique en espace libre
Visible et proche infra-rouge
380nm < λ < 780nm et 780nm < λ < 2µm

Liaison satellite en ondes radio millimétriques
λ < 1cm
f > 30GHz

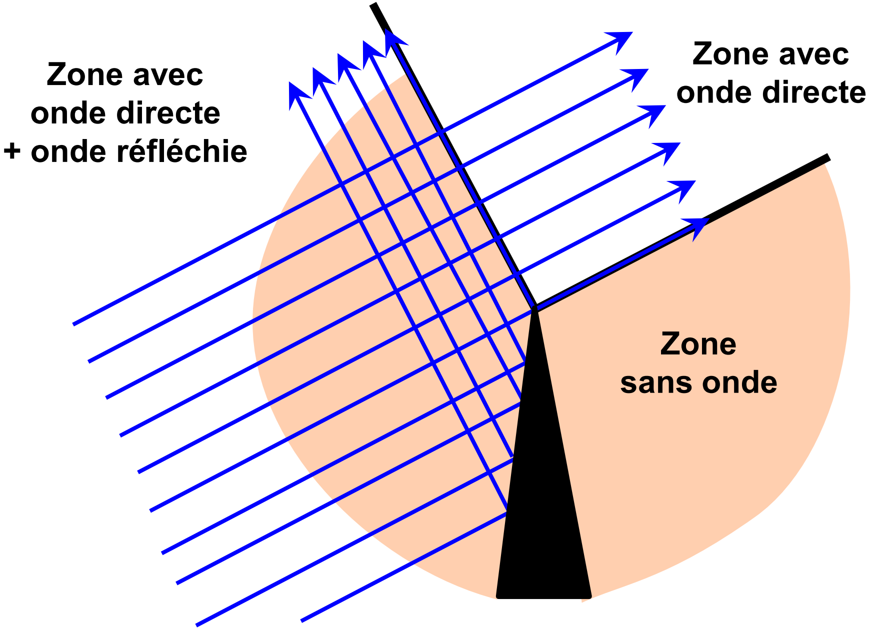
Liaison en ondes radio décimétriques ou centimétriques
1 cm < λ < 1 m
30 GHz > f > 300 MHz

INTERACTIONS ONDE-ENVIRONNEMENT
La diffraction

- Bilan des modèles précédents au voisinage d'un obstacle de très grande dimension devant λ

- Résultats non satisfaisants
  - Discontinuité aux frontières
  - Zone avec aucune onde

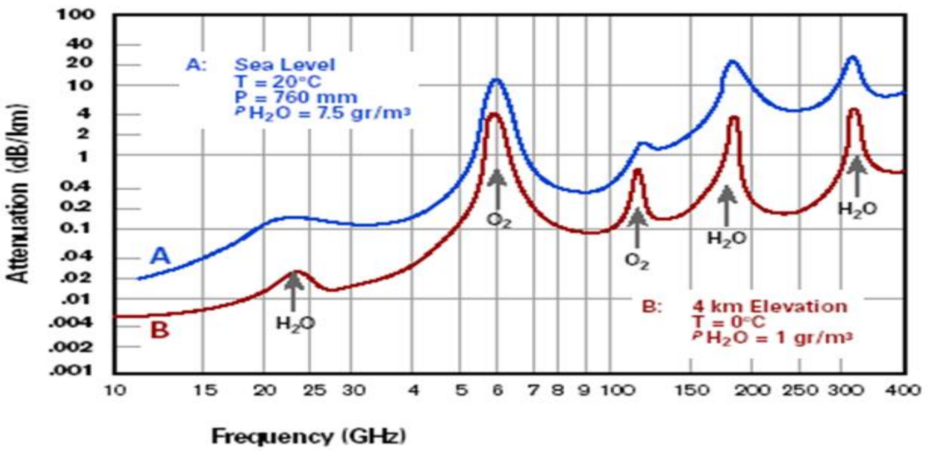
- Nécessité de la notion d'onde diffractée
  - Théorie Géométrique de la Diffraction
  - Indispensable pour les configurations radio-mobiles



INTERACTIONS ONDE-ENVIRONNEMENT

L'absorption (affaiblissement supplémentaire)

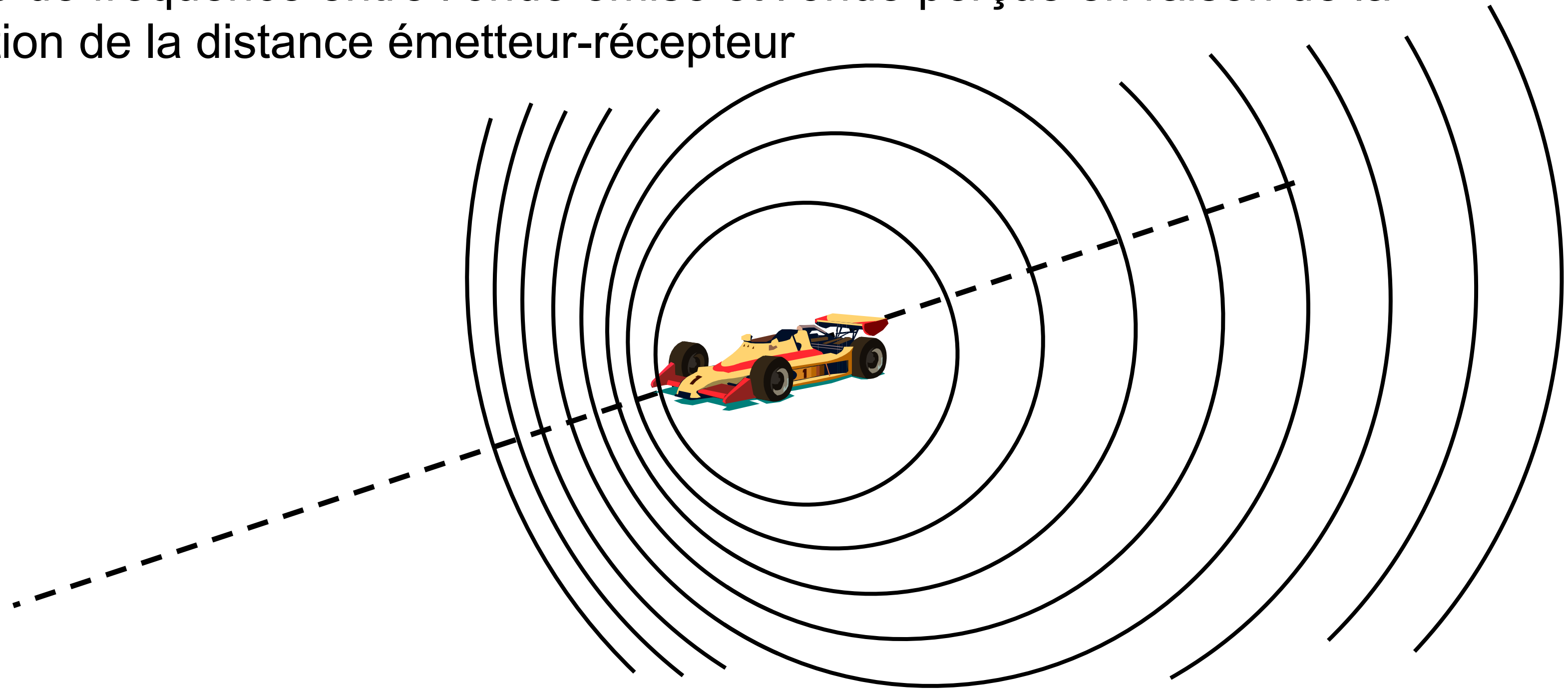
- Transformation de l'énergie de l'onde incidente en chaleur
- Le taux d'absorption dépend de la fréquence et des caractéristiques du milieu
- Exemple d'une onde électromagnétique dans l'air



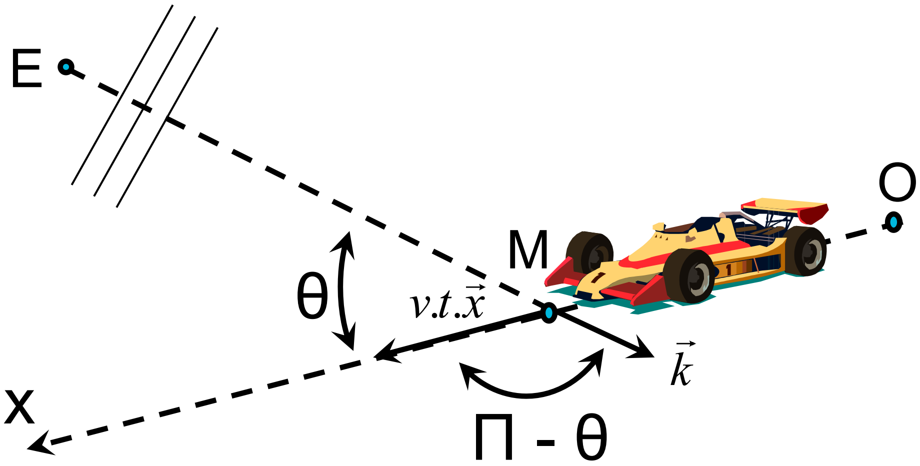
INTERACTIONS ONDE-ENVIRONNEMENT

L'effet Doppler-Fizeau : Constat physique

- Décalage de fréquence entre l'onde émise et l'onde perçue en raison de la modification de la distance émetteur-récepteur



- Décalage de fréquence entre l'onde émise et l'onde perçue en raison de la modification de la distance émetteur-récepteur



$$E(x,t) = E_0 \exp\left(j\left(\omega_0 t - \vec{k}.\overrightarrow{EM}\right)\right)$$

$$\text{où } \overrightarrow{EM} = \overrightarrow{EO} + \overrightarrow{OM}$$

$$E(x,t) = E_0 \exp\left(j\left(\omega_0 t - \vec{k}.\overrightarrow{OM}\right)\right)\exp\left(-j.\vec{k}.\overrightarrow{EO}\right)$$

$$E(x,t) = E_0 \exp\left(j\left(\omega_0 t + kx\cos(\theta)\right)\right)\exp\left(-j.\vec{k}.\overrightarrow{EO}\right)$$

$$E(x,t) = E_0 \exp\left(2\pi j\left(f_0 + \frac{v}{\lambda_0}\cos(\theta)\right)t\right)\exp\left(-j.\vec{k}.\overrightarrow{EO}\right)$$

