Deterministic radio propagation modeling and ray tracing

Vittorio Degli-Esposti

Alma Mater Studiorum - University of Bologna, Italy

Department of Electrical, Electronic and Information Engineering (DEI)

DEI at Marconi’s home (1/2)

Guglielmo Marconi
Inventor of Wireless Telegraphy
Nobel Prize 1909

DEI - Radio Propagation Group
Gabriele Falciasecca, Vittorio Degli-Esposti
Franco Fuschini, Enrico Vitucci et alii
Marconi Foundation

DEI at Marconi's home (2/2)

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Course outline

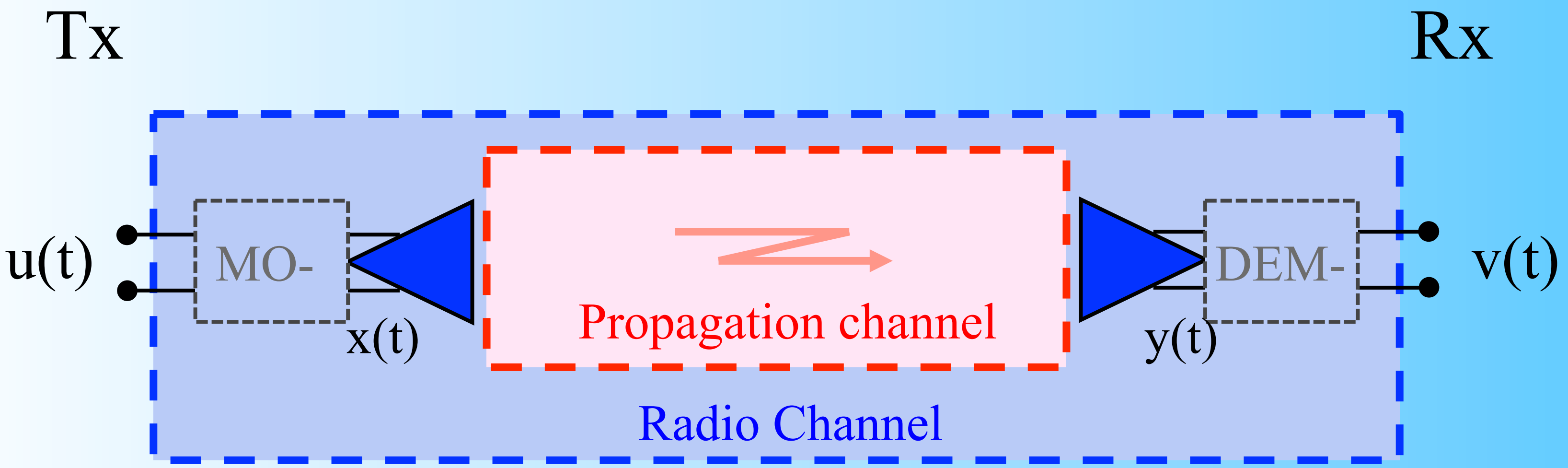
1) Introduction to deterministic propagation modelling
2) Geometrical Theory of Propagation I - The ray concept – Reflection and transmission
3) Geometrical Theory of Propagation II - Diffraction, multipath
4) Ray Tracing I
5) Ray Tracing II – Diffuse scattering modelling
6) Deterministic channel modelling I
7) Deterministic channel modelling II – Examples
8) Project - discussion

Course info

- Slides and material available at

  …
- There will be updates during the course
- Please print slides and take notes aside !
- A “Project” will be assigned based on course content and exercises
- Last lesson will be on project correction and discussion

The radio/propagation channel



u(t), v(t) baseband-equivalent input and output signals
x(t), y(t) passband (RF) input and output signals

Propagation models ⟺ propagation channel

Channel models ⟺ radio channel

Propagation/channel models

- ***Propagation models:*** the focus is on propagation mechanisms (attenuation, obstruction, scattering, multipath, etc.)

Electromagnetic/propagation theory

- ***Channel models:*** the focus is on the effects on the transmitted signal (attenuation, distortion, dispersion, etc.)

Communication theory

Different points of view on the ***same thing***

Traditional models: path loss (1/4)

Case 1) free-space ➔ ***Friis equation***

$$\boxed{P_R = P_T \; G_T \, G_R \left(\frac{\lambda}{4\pi \, R}\right)^2 = P_R(R_0)\left(\frac{R_0}{R}\right)^2}$$

R_o reference distance

Therefore power ***Path Loss*** **L** increases with the square of link distance R

$$\boxed{L(R) = P_T \big/ P_R = \frac{1}{G_T \cdot G_R} \cdot \left(\frac{4\pi R}{\lambda}\right)^2 = L(R_o)\left(\frac{R}{R_o}\right)^2}$$

Path Gain **(PG)** is the inverse of L

$$\boxed{PG = 1/L = P_R / P_T}$$

Traditional models: path loss (2/4)

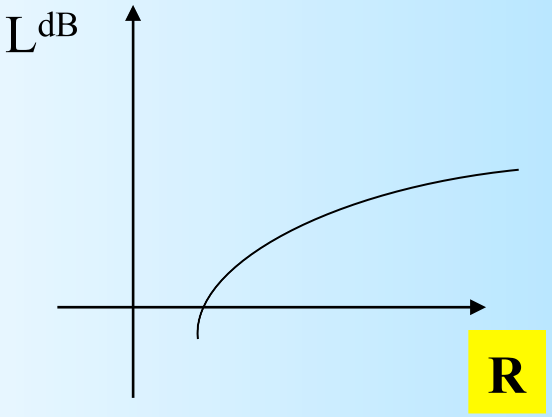
Expressing L in dB:

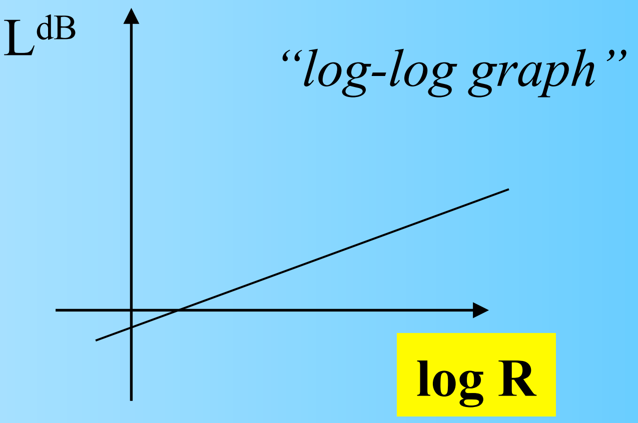
$$\boxed{L^{dB}\left(R\right)=L^{dB}(R_o)-10\cdot 2\ \log R_o+10\cdot 2\ \log R=K(f)+10\cdot 2\ \log R}$$