Décalage fréquence Doppler

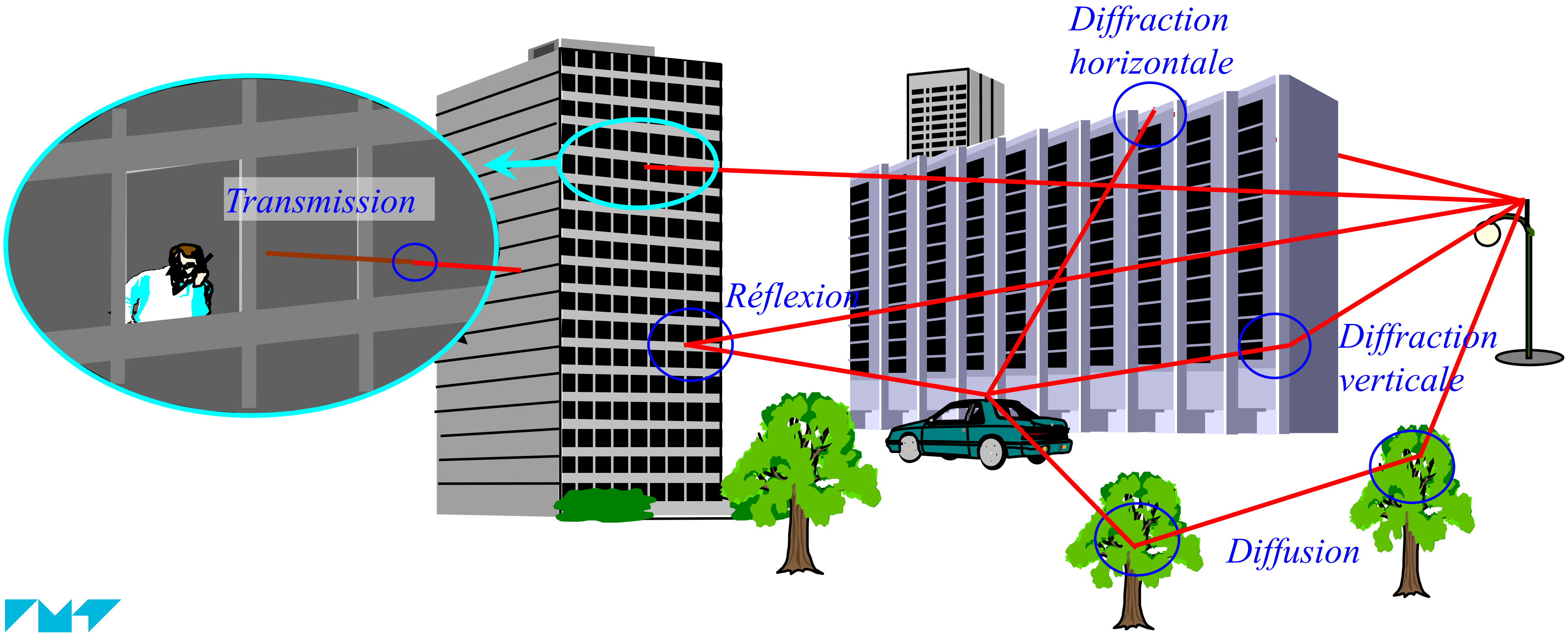
PROPAGATION MULTI TRAJETS

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

PROPAGATION MULTI-TRAJETS

Vision physique : Différents trajets possibles entre l'émetteur et le récepteur

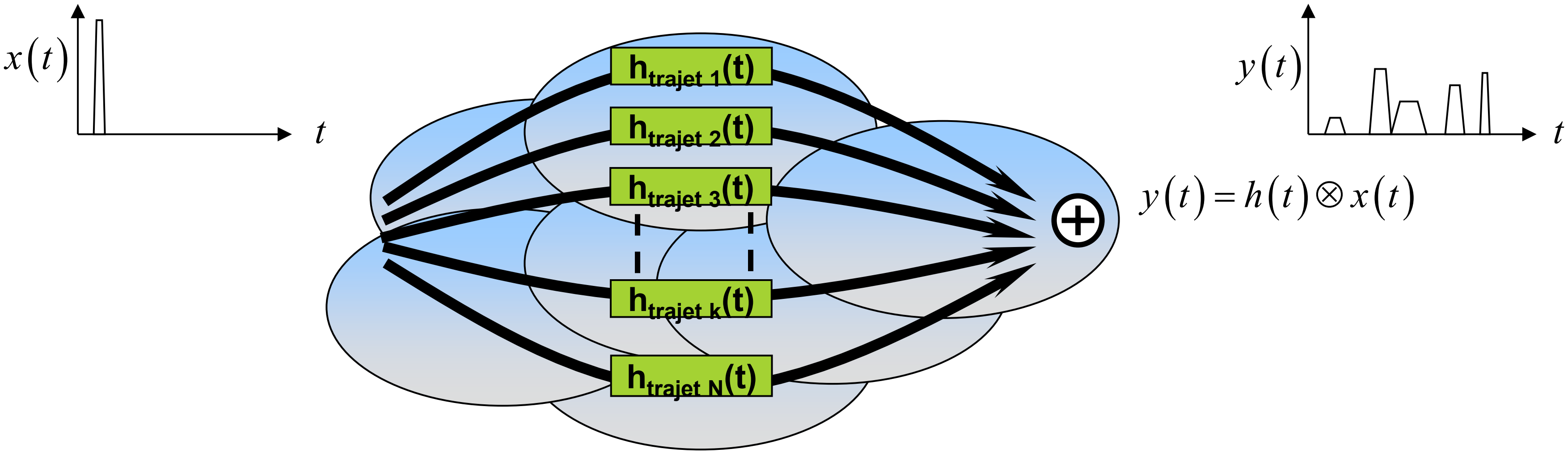
- Exemple de liaisons radio en milieu urbain



PROPAGATION MULTI-TRAJETS

Vision modèle

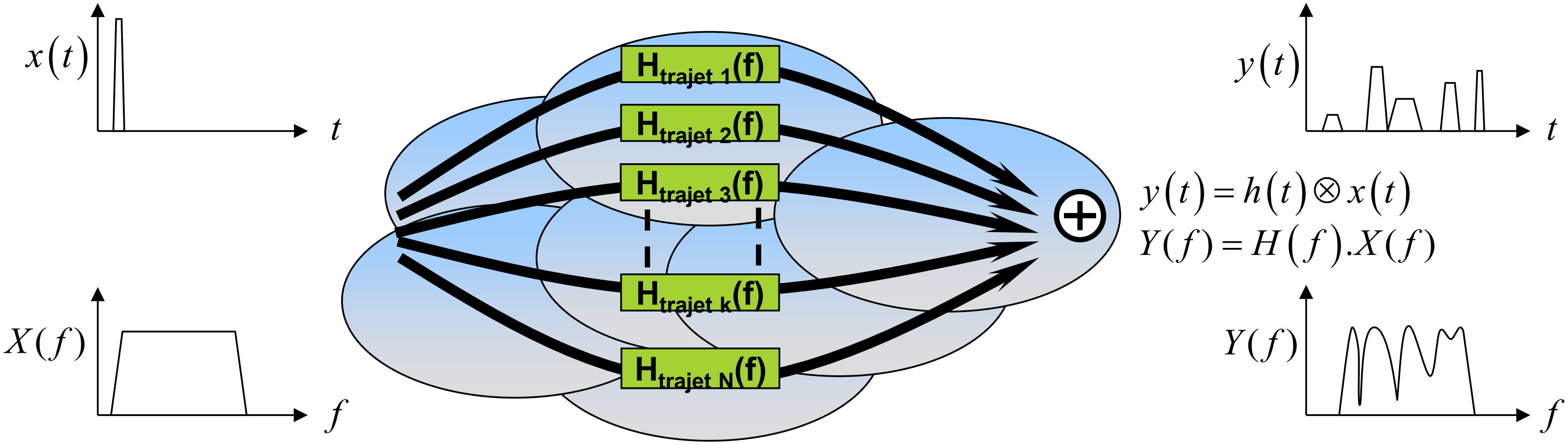
- Chaque trajet est une fonction de transfert élémentaire



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

$$h(t) = \sum_{k=1}^{N} h_{Trajet\ k}(t)$$

- Chaque trajet est une fonction de transfert élémentaire



$$y(t) = h(t) \otimes x(t)$$
$$Y(f) = H(f).X(f)$$

$$h(t) = \sum_{k=1}^{N} h_{Trajet\ k}(t) \qquad H(f) = \sum_{k=1}^{N} H_{Trajet\ k}(f)$$

PROPAGATION MULTI-TRAJETS

Influence de l'étalement temporel sur une liaison

- Exemple en transmission analogique → « Images fantômes » ou images floues

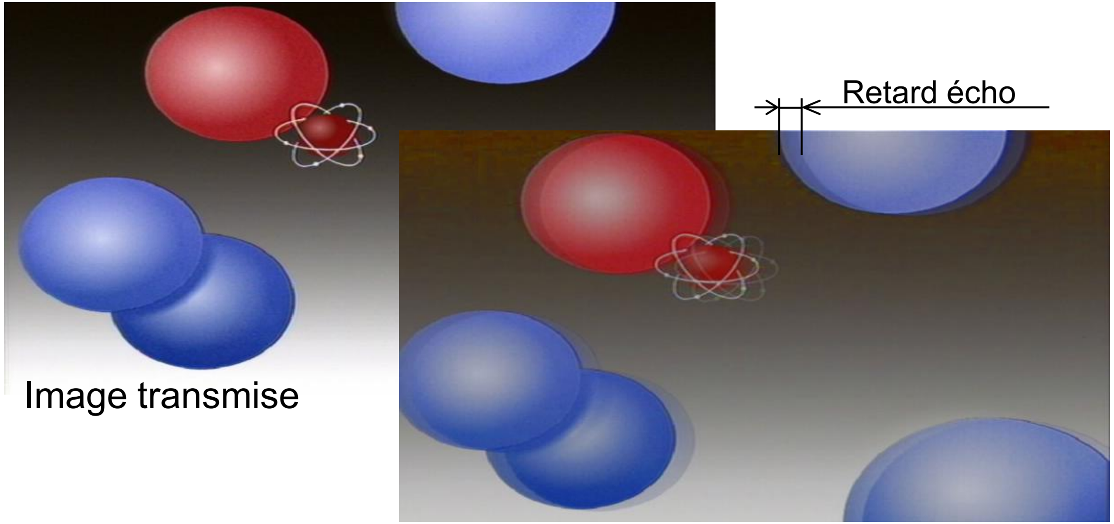
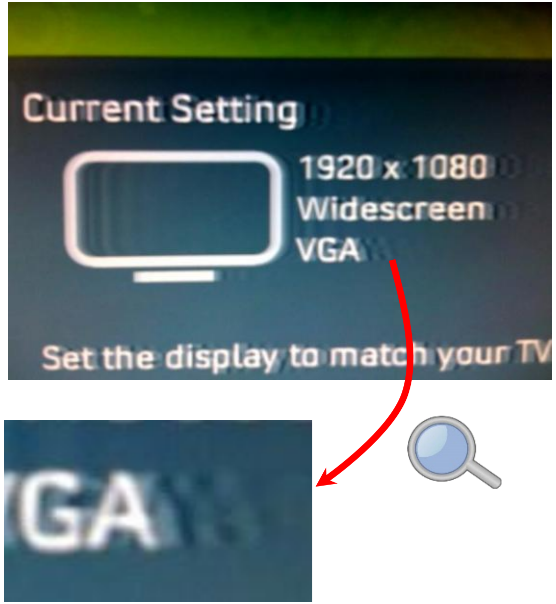


Image transmise

Image reçue

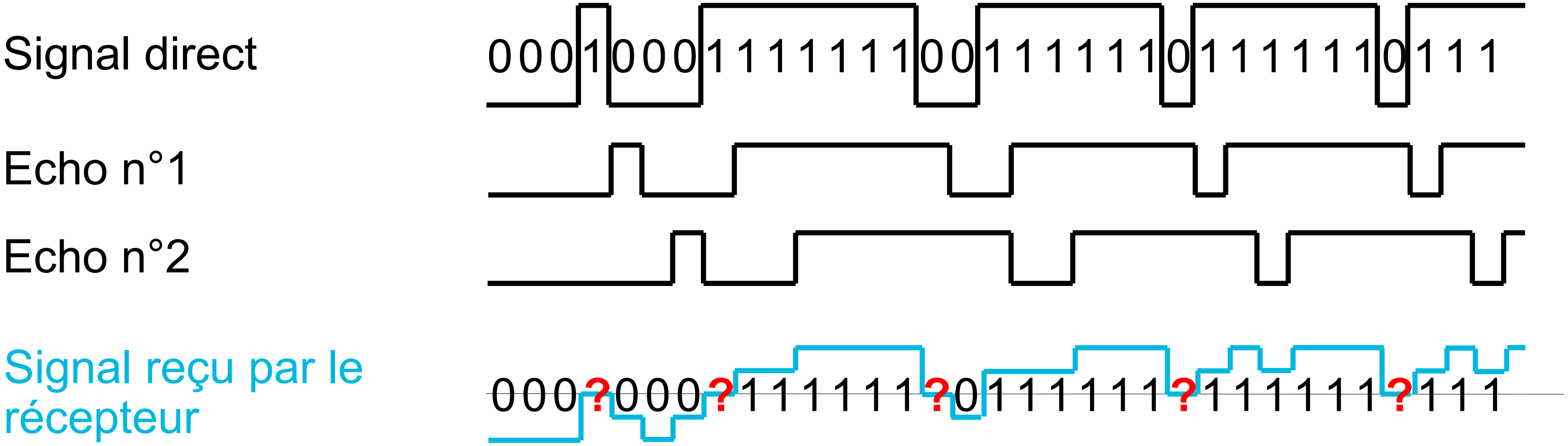


Au moins 3 échos visibles

PROPAGATION MULTI-TRAJETS

Influence de l'étalement temporel sur une liaison

- Exemple en transmission numérique

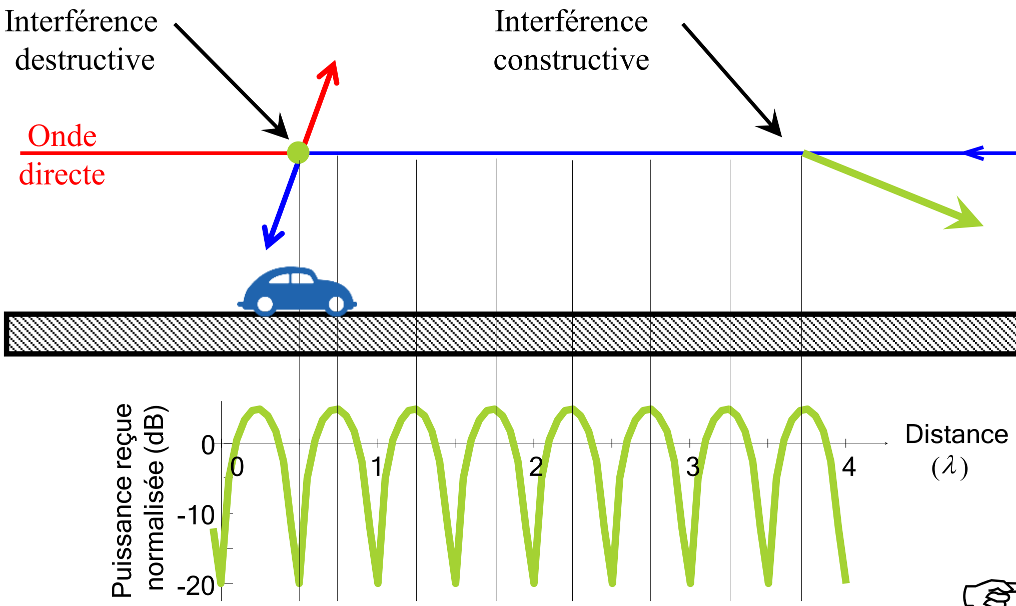


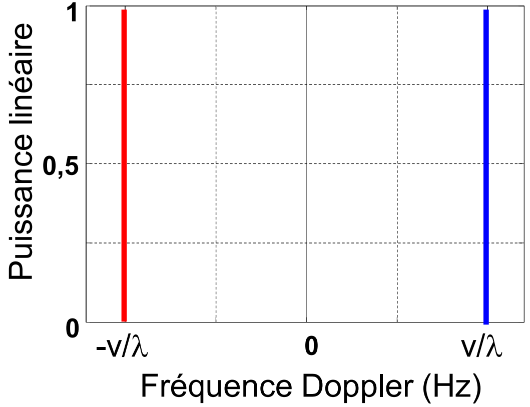
☞ Interférence entre bits → Erreurs de transmission