L^{dB} in free space is logarithmic with R

or

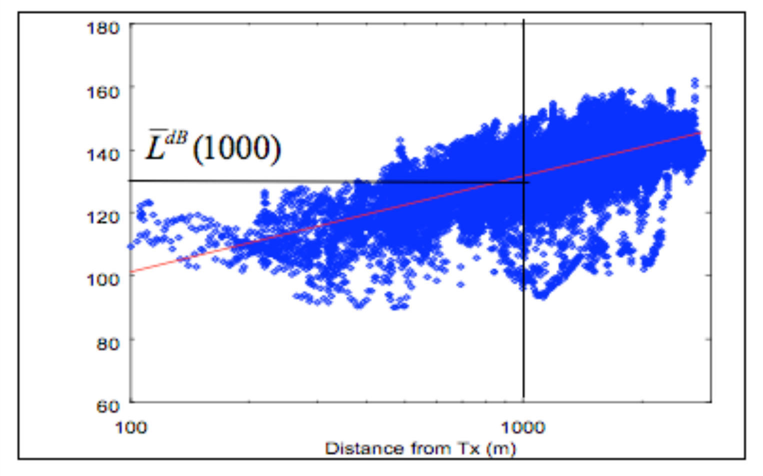
L^{dB} in free space is linear with log R. The line slope is determined by the exponent “2”





Traditional models: path loss (3/4)

Case 2) real environment ➔ ***Hata-like models***



$$\boxed{\bar{L}(R) = \bar{L}(R_o)\left(\frac{R}{R_o}\right)^{\alpha}}$$

$$\Downarrow$$

$$\boxed{\bar{L}^{dB}(R) = K(f,\alpha) + 10 \cdot \alpha \log R}$$

An attenuation law similar to free space is assumed but with a different exponent:

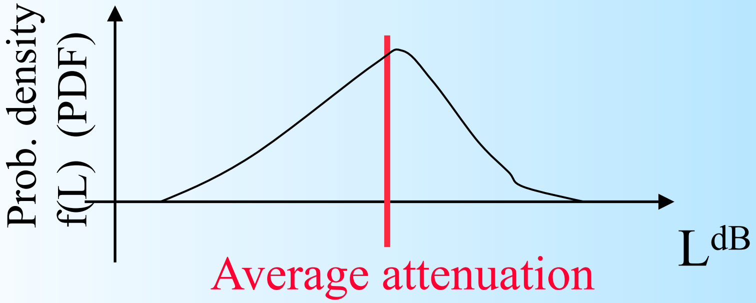
α path loss exponent or **path loss factor** α > 2

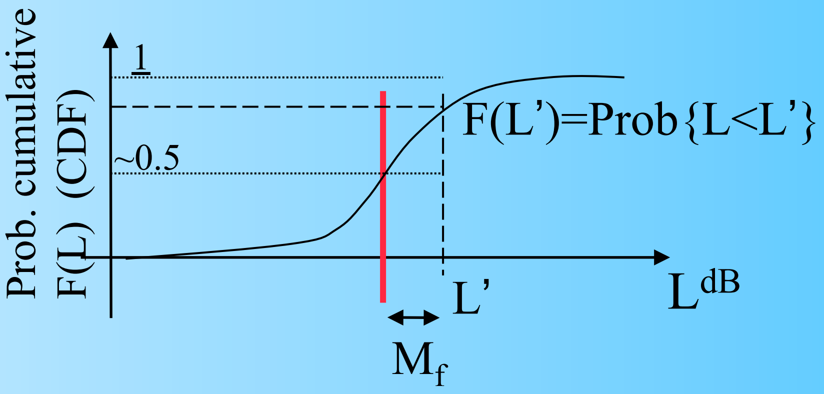
α is derived through fitting (regression line) on a set of measured path loss data
➔ *empirical modeling*

Traditional models: path loss (4/4)

Hata-like models give the **mean** path loss

Deviations from the mean value are called ***fading***: slow fading (or shadowing) and fast fading (Rayleigh fading) and are usually described through ***statistical distributions*** ➔ *statistical modeling*

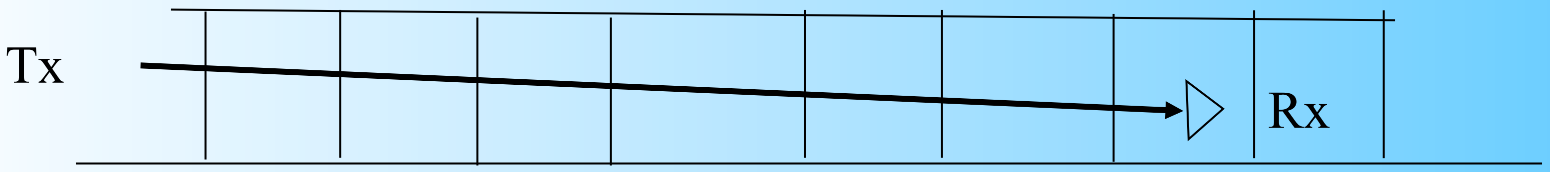




Hata-like models ➔ *empirical-statistical models*

Other functional dependences of L

However, in some cases not only α changes w.r.t. free space, but <u>the overall functional dependance with R changes</u>. Ex: indoors:



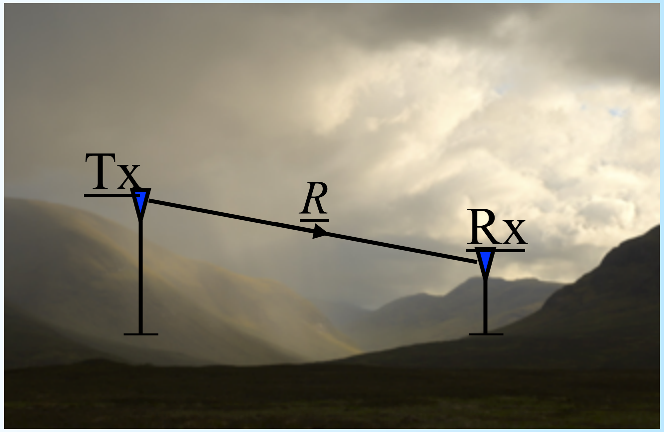
office rooms

$$L^{dB}(R) = L_0^{dB}(R) + L_W^{dB} \cdot N_W = K + 20\log R + \left(\frac{L_W^{dB} N_W}{R} \right) \cdot R$$

Multi-wall model

Specific attenuation [dB/m]

Ex: propagation through a lossy medium



$$L^{dB}(R) = L_0^{dB}(R) + \alpha_S \; [dB/m] \cdot R$$

Linear model

Deterministic vs. stochastic models

- Models are defined ***stochastic*** or ***statistical*** if only statistics of propagation parameters are provided on the base of a generic environment description. <u>Simple and fast</u>

⇨ Ex: Mean path loss vs. distance
Standard dev. of the fading

- On the opposite models are defined ***deterministic*** if the actual values of propagation parameters are provided for a specific environment. A detailed description of the environment is required. <u>Complex and CPU time consuming</u>

⇨ Ex: Actual path loss in a given env. Many other parameters …

In the future detailed environment databases and high-power computation will be cheap ➔ deterministic modelling will be more and more popular

Similarity with GPS navigators for cars

Use of propagation models

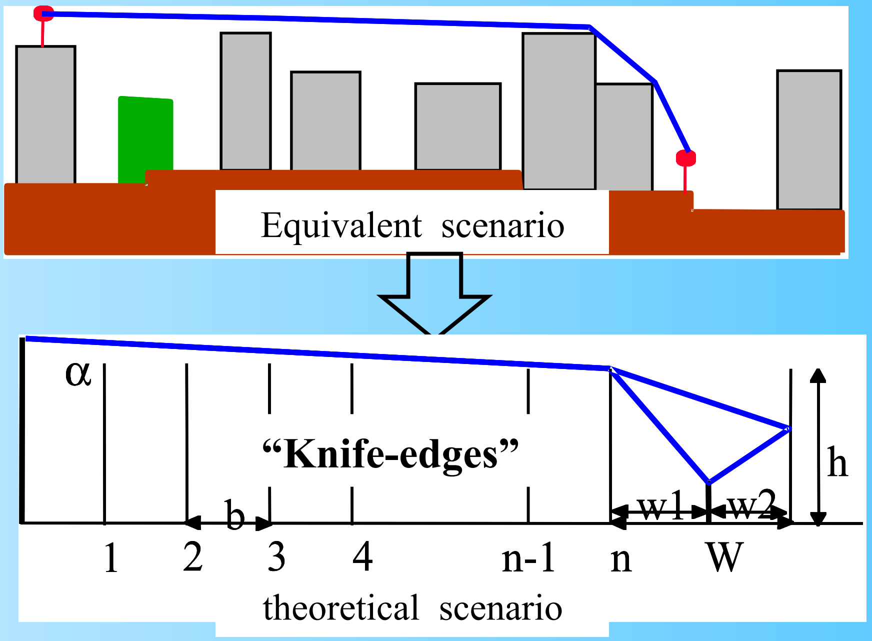
- In the ***design phase*** of a wireless system, to properly design radio interface and system architecture
- In the ***deployment phase*** to guarantee coverage over the service area
- In the ***optimization phase*** to optimize the network and improve service quality

- ***Statistical*** models are more ***general*** and ***concise***, and are mainly used in the design phase
- ***Deterministic*** models are more ***site-specific*** and ***accurate*** and are mainly used in the deployment phase.
- Nowadays advanced deterministic models are also used as *study tools* in the design phase

Deterministic path-loss models

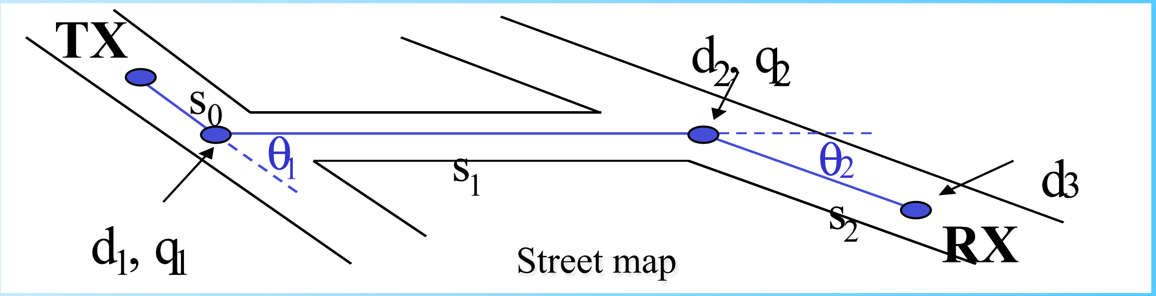
Over-Roof-Top models

- Epstein–Peterson
- Deygout
- Walfish-Ikegami
- Saunders and Bonar



Lateral propagation models

- Berg’s model
- others…

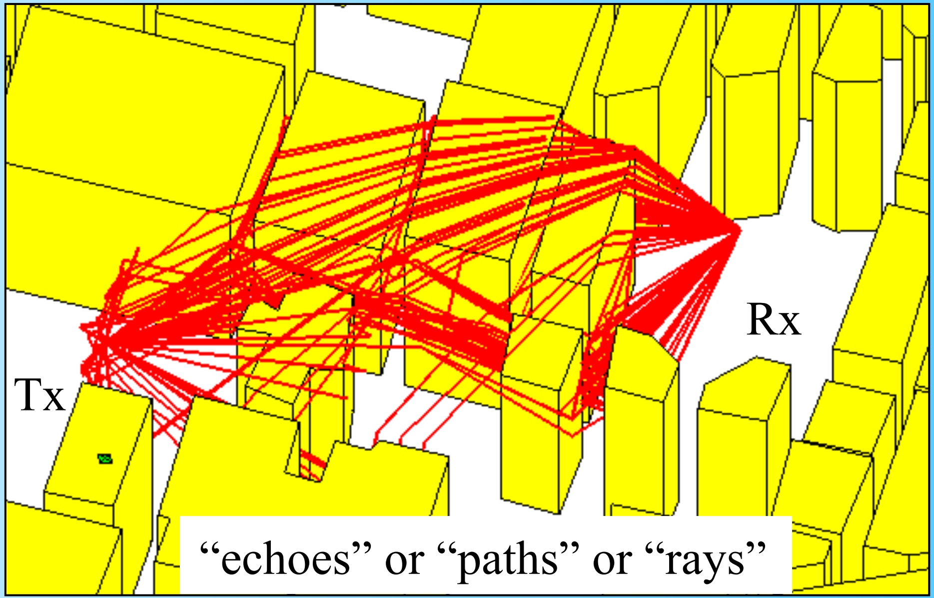


But is path loss enough?

Presence of obstacles

⇕

Multipath propagation

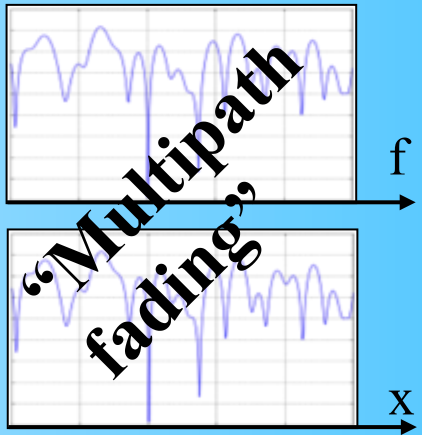


“echoes” or “paths” or “rays”

Multipath determines :

Time-dispersion $\overset{\mathcal{F}}{\Longleftrightarrow}$ frequency selectivity

Angle-dispersion $\overset{\mathcal{F}}{\Longleftrightarrow}$ space selectivity



“Multipath fading”

Not anymore !