PROPAGATION MULTI-TRAJETS

Variabilité spatiale du signal reçu

- Exemple avec deux trajets opposés de même amplitude



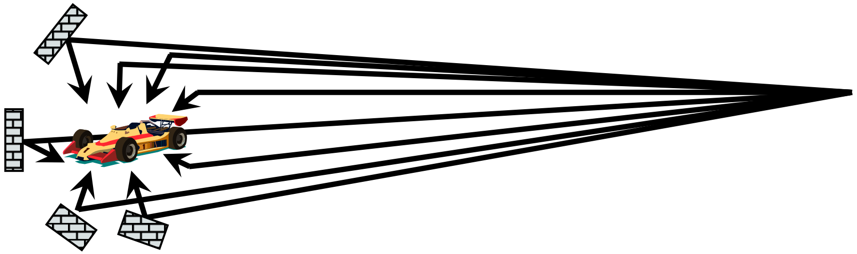


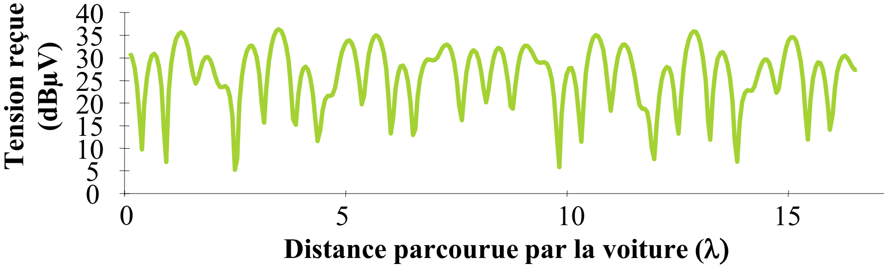
☞ Perte de signal → paquet d'erreurs

PROPAGATION MULTI-TRAJETS

Variabilité du signal reçu

- En pratique de nombreux trajets autour du récepteur





- L'existence de plusieurs trajets induit de l'interférence
- La variabilité du signal reçu apparaît avec :
  - Le déplacement de l'émetteur
  - Le déplacement du récepteur
  - Le déplacement des obstacles

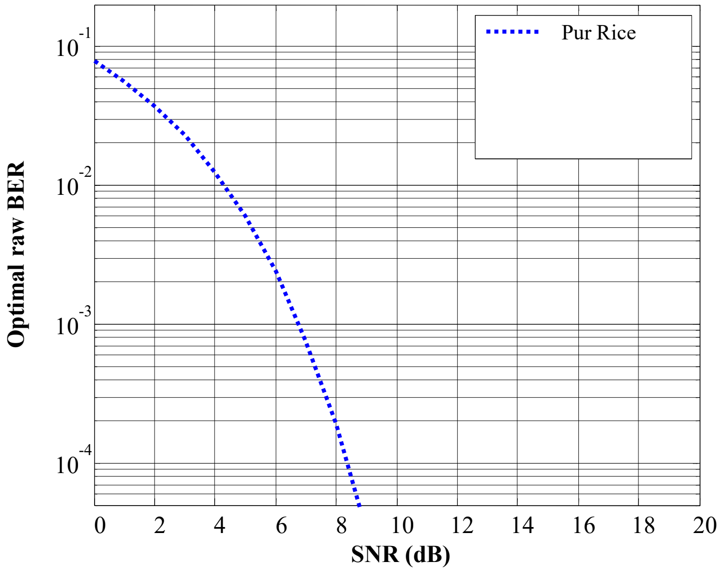
CHANNEL INFLUENCE ON COMMUNICATIONS

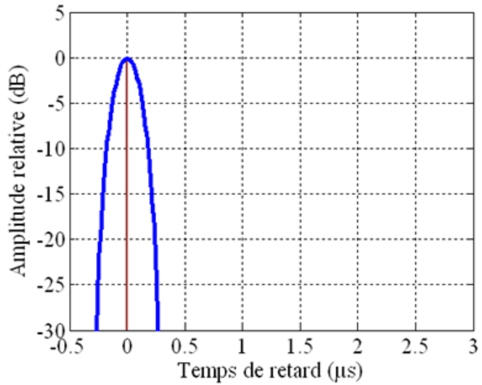
IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

CHANNEL INFLUENCE ON COMMUNICATIONS

Examples on bit error rate

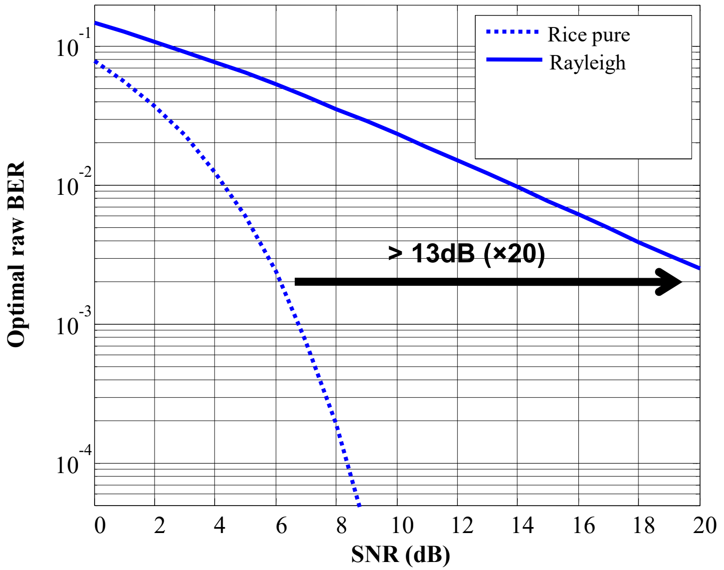
- Constant channel with a gaussian noise

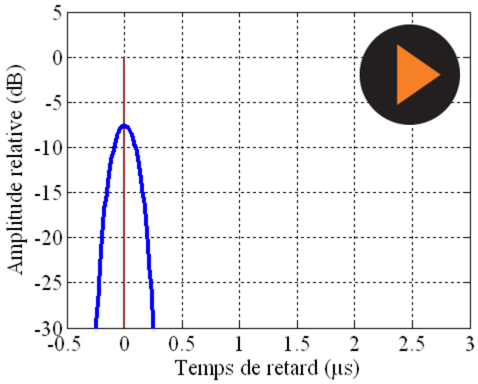




☞ The higher SNR the better performance

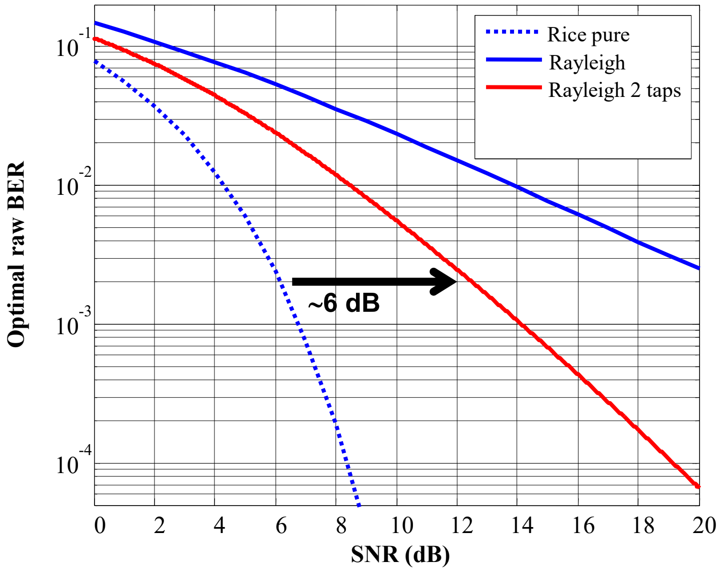
- One path with Rayleigh fast fading

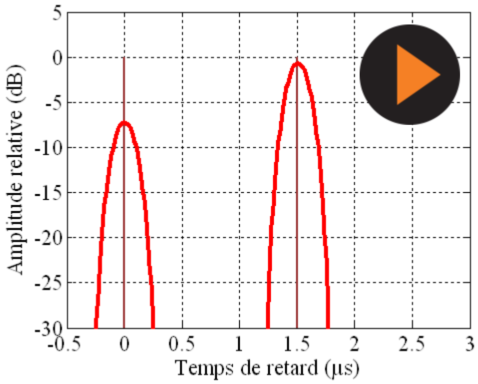




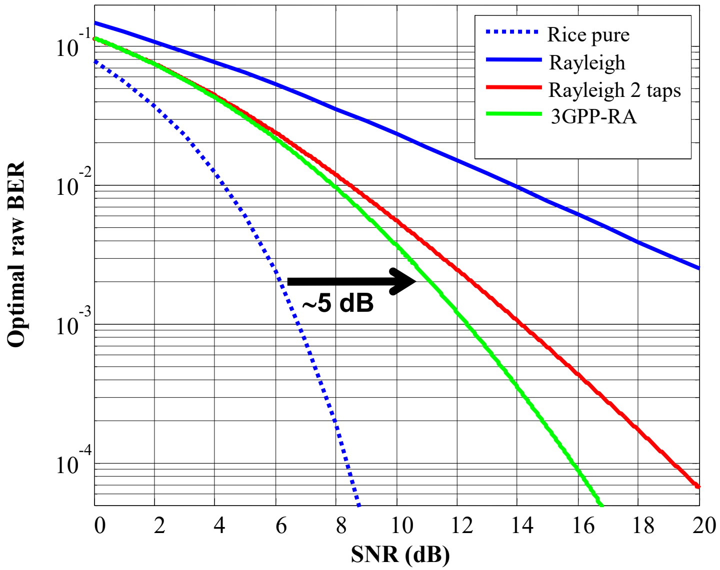
☞ Fast fading decreases system performance

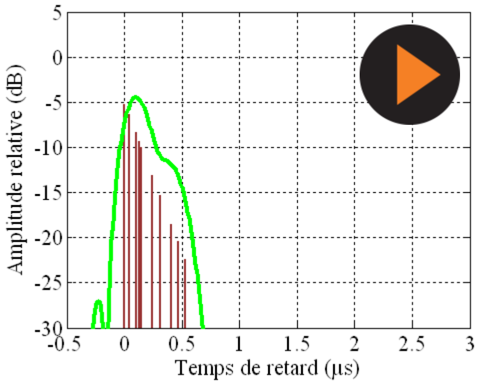
- 2 paths with independent Rayleigh fast fading