Multidimensional propagation characterization

- Propagation channel characterization in terms of path-loss, path-gain or received power is usually called ***narrowband characterization***
- Propagation channel characterization in time/frequency (power-delay profile, delay spread, power-Doppler profile, Doppler spread, Coherence bandwidth or Coherence time, frequency response, etc.) is usually called ***wideband characterization***
- Propagation channel characterization in terms of all of the previous parameters and also in terms of spatial parameters (angle of arrival/emission, space, power-angle profiles, angle spread, etc.) is called ***multidimensional characterization***

In short: multidimensional characterization is the characterization of multipath propagation with respect to all dimensions: path-loss, time, frequency, Doppler frequency, space

Trend: UWB, MIMO

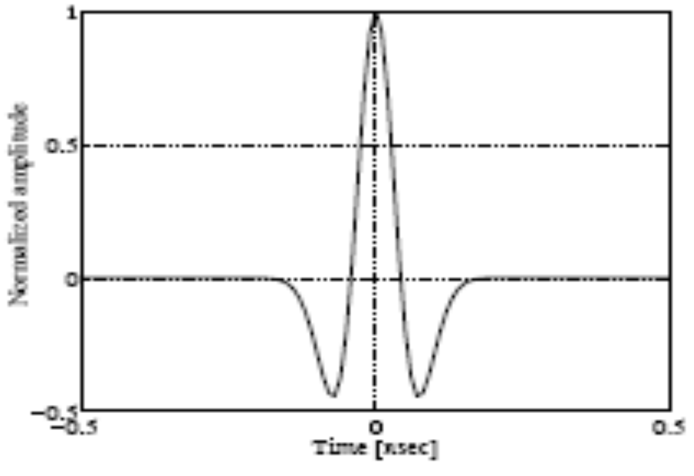
- Future systems will extend operation over wide bandwidths: Ultra Wide Bandwidth, UWB
- Future systems will also exploit space: multiple, properly spaced antennas, i.e. MIMO
- UWB and MIMO require ***multidimensional characterization*** for design, deployment, optimization

Ultra Wide Band (UWB) transmission

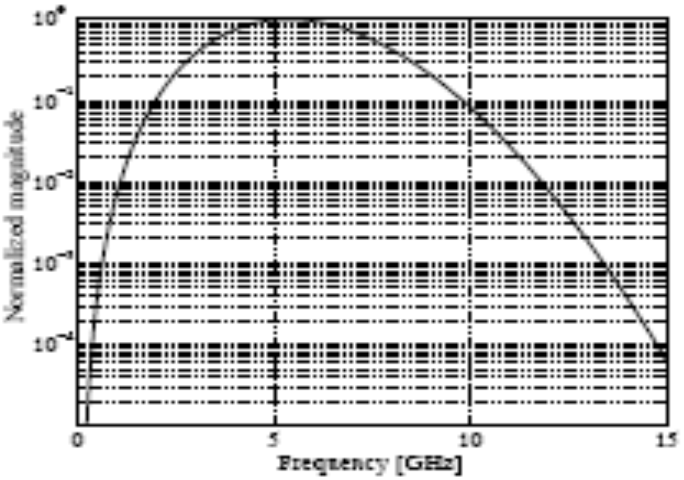
Classic UWB transmission is pulse, **carrierless** transmission.

OFDM transmission can also be considered UWB

The relative bandwidth is very wide



(a)



(b)

UWB transmission

- UWB Radio definition :

  Bandwidth > 25% of center frequency or > 500 MHz (FCC)

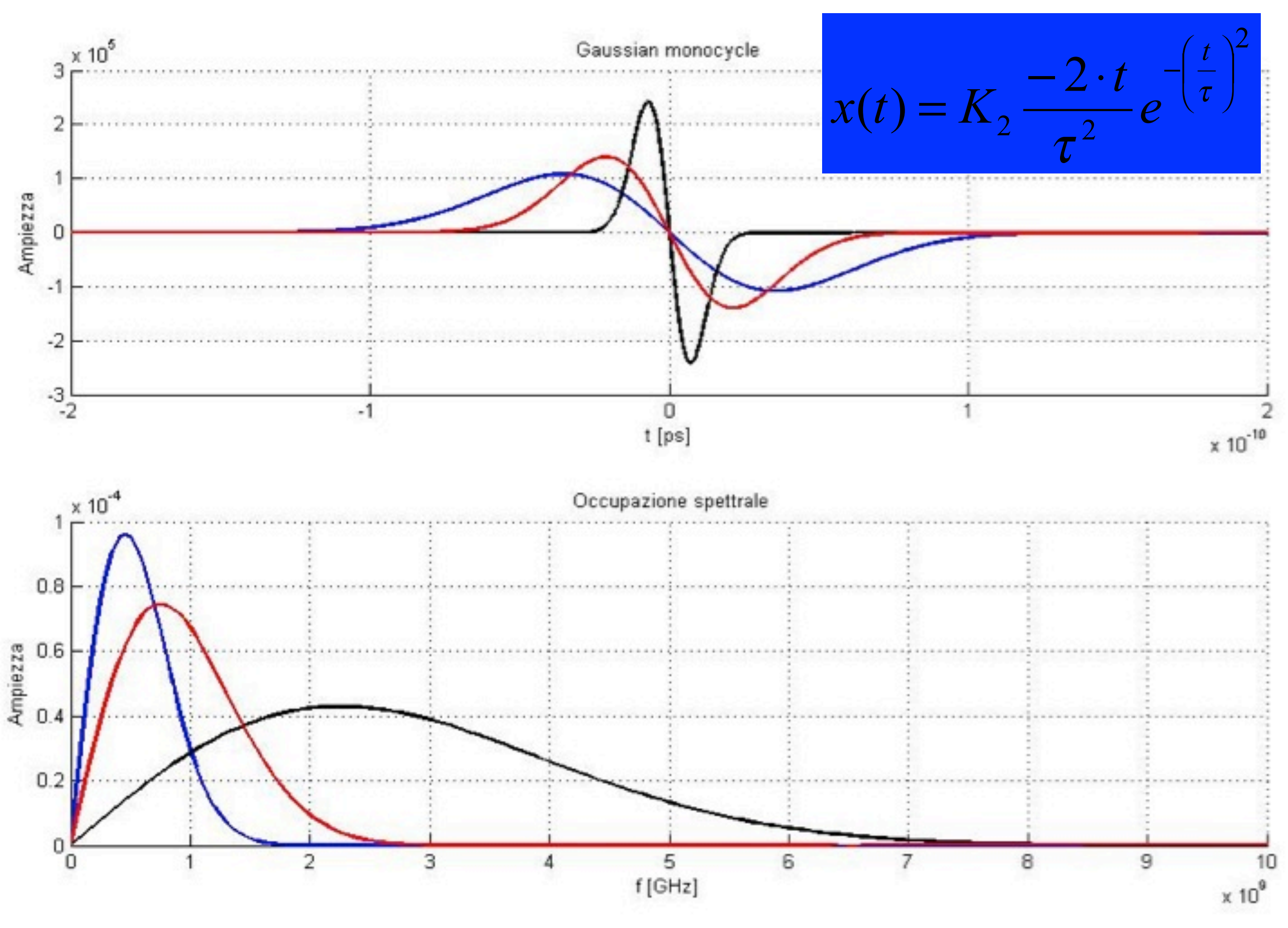
- Wide bandwidth and low-power density spectrum makes it possible to share spectrum with other systems

- Wide band signals are natural for radar, positioning and sensing applications.