- Representative channel in rural area

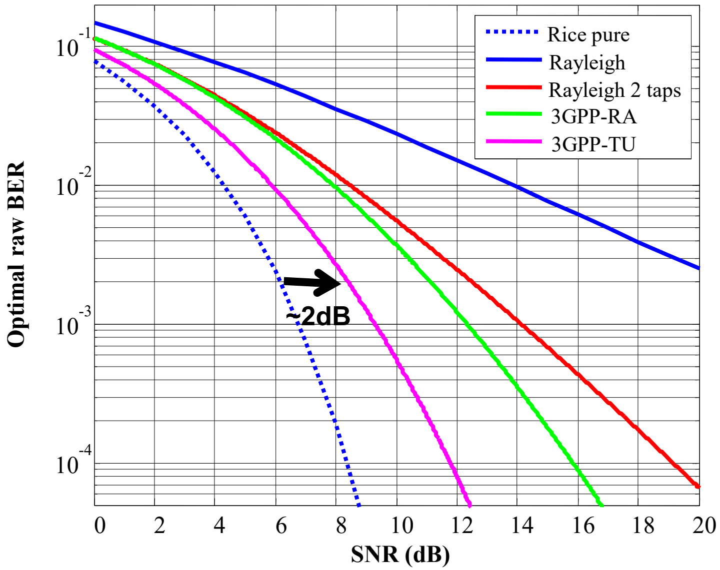


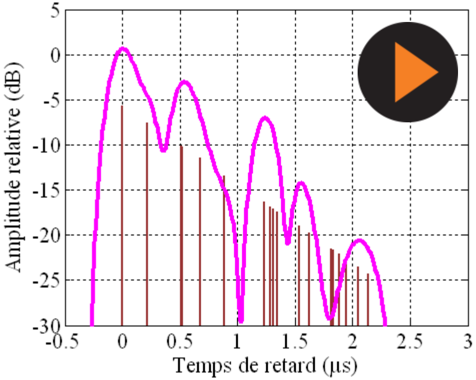


CHANNEL INFLUENCE ON COMMUNICATIONS

Examples on bit error rate

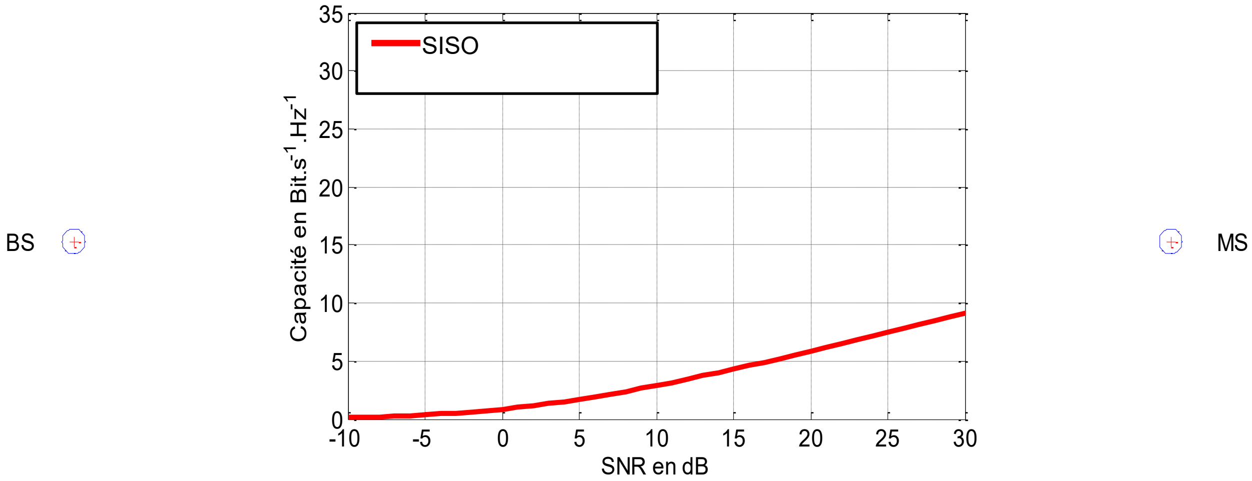
- Representative channel in urban area





☞ Time spreading can increase system performance

- Influence of power on SISO channel



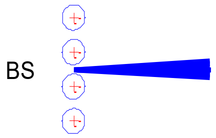
☞ Power level increases capacity… but it is inside a **LOGARITHM** !

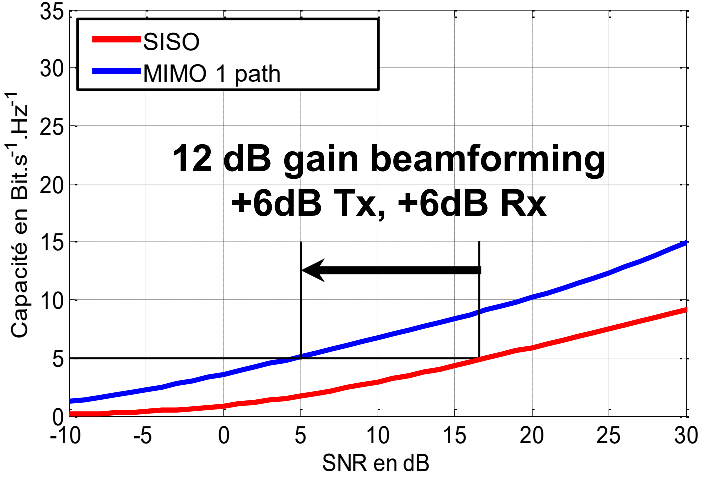
CHANNEL INFLUENCE ON COMMUNICATIONS

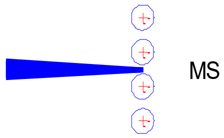
Channel capacity

- MIMO channel with a single path

With these hypothesis
- farfield condition
- single ray,
- single polarization
The rank is 1