Pulse distortion and frequency selectivity MUST be considered here ! ➔ Wideband propagation modelling

Common pulse types (1/2)

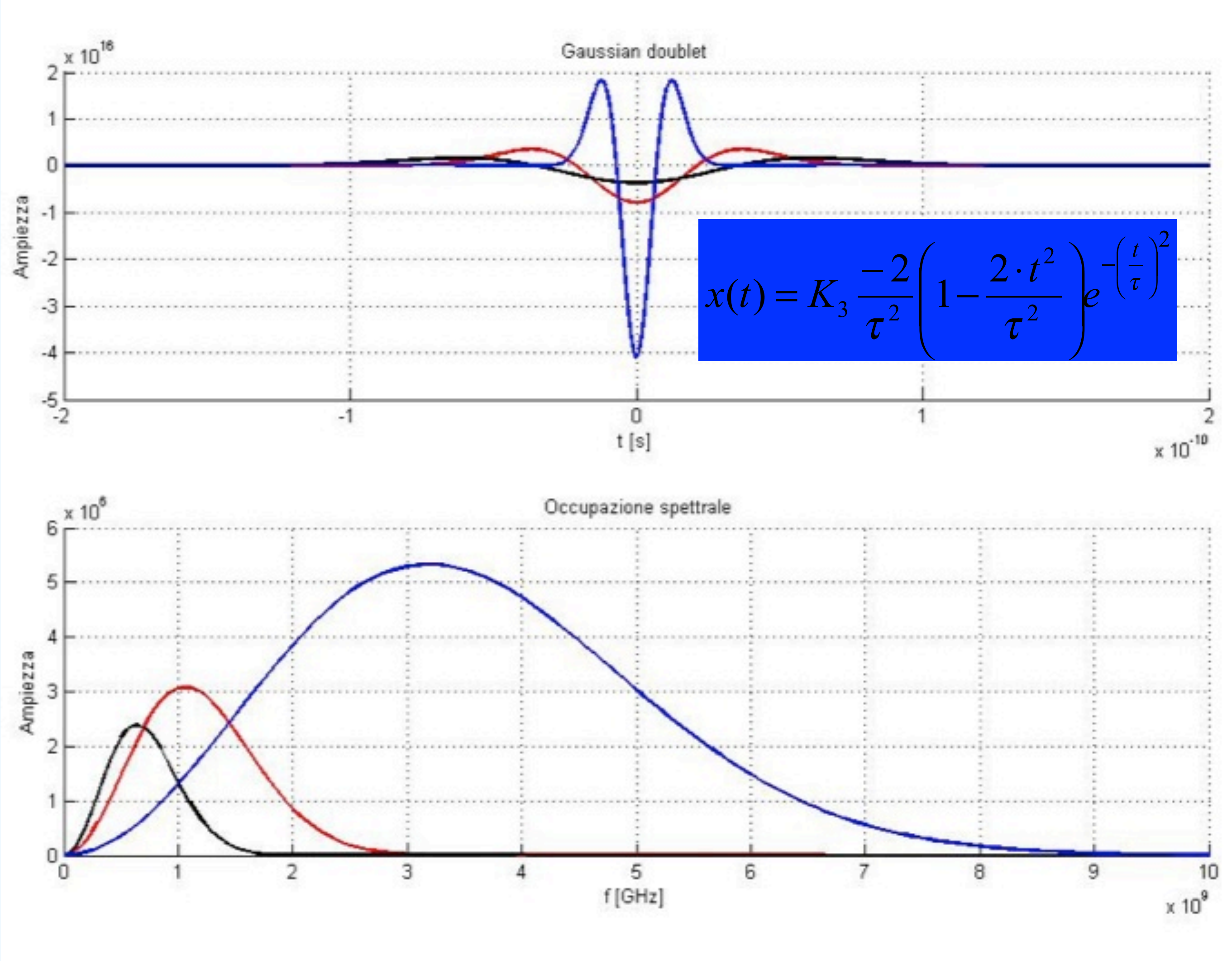
Gaussian monocycle



$$x(t) = K_2 \frac{-2 \cdot t}{\tau^2} e^{-\left(\frac{t}{\tau}\right)^2}$$

Common pulse types (2/2)