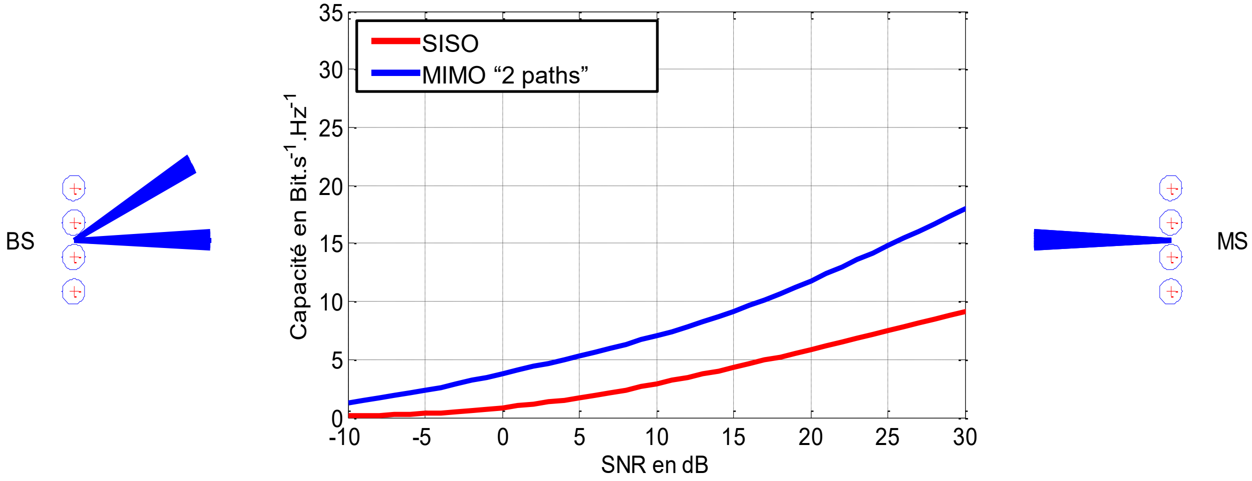




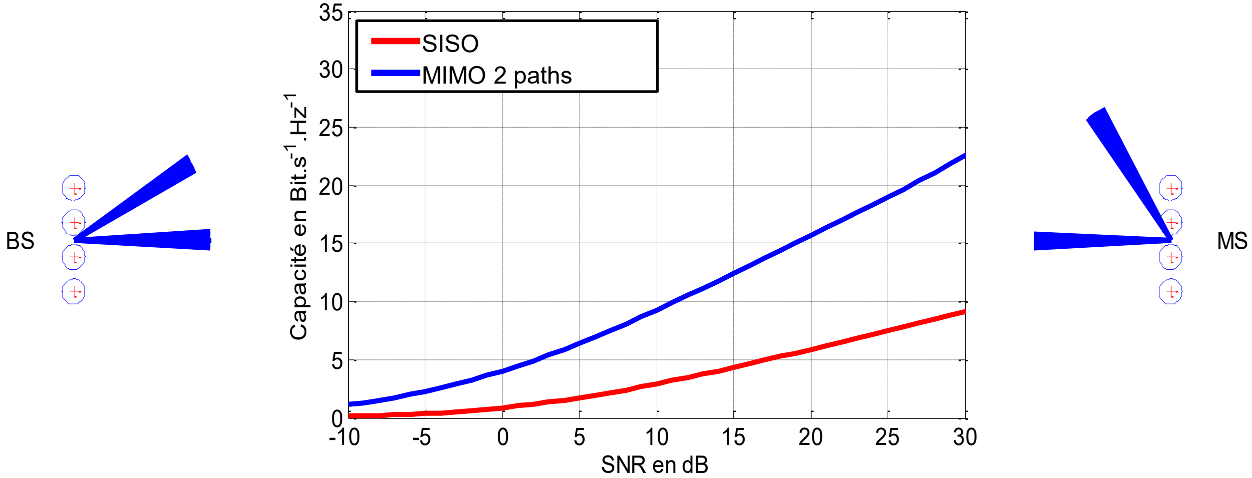


With 1 path, capacity gain is just coming from the power gain

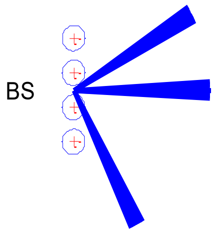
- MIMO link with spatial spreading

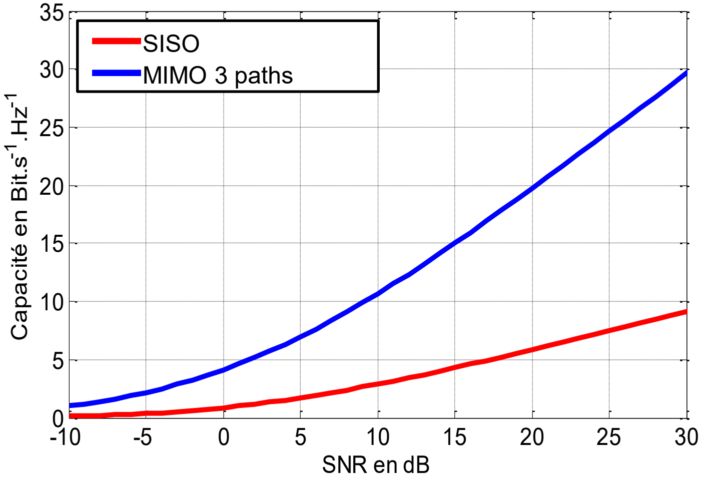


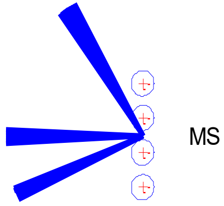
- MIMO link with spatial spreading



- MIMO link with spatial spreading

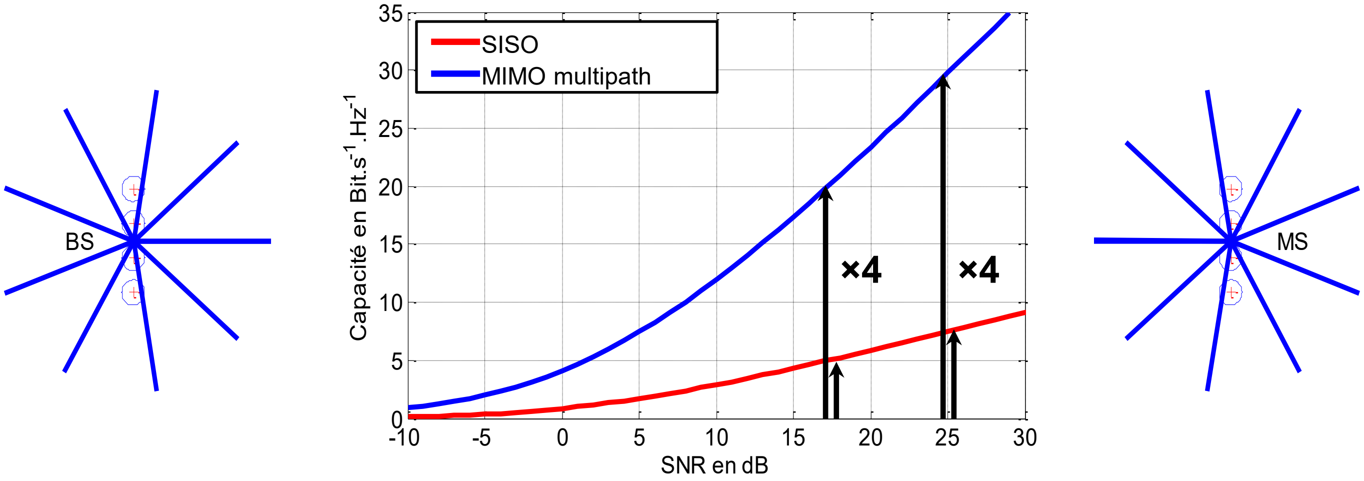






CHANNEL INFLUENCE ON COMMUNICATIONS
Channel capacity

- MIMO link with spatial spreading



☞ Spatial spreading increases MIMO channel capacity

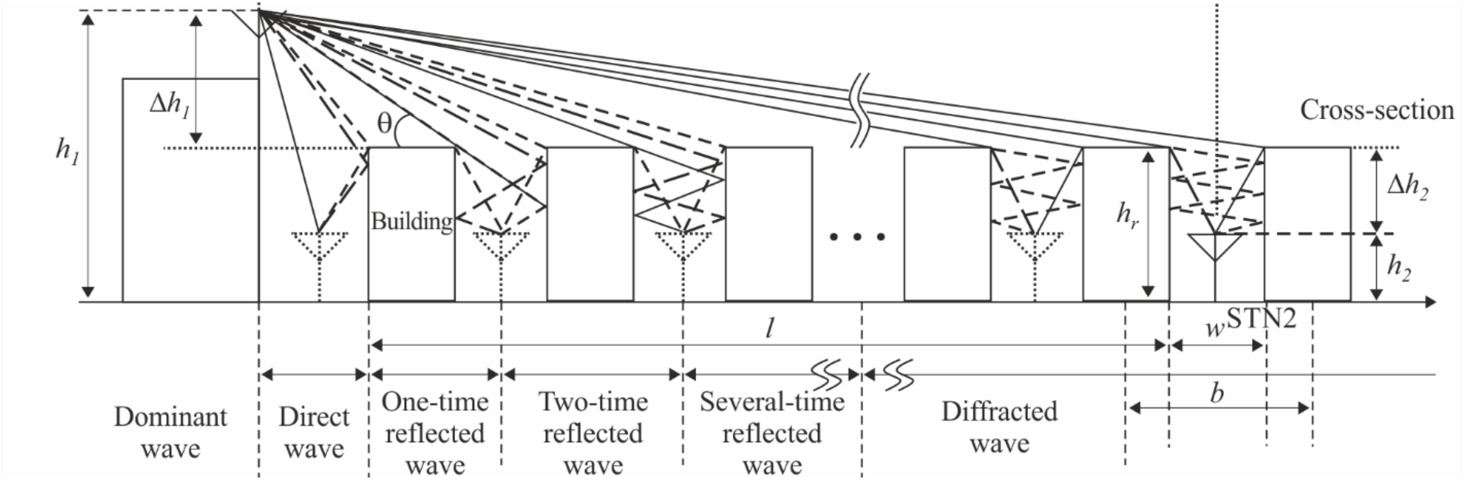
PATH LOSS CHANNEL MODELS

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

PATH LOSS CHANNEL MODELS

Complexity of propagation mechanisms

- Example in urban area avec propagation <u>over</u> roof top level
  - Propagation mostly along vertical profile
  - Reflected and diffracted paths combined at the receiver
  - Dominant phenomena depending on TX-RX distance

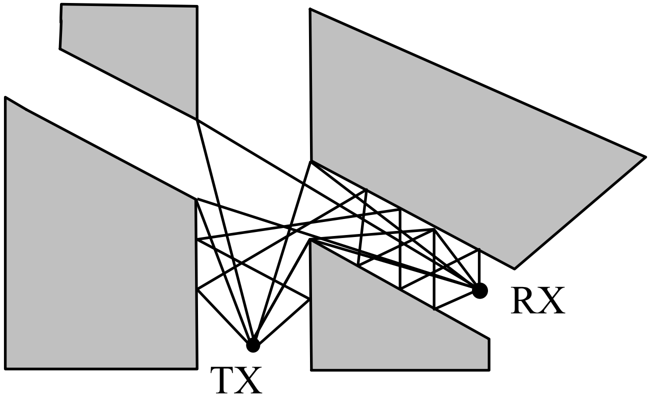


Figures : UIT recommandation 1411

PATH LOSS CHANNEL MODELS

Complexity of propagation mechanisms

- Example in urban area with propagation below mean roof top level
  - Propagation in the horizontal plane, guided by street canyon
  - Each street is a possible path
  - Reflected and diffracted paths combined at the receiver



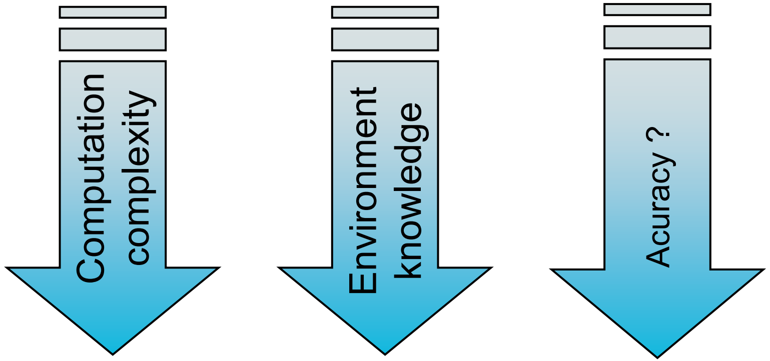
PATH LOSS CHANNEL MODELS

Path loss model

- Prediction of the AVERAGE loss of the propagation channel

- Different approaches
  - empirical
  - semi-empirical
  - deterministic

- Model examples
  - Friis (free space propagation)
  - One-slope (indoor)
  - Okumura-Hata (outdoor)
  - Erceg model (outdoor)
  - COST 231 (outdoor)
  - Keenan-Motley (indoor)
  - Ray tracing / ray launching

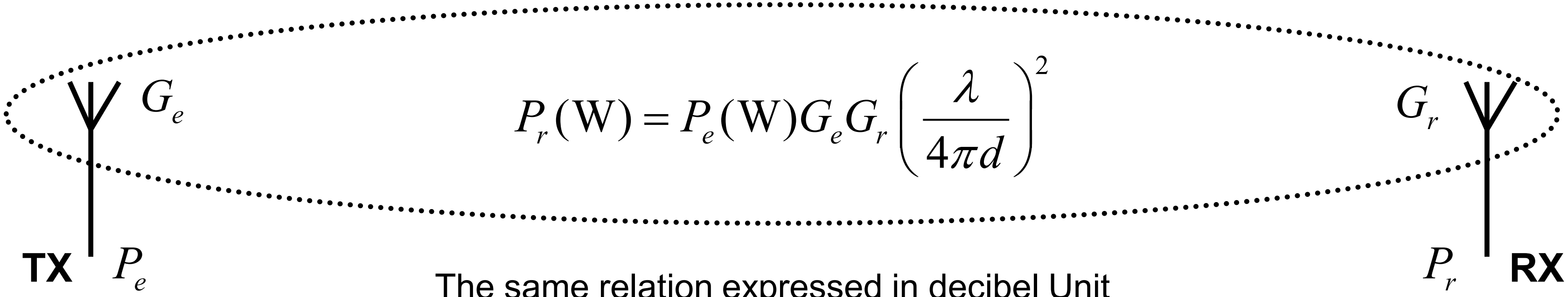


PATH LOSS CHANNEL MODELS

The Friis Formula

- Received power level computation in LOS condition

- Requirement
  - The first Fresnel zone without any obstacle
  - Far field condition



$$P_r(\mathrm{W}) = P_e(\mathrm{W}) G_e G_r \left(\frac{\lambda}{4\pi d} \right)^2$$

The same relation expressed in decibel Unit

$$P_r(\mathrm{dBm}) = P_e(\mathrm{dBm}) + G_e(\mathrm{dBi}) + G_r(\mathrm{dBi}) - L_0$$

$$L_0 = 32{,}44 + 20\log_{10}(f_{MHz}) + 20\log_{10}(d_{km})$$

PATH LOSS CHANNEL MODELS

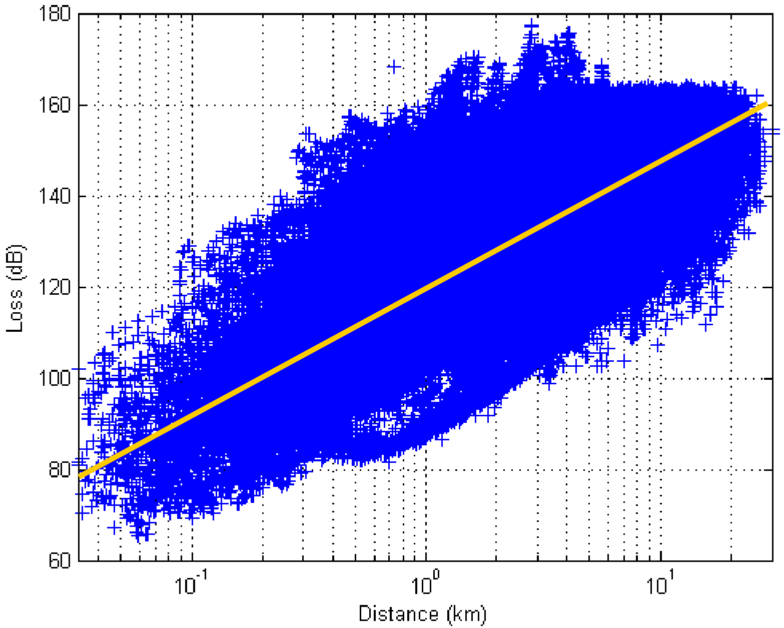
Okumura-Hata model

- Simple model for dimensioning
  - No data base, just environment classification
  - Based on many measurement campaigns
  - Empirical approach with abacus (Okumura 1968)
  - Analytical formula (Hata 1980)

$$Loss = A + B\log_{10}(f) + C\log_{10}(d)$$
$$+D(h_{Mobile}) + E(h_{Base})$$

with A and B depending on frequency, Antenna heigh et environment

- Single slope model
- Several optimizations for 2G, 3G… 5G…
- Many uses for dimensioning



- Optimization example COST 231 projet → COST-HATA model
- Model description

$$
\begin{aligned}
Loss_{dB} = & \, 46,3 \\
& + 33,9 \log_{10}\left(f_{MHz}\right) \\
& - 13,82 \log_{10}\left(h_m^{Base}\right) \\
& - a\left(h_m^{Mobile}\right) \\
& + \left(44,9 - 6,55 \log_{10}\left(h_m^{Base}\right)\right) \log_{10}\left(d_{km}\right) \\
& + C_m
\end{aligned}
$$

f_{MHz}	1500 … 2000 MHz
h_m^{Base}	30 … 200 m
h_m^{Mobile}	1… 10 m
d_{km}	1… 20 km

$$
\begin{aligned}
a\left(h_m^{Mobile}\right) = & \left(1,1 \log_{10}\left(f_{MHz}\right) - 0,7\right) h_m^{Mobile} \\
& - \left(1,56 \log_{10}\left(f_{MHz}\right) - 0,8\right)
\end{aligned}
$$

$$
C_m = \begin{cases} 0 \text{ dB} & \text{for medium sized city and suburban} \\ 3 \text{ dB} & \text{for metropolitan centres} \end{cases}
$$

PATH LOSS CHANNEL MODELS
Motley-Keenan model

- Semi empirical model for indoor based on direct ray
- Free space loss with additional loss due to wall transmissions

$$L(dB) = L_{FS} + k_w L_w + k_f L_f$$

- Advanced models include type of walls and floor improvement proposed in COST 231

$$L(dB) = L_{FS} + L_C + \sum_{i=1}^{I} k_{wi} L_{wi} + k_f^{\left[\frac{k_f+2}{k_f-1} - b\right]} L_f$$

L_{FS} Free Space loss

L_C Constant

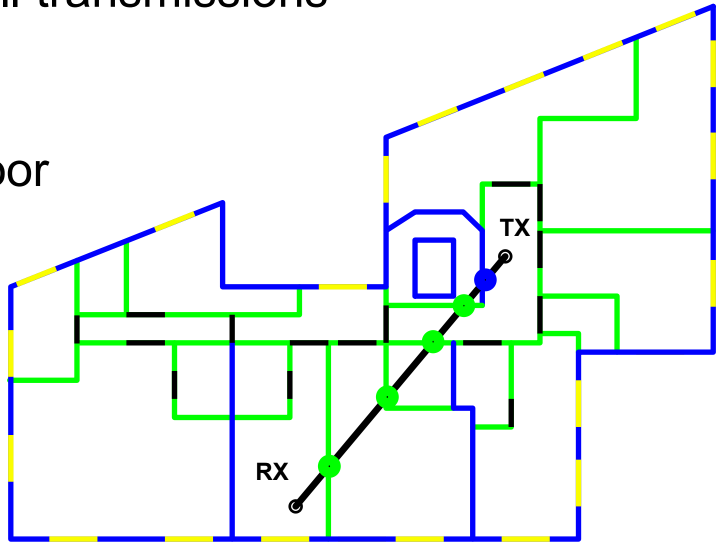
K_{wi} Number of wall (type i)