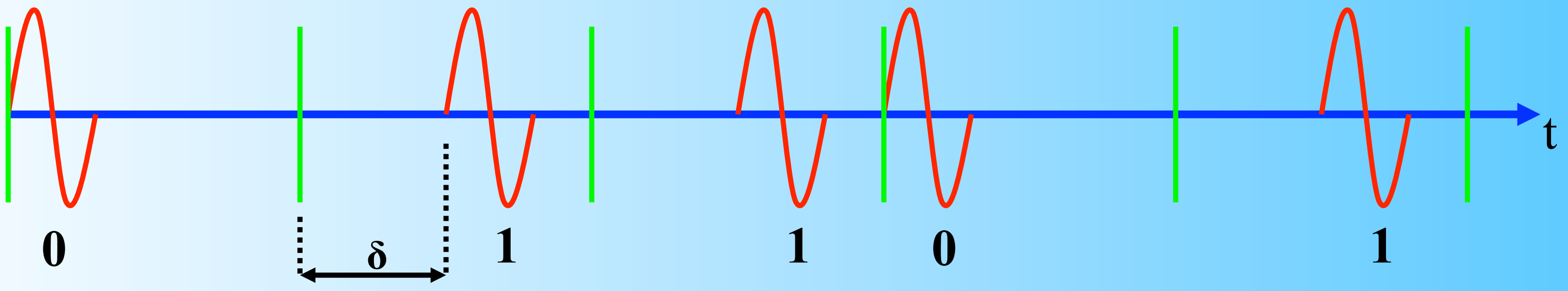
Gaussian doublet



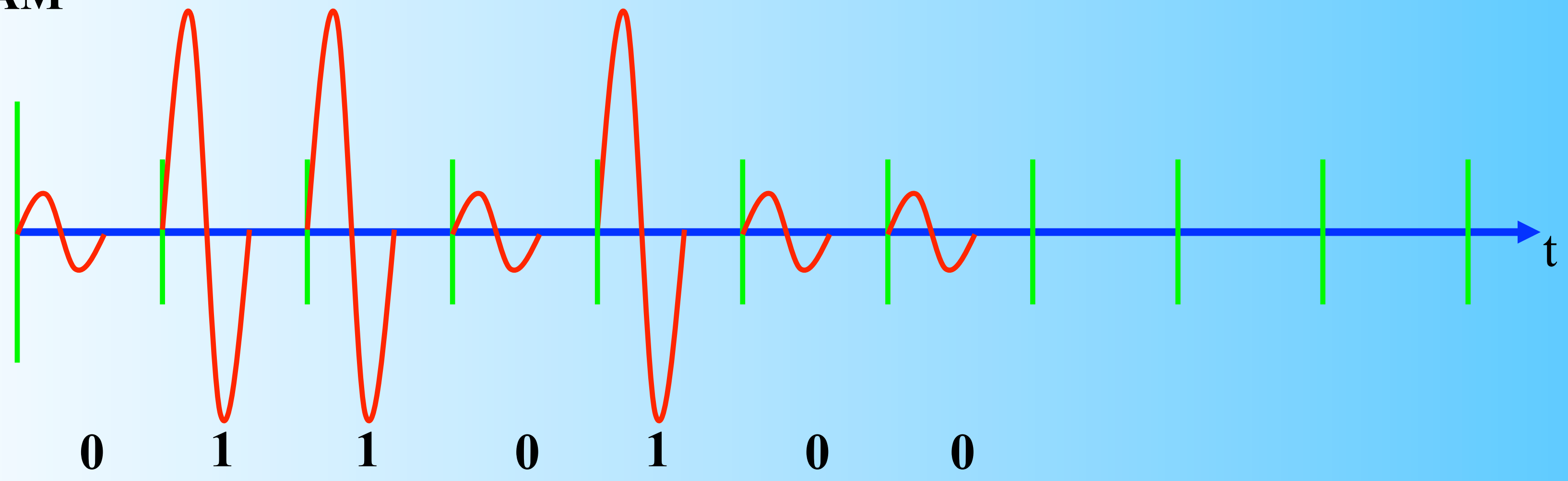
$$x(t) = K_3 \frac{-2}{\tau^2}\left(1-\frac{2\cdot t^2}{\tau^2}\right)e^{-\left(\frac{t}{\tau}\right)^2}$$

Pulse-modulation techniques

- **PPM**



- **PAM**

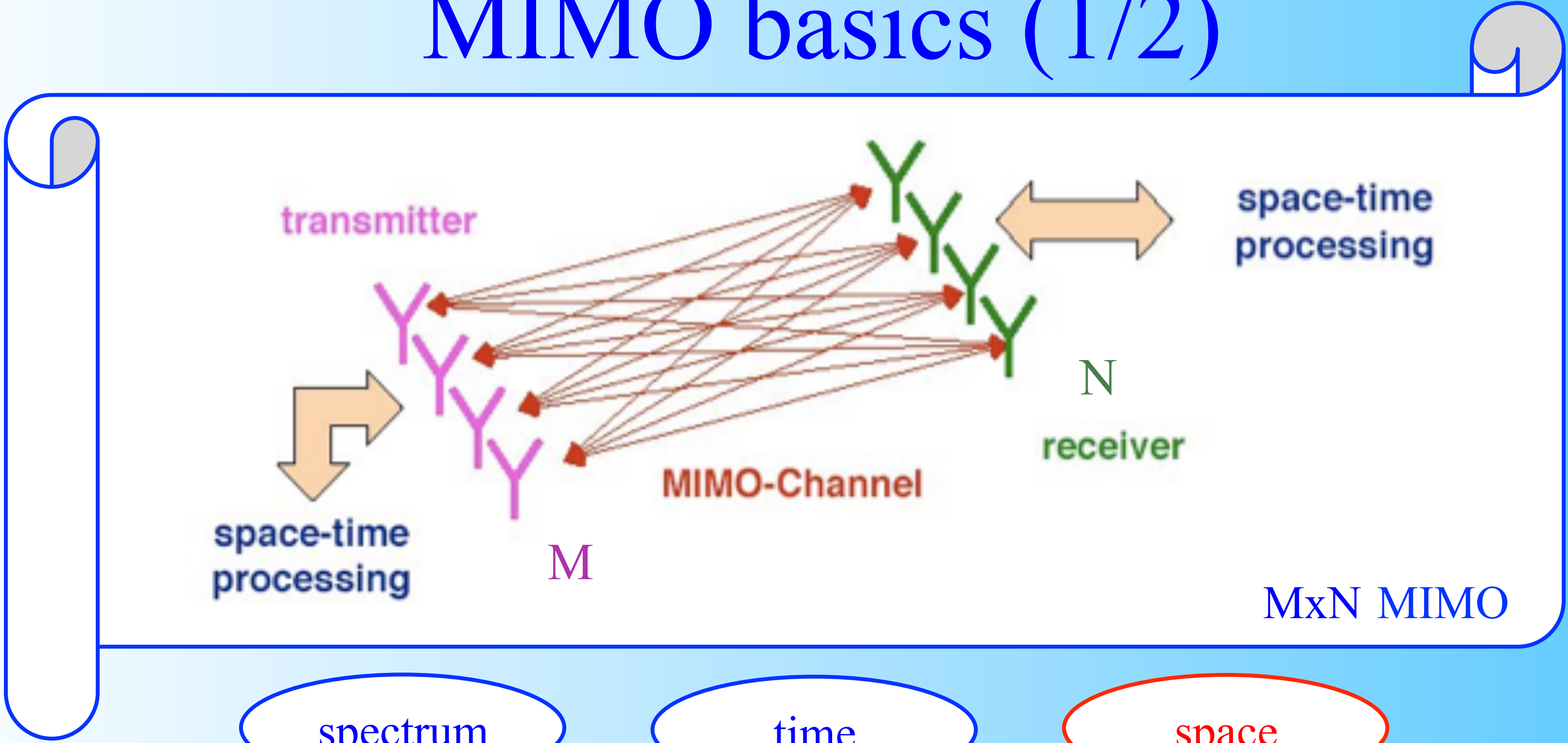


Multipath channel: combat or exploit ?

- The propagation channel is the part of a radio system that cannot be engineered
- It sets the ultimate limits for communication performance
- Traditional transmission techniques combat multipath impairments
- Recent transmission techniques exploit multipath → MIMO

The space domain (multipath) MUST be considered here !
→ Multidimensional propagation modelling

MIMO basics (1/2)



spectrum

time

space

- The basic idea of MIMO is to exploit <u>also</u> the space domain
- MIMO is not a technique, is a <u>theoretical framework</u> encompassing **diversity** techniques, **smart-antenna** techniques, **channel coding** techniques

MIMO basics (2/2)

- Similarity to audio surround techniques: to exploit the space domain it takes multiple inputs (microphones) and multiple outputs (speakers)
- Is MIMO a matter of antenna technology ? It would be like stating that audio surround is a matter of microphone technology !
- Is MIMO a matter of signal processing / coding? Not only…
- MIMO includes all of the above, but it's a matter of propagation in the first place
- Multipath propagation characteristics set the <u>degrees of freedom</u> of the channel and therefore MIMO potential

MIMO Potential

- **Array Gain**

  Higher directivity and Space Division (SD) through “smart antennas”

- **Diversity Gain**

  Multipath fading mitigation

- **Multiplexing Gain**

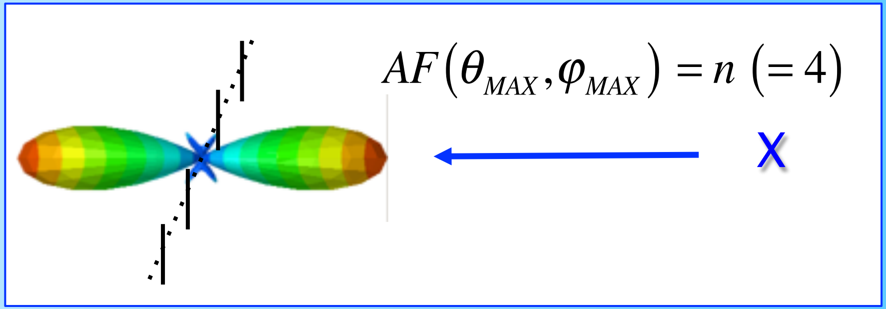
  Use of multipath to increase channel capacity (maximum error-less bitrate)

Array Gain

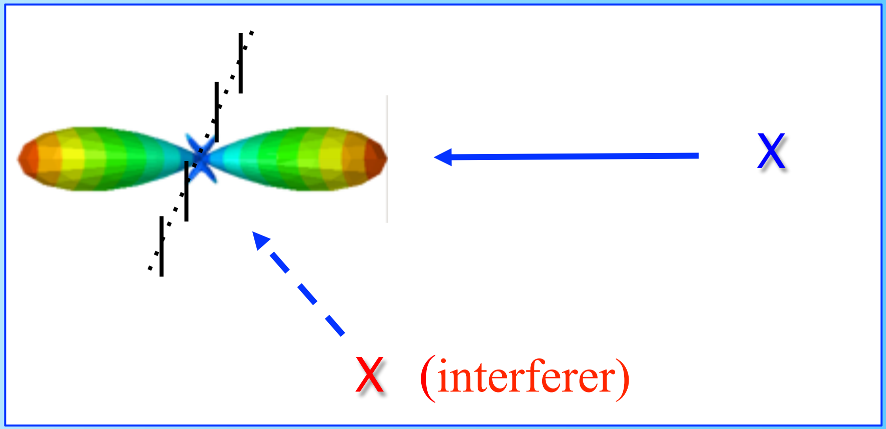
Using **phased arrays** (***beamforming***) it is possible to increase SNR and SIR

- Higher directivity

$$G_{array}(\theta,\varphi) = AF(\theta,\varphi) \cdot G_o(\theta,\varphi)$$



- Space Division (SDMA)



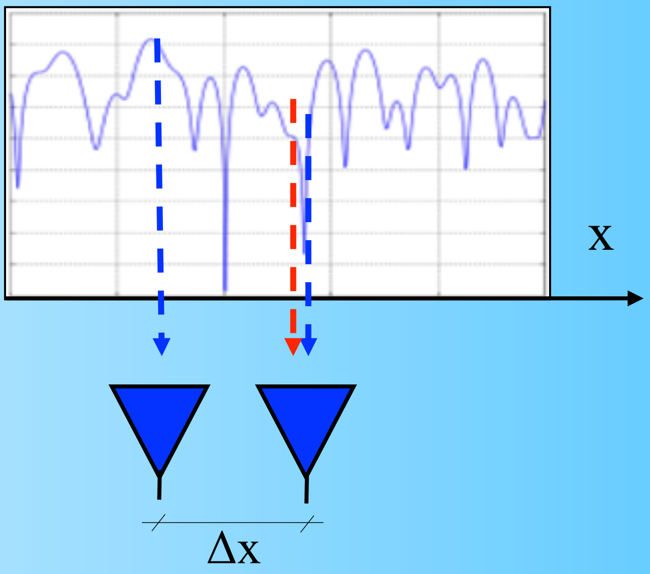
Channel State Information (CSI) at the Tx and/or at the Rx is necessary !

Diversity Gain

- Rx diversity

SNR increase by <u>combining</u> the signals received from multiple antennas. Signals must be <u>incorrelated</u>:

$$\Delta x > \lambda/2$$



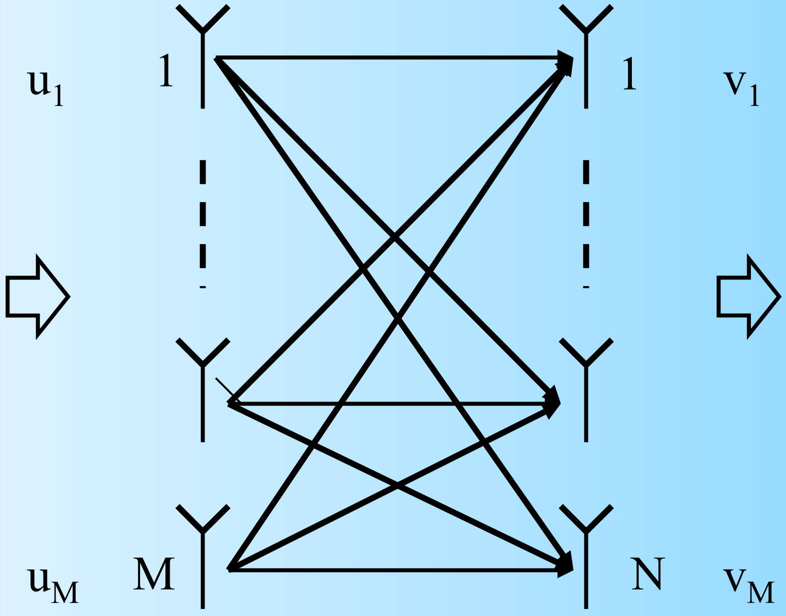
- Tx diversity

In basic Tx-diversity schemes, the same signal is transmitted from multiple antennas at the Tx. Controlled redundancies at the Tx are introduced, which can then be exploited by appropriate <u>signal processing techniques</u> at the Rx ➔ increase in SNR. <u>CSI at the Tx is necessary !</u>

Multiplexing Gain

- Spatial multiplexing offers a linear increase in the transmission rate (or capacity) with "min{N,M}" for the same bandwidth and with no additional power expenditure.
- Why? Because it is possible to exploit the multipath to carry different information streams

Ex: time-discrete representation of a MIMO channel



MIMO channel

MIMO channel matrix

$$\mathbf{H} = \begin{bmatrix} h_{11} & . & . & h_{1M} \\ . & . & . & . \\ . & . & . & . \\ h_{N1} & . & . & h_{NM} \end{bmatrix}$$

$$\mathbf{v} = \mathbf{H} \cdot \mathbf{u} \left(+ \mathbf{n} \right)$$

Multiplexing Gain: theory

- How to reconstruct the input vector **u** from the output vector **v**?