L_{wi} Loss of the wall (type i)

k_f Number of crossed floor

L_f Loss of a floor

b Constant

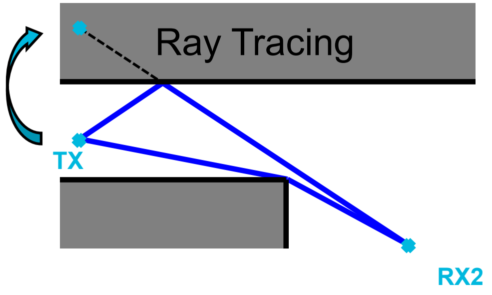


J. Keenan and A. Motley. Radio coverage in buildings.British TelecomTechnology Journal, 8(1):19–24, 1990
Digital mobile radio towards future generation systems: COST 231 Final Report

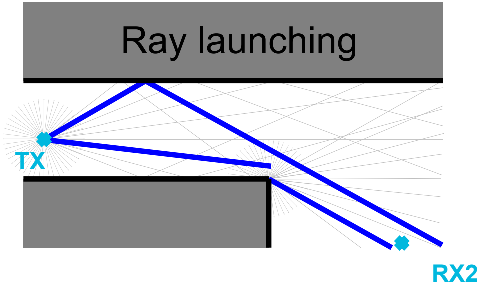
PATH LOSS CHANNEL MODELS

Ray models

- Two different technics
  - Ray tracing → point to point simulation
  - Ray launching → suitable for coverage

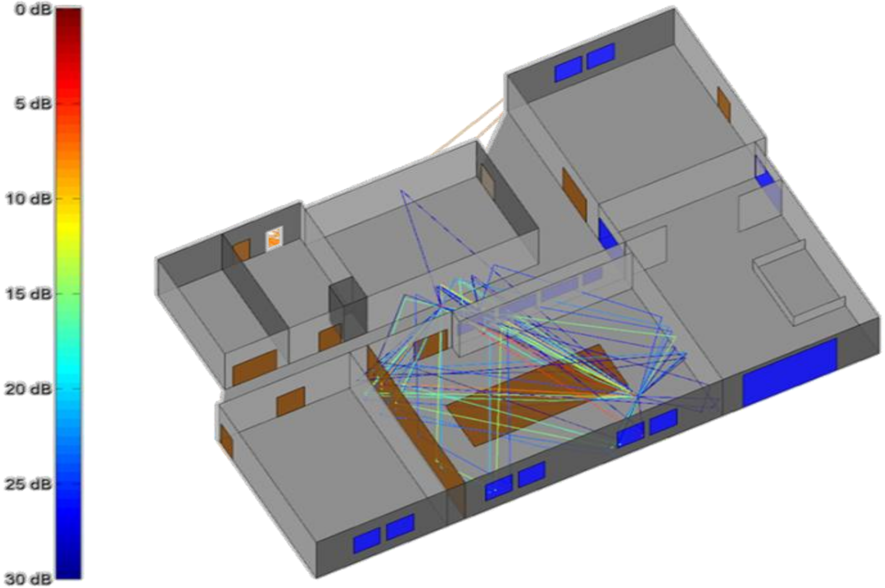


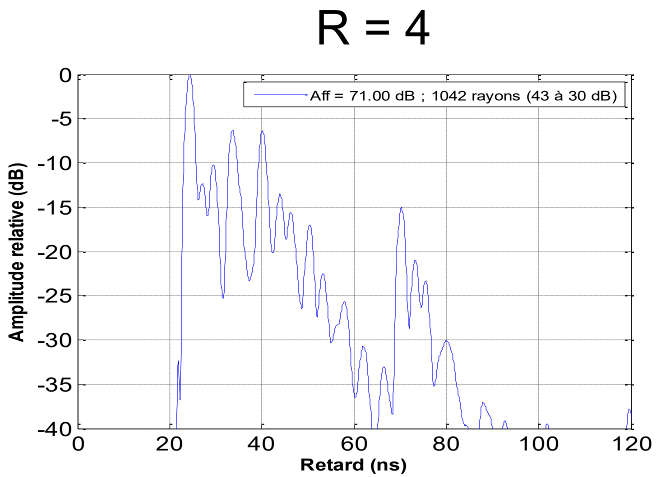
- Computation constraints
  - Required very accurate data base
  - High computational cost



- More than a simple path loss model
  - Channel impulse response
  - Direction of arrival and departure of rays
  - MIMO channel capacity
  - Wideband channel parameters…

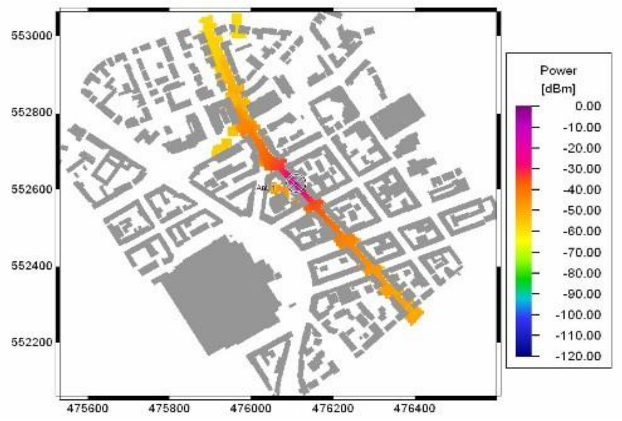
- Many rays are computed but just a few are significant



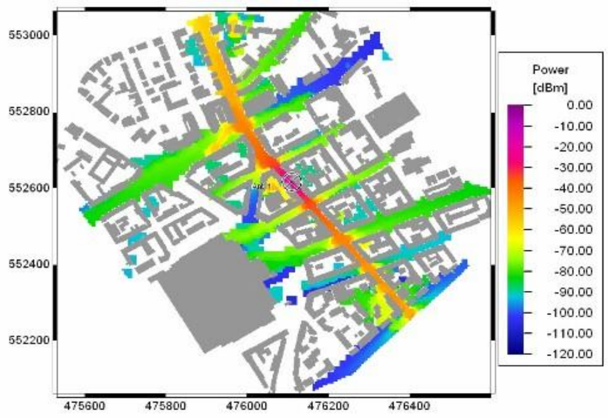


- The configuration of the physical interaction number is really important
  - Too small → Fast computation but inaccurate results
  - Too high → Accurate results but infinite simulation time !!!

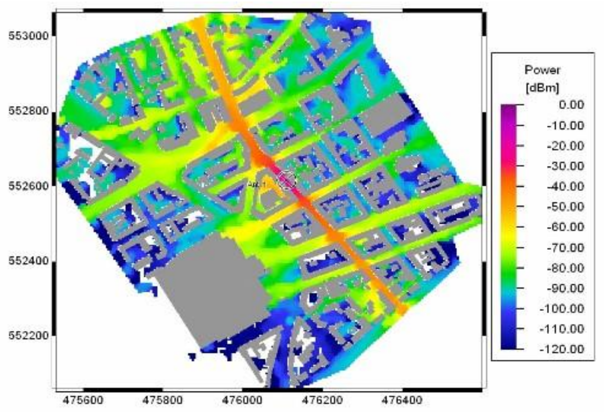
⇨ Trade-off to find



direct
1 Reflection



direct
2 Reflections
1 Diffraction

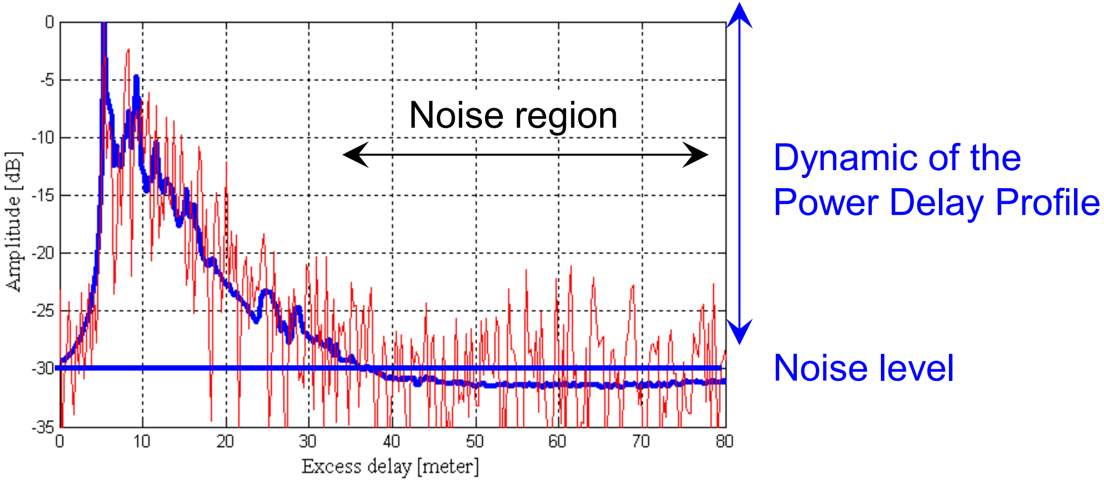


direct
6 Reflections
2 Diffractions
2 R + 1 D

WIDEBAND CHANNEL MODELS

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

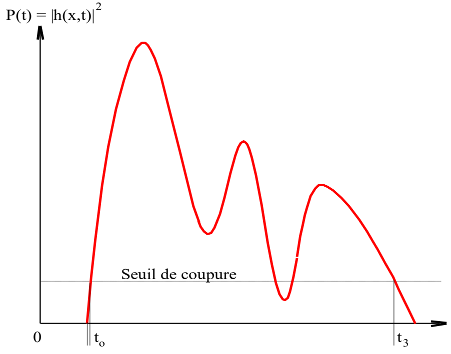
- PDP Power Delay Profile



$$PDP(\tau) = \sqrt{\frac{1}{N}\sum_{k=1}^{N} \left| h_k(\tau) \right|^2}$$

- Mean delay : τ_m

$$\tau_m = \frac{\int_{t_0}^{t_3} \tau P(\tau) d\tau}{\int_{t_0}^{t_3} P(\tau) d\tau} \quad \text{or} \quad \frac{\sum_k \tau_k P(\tau_k)}{\sum_k P(\tau_k)}$$



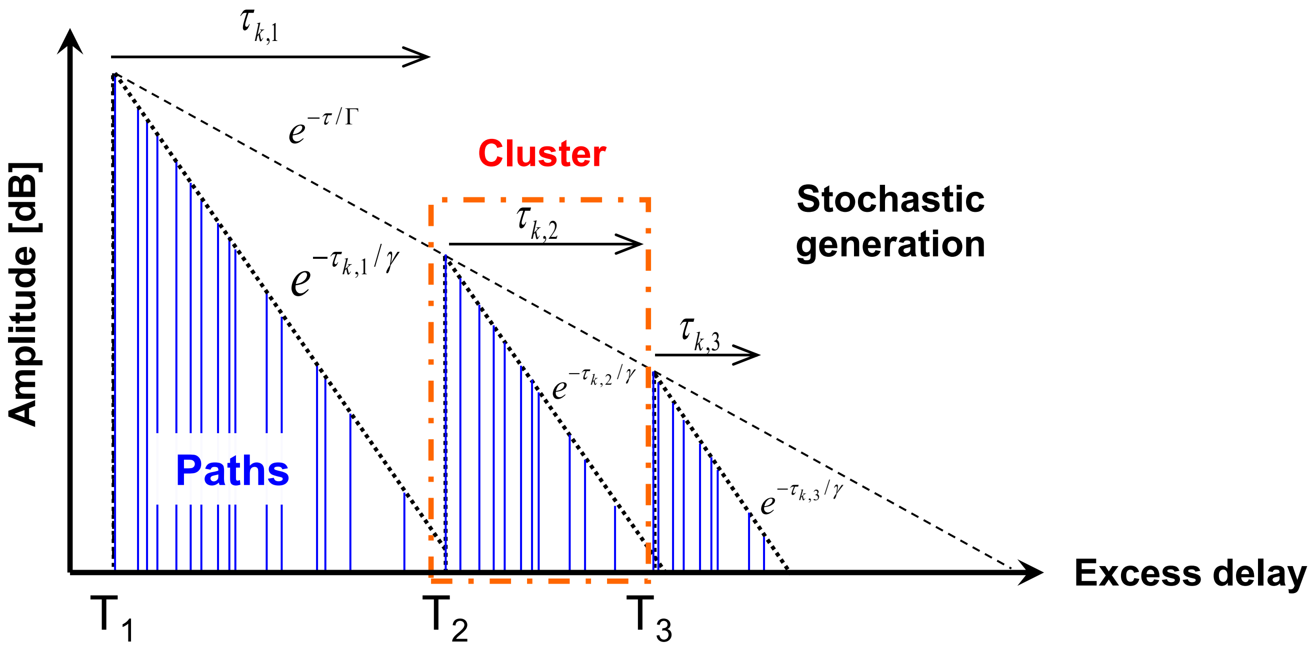
- Root mean square delay spread : ds

$$ds^2 = \frac{\int_{t_0}^{t_3} (\tau - \tau_m)^2 P(\tau) d\tau}{\int_{t_0}^{t_3} P(\tau) d\tau} \quad \text{or} \quad \frac{\sum_k (\tau_k - \tau_m)^2 P(\tau_k)}{\sum_k P(\tau_k)}$$

- Same parameters in Doppler Domain
  - Mean Doppler offset
  - Rms Doppler Spread

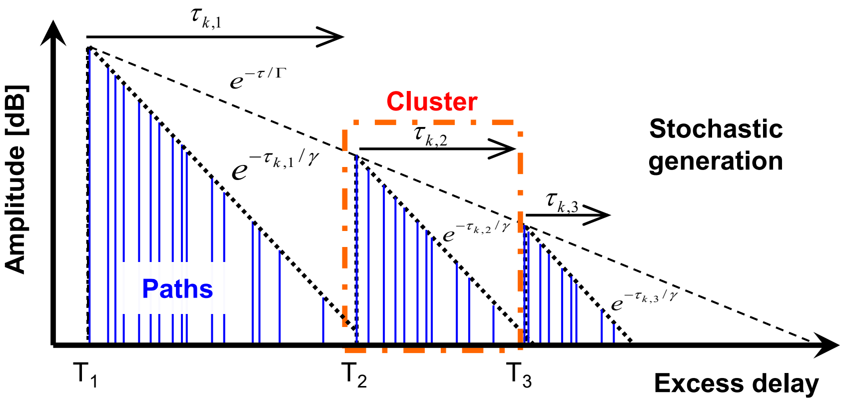
- Two important modelling approaches introduced in 1987
  - Stochastic modelling
  - Cluster of paths

- Principle



A. Saleh and R. Valenzuela, "A Statistical Model for Indoor Multipath Propagation," in IEEE JSAC, vol. 5, no. 2, pp. 128-137, February 1987.

- Two important modelling approaches introduced in 1987
  - Stochastic modelling
  - Cluster of paths



- Principle

$$h(\tau)=\sum_{l=1}^{L}\sum_{k=1}^{K_l}\beta_{k,l}\, e^{j\theta_{k,l}}\,\delta\left(\tau-T_l-\tau_{k,l}\right)$$

T_l, $\tau_{k,l}$: Cluster and rays time of arrival
L : Number of clusters
Λ, λ : arrival rate of clusters Λ and rays λ
Γ, γ : Inter and intra cluster decay
$\theta_{k,l}$: Arbitrary angle [0, 2 π[
K_l : Number of rays in cluster l

$$\overline{\beta_{k,l}^2}=\overline{\beta^2(0,0)}\,e^{-T_l/\Gamma}\,e^{-\tau_{k,l}/\gamma}$$

$$p\left(\tau_l-\tau_{l-1}\right)=\lambda\, e^{-\lambda(\tau_l-\tau_{l-1})}$$

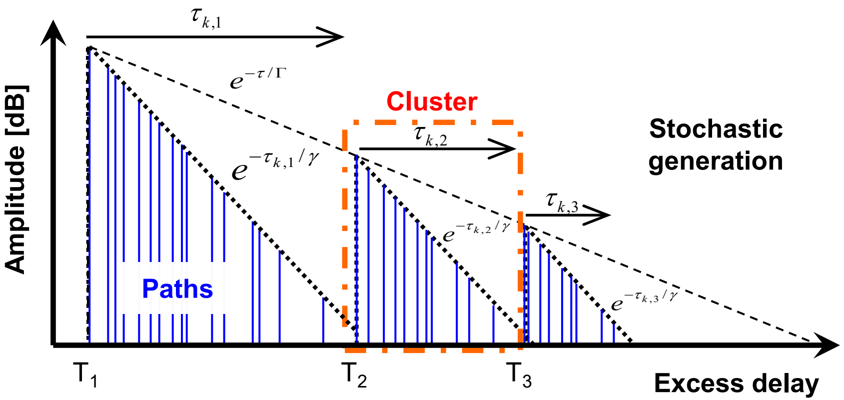
$$p\left(T_l-T_{l-1}\right)=\Lambda\, e^{-\Lambda(T_l-T_{l-1})}$$

A. Saleh and R. Valenzuela, "A Statistical Model for Indoor Multipath Propagation," in IEEE JSAC, vol. 5, no. 2, pp. 128-137, February 1987.

WIDEBAND CHANNEL MODELS

The Saleh and Valenzuela model

- Two important modelling approaches introduced in 1987
  - Stochastic modelling
  - Cluster of paths



- Principle

$$h(\tau)=\sum_{l=1}^{L}\sum_{k=1}^{K_l}\beta_{k,l}\, e^{j\theta_{k,l}}\;\delta(\tau-T_l-\tau_{k,l})$$

- Inspired many channel models

- Difficult to implement in 1987

A. Saleh and R. Valenzuela, "A Statistical Model for Indoor Multipath Propagation," in IEEE JSAC, vol. 5, no. 2, pp. 128-137, February 1987.

WIDEBAND CHANNEL MODELS

802.15.4a channel model

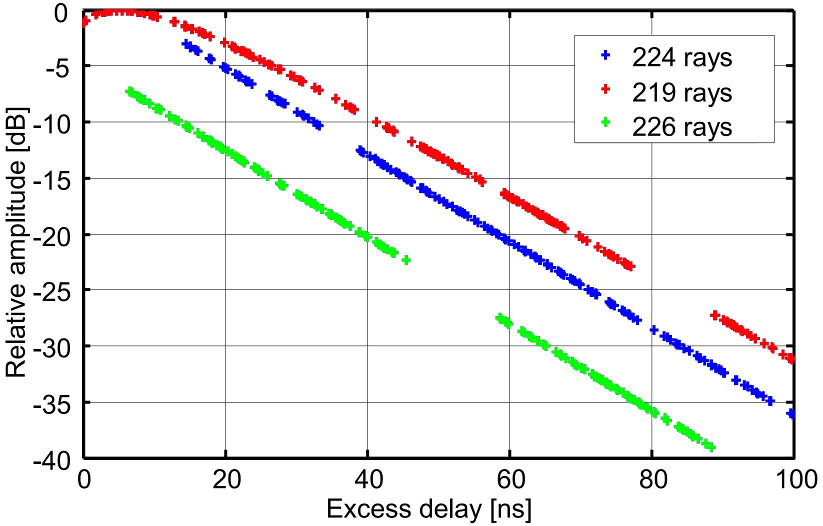
- Developed between 09/2003 → 09/2004
- Saleh and Valenzuela inspired
- Standard for sensor networks
- 6 typical environments
  - Indoor residential
  - Indoor office
  - Industrial
  - Body Area Network
  - Outdoor
  - Agricultural area
- Parameter example in residential area
- Matlab™ code available

Channel impulse response model

	Residential	
	LOS	NLOS
Pathloss		
PL_0 [dB]	43.9	48.7
n	1.79	4.58
$S[dB]$	2.22	3.51
A_{ant}	3dB	3dB
κ	1.12±0.12	1.53±0.32
Power delay profile		
$\bar{L}$	3	3.5
Λ [1/ns]	0.047	0.12
λ_1, λ_2 [1/ns],β	1.54, 0.15 , 0.095	1.77, 0.15, 0.045
Γ [ns]	22.61	26.27
k_γ	0	0
γ_0 [ns]	12.53	17.50
$\sigma_{\mathrm{cluster}}$ [dB]	2.75	2.93
Small-scale fading		
m_0 [dB]	0.67	0.69
k_m	0	0
$\hat{m}_0$ [dB]	0.28	0.32
$\hat{k}_m$,	0	0
$\tilde{m}_0$	NA: all paths have	same m-factor distribution

A. Molish et al, IEEE 802.15.4a channel model - final report, 2004

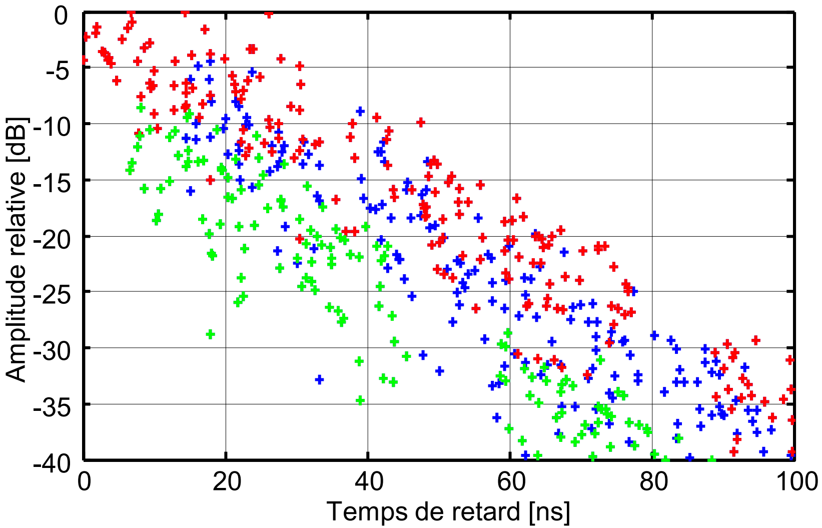
- Generation example
  - Step 1 : Clusters and rays random generation



WIDEBAND CHANNEL MODELS

802.15.4a channel model

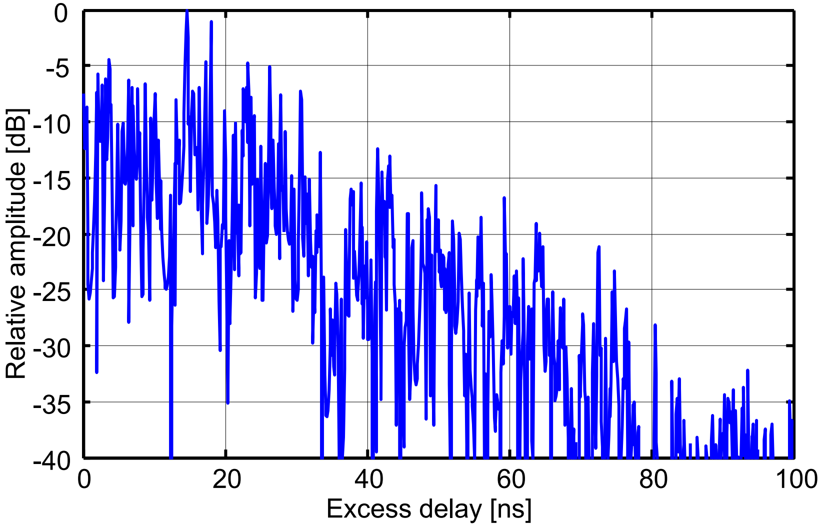
- Generation example
  - Step 1 : Clusters and rays random generation
  - Step 2 : Adding shadowing effect



WIDEBAND CHANNEL MODELS

802.15.4a channel model

- Generation example
  - Step 1 : Clusters and rays random generation
  - Step 2 : Adding shadowing effect
  - Step 3 : Adding frequency dependence

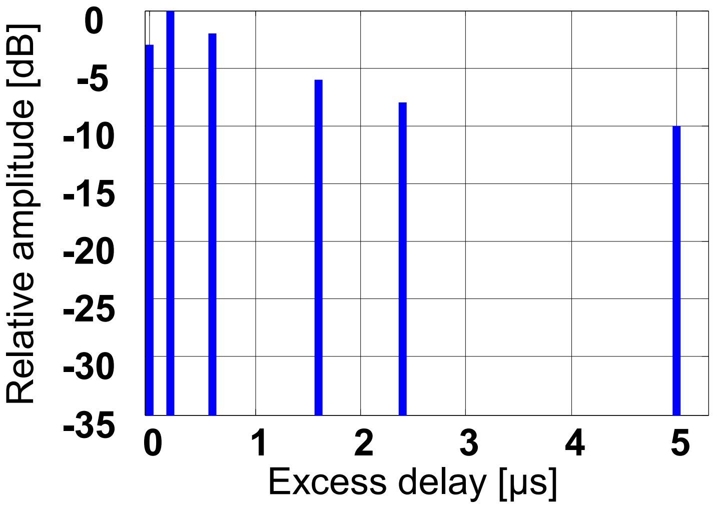


WIDEBAND CHANNEL MODELS

Tapped-delay line models

- The channel impulse response is modeled by a limited set of paths

$$h(\tau,t)=\sum_{i=1}^{N} g_i(t).\delta(\tau-\tau_i)$$

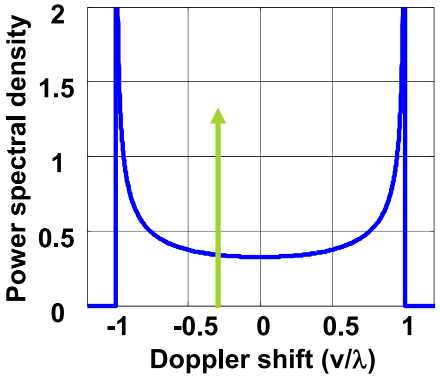


- Each path is defined by
  - An excess delay
  - A mean attenuation
  - A statistical distribution
  - A doppler spectrum