$$\mathbf{v} = \mathbf{H} \cdot \mathbf{u} \left(+ \mathbf{n} \right)$$

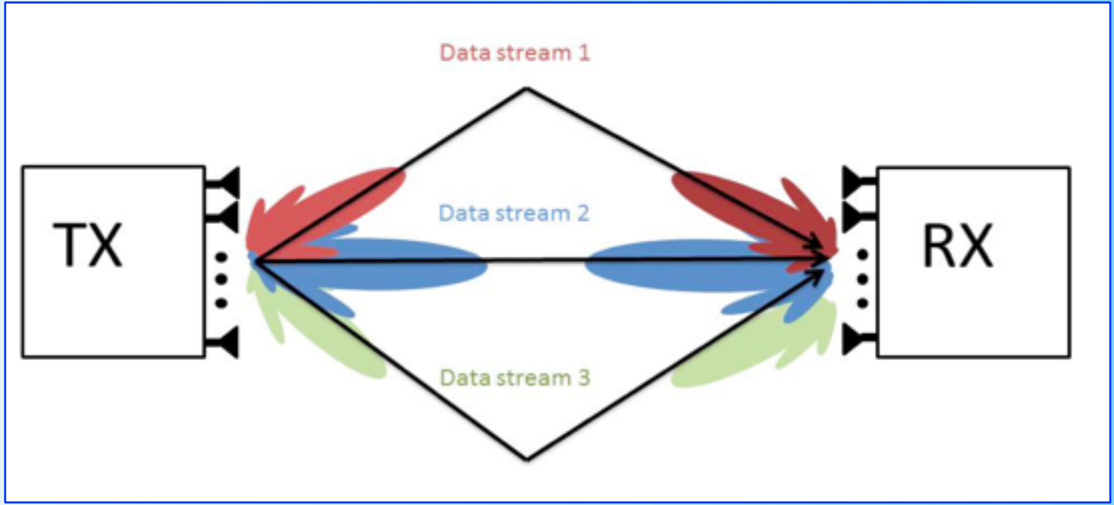
- If **H** has full rank it is possible to solve the linear system: **v** → **u**
- It must be $N \geq M$
- Noise need to be low (high SNR)

- What determines **H** rank? The multipath radio channel !

H rank ←→ # independent paths ←→ # degrees of freedom

H ≈ CSI at the Tx and/or at the Rx is once again necessary !

Multiplexing example/utopia



Here **beamforming** is enforced to multiplex different data-streams over different paths

From this example it is evident that the **degrees of freedom** of the channel is equal to the number of **independent paths**

It is not feasible ‘cause it is very difficult to match the antenna pattern to real-world multipath with simple antennas

Moreover CSI at the Tx AND at the Rx would be necessary

Multiplexing reality

In real systems multiplexing is achieved through proper ***space-time processing (or signal processing)***

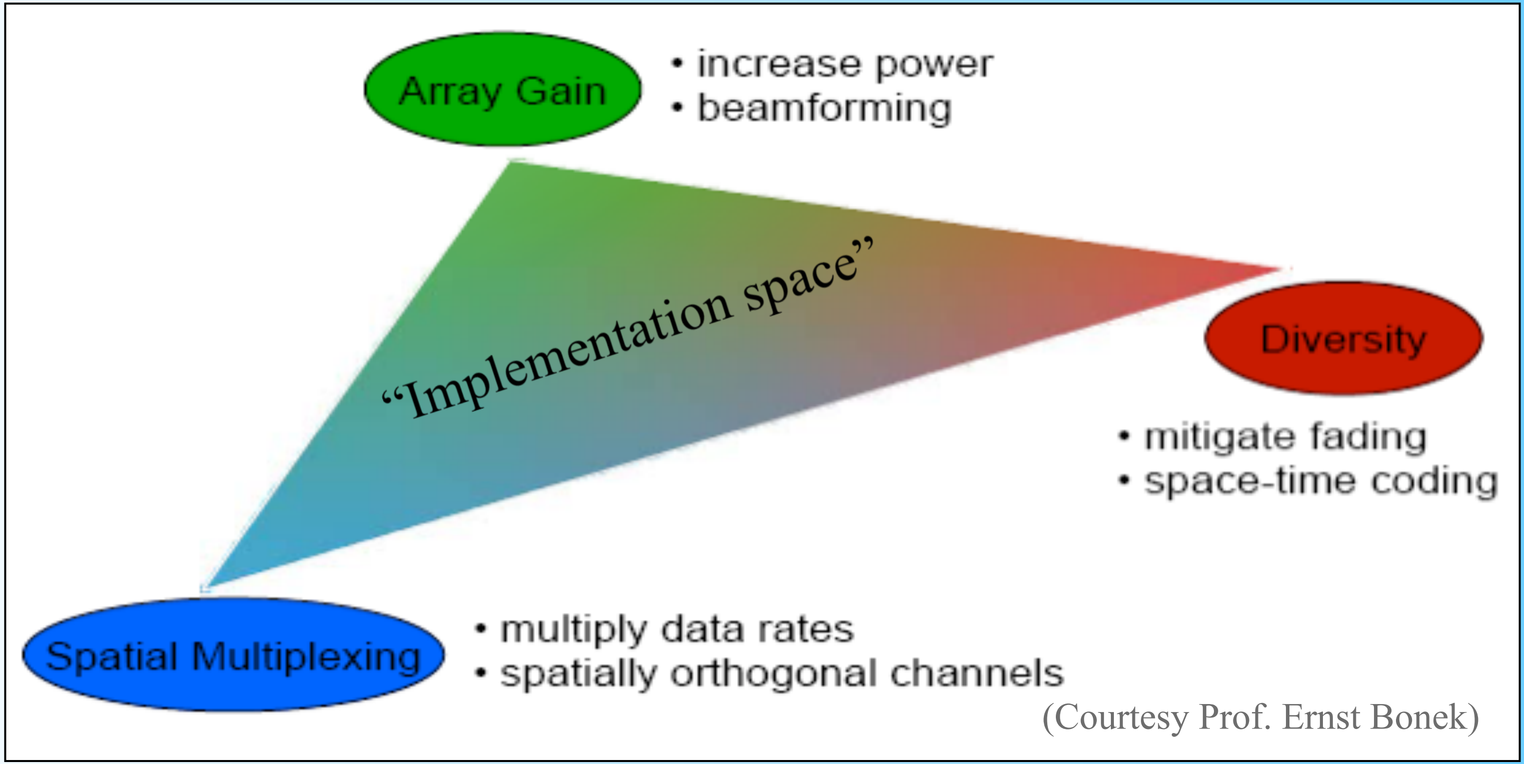
Beamforming is a particular signal processing technique

Precoding at the Tx and corresponding **decoding** at the Rx are necessary

To achieve full multiplexing gain complete CSI at both ends is necessary: the Rx must "sense" the channel characteristics and transmit them to the Tx through a **feedback loop**…problems with rapidly varying channels

With pure multiplexing there is no diversity gain: pure multiplexing and pure diversity are mutually exclusive

MIMO - from theory to implementation



Array Gain
- increase power
- beamforming

Diversity
- mitigate fading
- space-time coding

Spatial Multiplexing
- multiply data rates
- spatially orthogonal channels

(Courtesy Prof. Ernst Bonek)

How to implement a MIMO transmission technique?

Through multidimensional knowledge of the propagation channel !

Therefore…

There is need for deterministic propagation models which can take into account the actual physical interaction mechanisms with the environment

and

can simulate multipath propagation

and

can provide multidimensional propagation prediction

It is therefore necessary to consider the:
Geometrical Theory of Propagation (GTP) =
Geometrical Optics (GO) + Geometrical Theory of Diffraction (GTD)