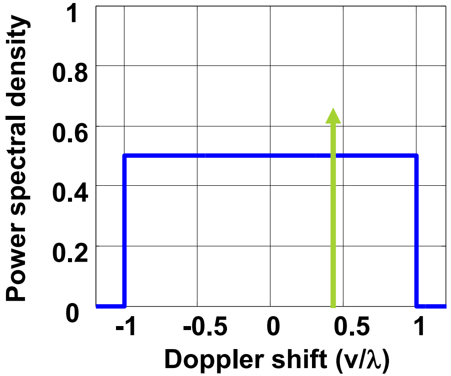
- The well-known TU channel model for GSM (1993)

- The doppler spectrum
  - Temporal correlation modelling
  - Rayleigh statistical distribution
  - Typical shapes are used in normalized channel models

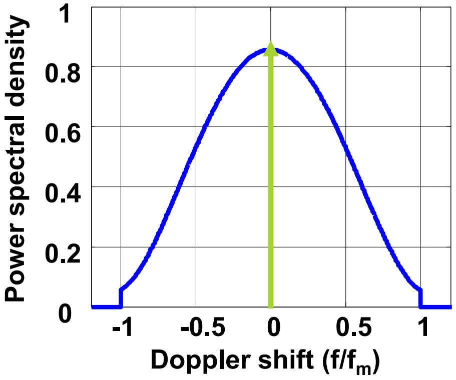
A dirac component can be added for Rice statistical distribution



"Class"ical shape (Mobile)



"Flat" shape (Indoor link)



"Rounded" shape (p2p link)

WIDEBAND CHANNEL MODELS

Tapped-delay line models

- Limitations
  - Single typical channel impulse response
  - Limited number of paths
  - Periodic transfer function

- Advantages
  - Very simple representation
  - Very simple implementation soft and hard
  - Many dedicated versions in normalization : 2,3,45G

WIDEBAND CHANNEL MODELS

Tapped-delay line models

- Models ETSI for GSM (1993)
- 6 or 12 paths
- 3 environments (x the speed)
  - RAx : Rural Area
  - TUx : Typical Urban
  - HTx : hilly terrain
- 2 models per environment
- 1 model for hardware testing
  - EQx : Equalization

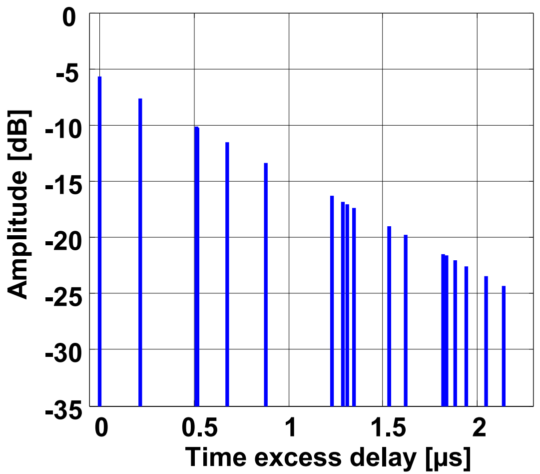
Tap number	Relative time (µs) (1)	Relative time (µs) (2)	Average relative power (dB) (1)	Average relative power (dB) (2)	doppler spectrum
1	0.0	0.0	- 3.0	- 3.0	CLASS
2	0.2	0.2	0.0	0.0	CLASS
3	0.5	0.6	- 2.0	- 2.0	CLASS
4	1.6	1.6	- 6.0	- 6.0	CLASS
5	2.3	2.4	- 8.0	- 8.0	CLASS
6	5.0	5.0	- 10.0	- 10.0	CLASS

ETSI, GSM 05.05-DCS, Radio transmission and réception octobre1993

WIDEBAND CHANNEL MODELS

Tapped-delay line models

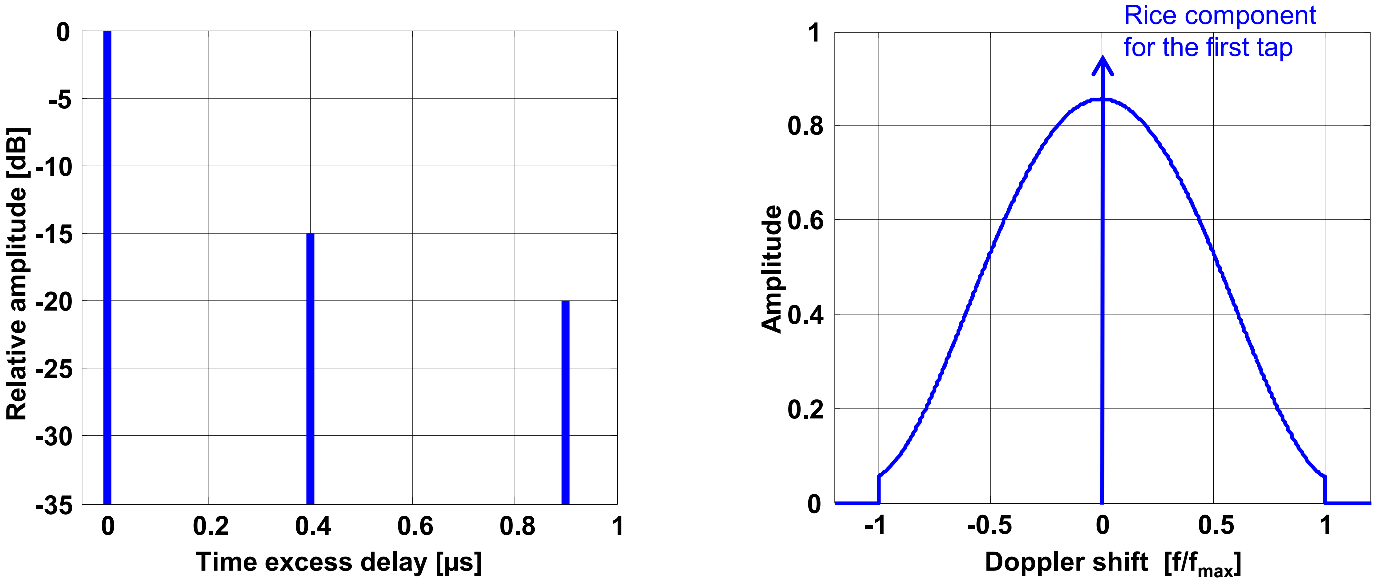
- 3GPP TR25.943 channel model (2000) → **6G** systems
- Improvement of GSM model : model paths, high bandwidth
- 3 environments
  - RAx : Rural Area
  - TUx : Typical Urban
  - HTx : hilly terrain
  -
- Influence Saleh et Valenzuela
  - Exponential decay
  - Arbitrary time of arrival



Tap number	Relative time (µs)	average relative power (dB)	Doppler spectrum
1	0	-5.7	Class
2	0.217	-7.6	Class
3	0.512	-10.1	Class
4	0.514	-10.2	Class
5	0.517	-10.2	Class
6	0.674	-11.5	Class
7	0.882	-13.4	Class
8	1.230	-16.3	Class
9	1.287	-16.9	Class
10	1.311	-17.1	Class
11	1.349	-17.4	Class
12	1.533	-19.0	Class
13	1.535	-19.0	Class
14	1.622	-19.8	Class
15	1.818	-21.5	Class
16	1.836	-21.6	Class
17	1.884	-22.1	Class
18	1.943	-22.6	Class
19	2.048	-23.5	Class
20	2.140	-24.3	Class

3GPP, TR 25.943, Technical Specification Group Radio Access Network, 2000-2024

- IEEE 802.16 channel model (2001) : point to point communication



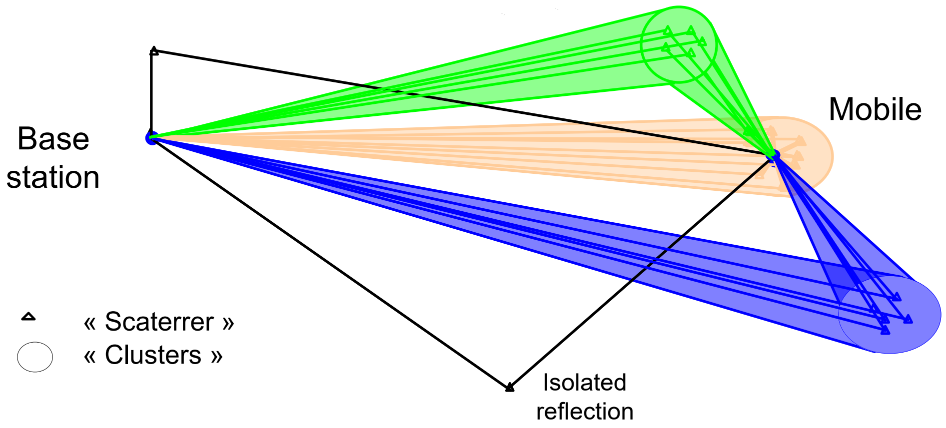
Example of the SUI-1 channel model (3 paths)

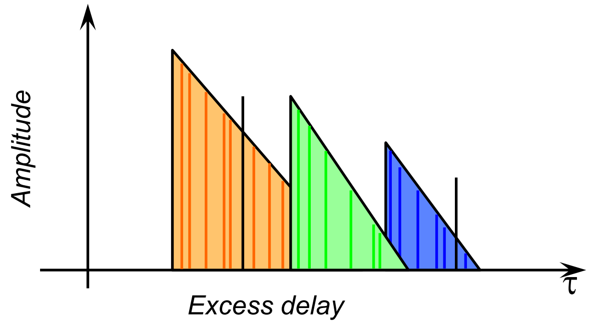
IEEE 802.16, **Channel Models for Fixed Wireless Applications**, juillet 2001

WIDEBAND CHANNEL MODELS

Stochastic geometric models

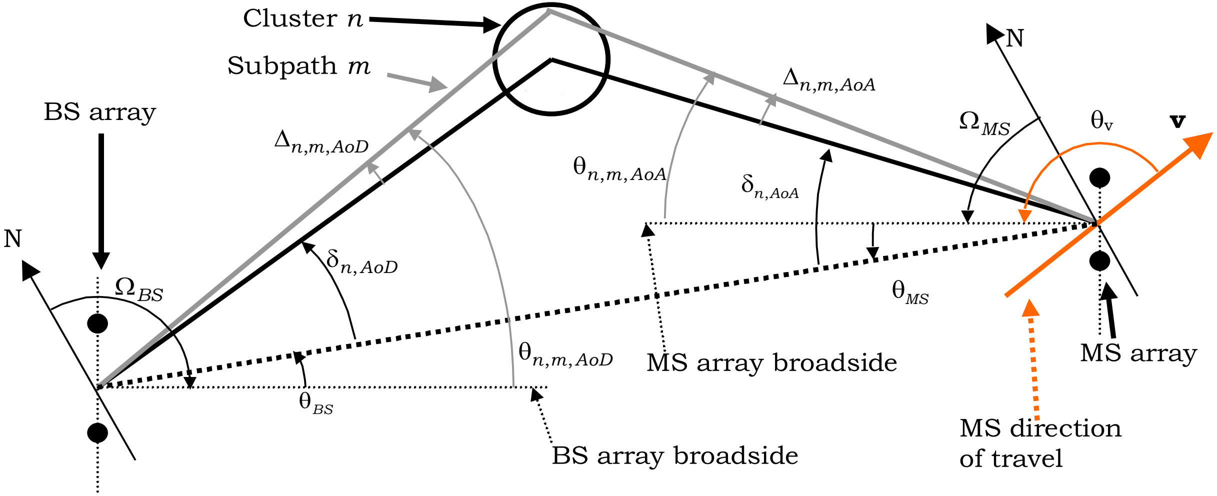
- Double directional model [2001] → suitable for MIMO
- Single bound channel model
- Position of the “scatters” defined by a random process

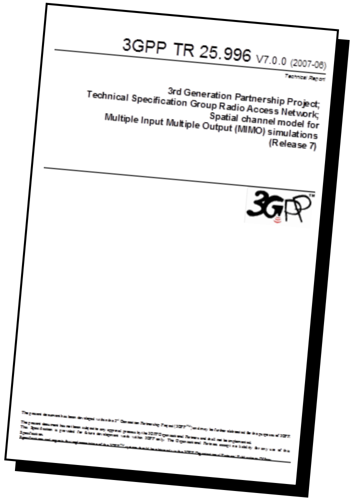




M. Steinbauer et al. "The double-directional radio channel," IEEE Antennas and Propagation Magazine, Aug. 2001.

- Example of 3G channel models




3GPP TR 25.996 V7.0.0 (2007-06)
Technical Report
3rd Generation Partnership Project;
Technical Specification Group Radio Access Network;
Spatial channel model for
Multiple Input Multiple Output (MIMO) simulations
(Release 7)