Radio channel modeling: from GSM to LTE

and beyond…

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Outline

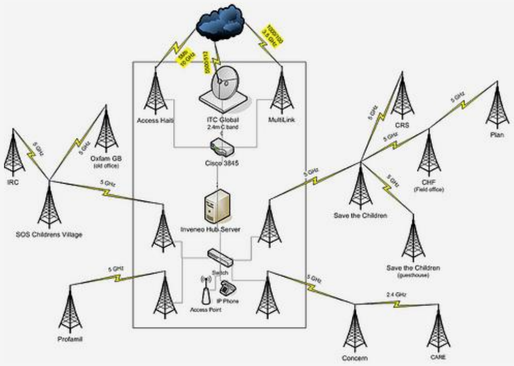
- ☐ Introduction: why do we need channel models ?
- ☐ Basics
- ☐ Narrow band channels
- ☐ Wideband channels
- ☐ MIMO channels
- ☐ Multi-link channels
- ☐ Perspectives & conclusion

Introduction: why do we need channel models ?

Why do we need channel models ?

❑ From the operator's point of view

- For network planning, BST deployment
- As inputs to engineering rules & tools



❑ From the manufacturer's point of view

- For performance evaluation
- For device/equipment design optimization

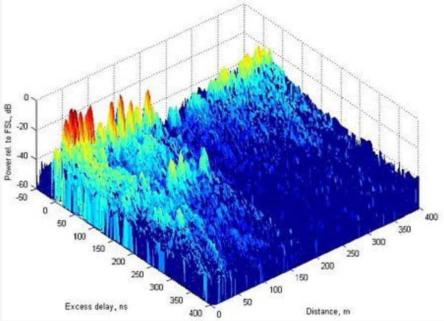
❑ From the researcher's point of view

- For trying novel network architectures
- For evaluating novel antenna technologies

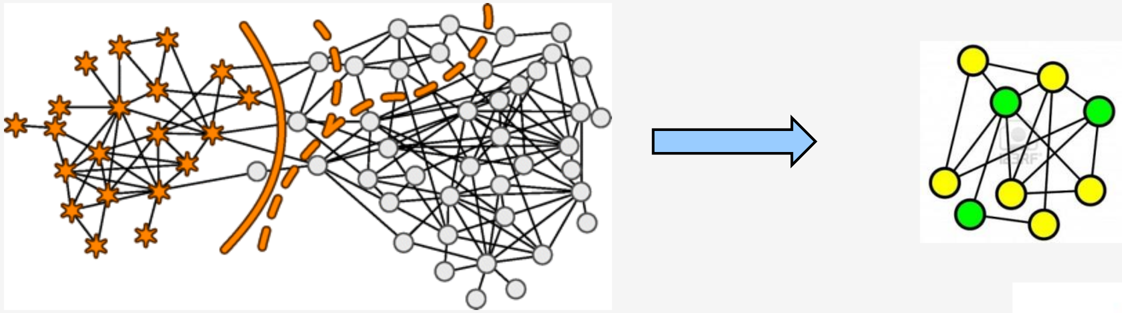
Why do we need channel models ?

❑ How to proceed ?

1. Propagation research done by researchers



2. Extract the substance of the channel physics into something tractable

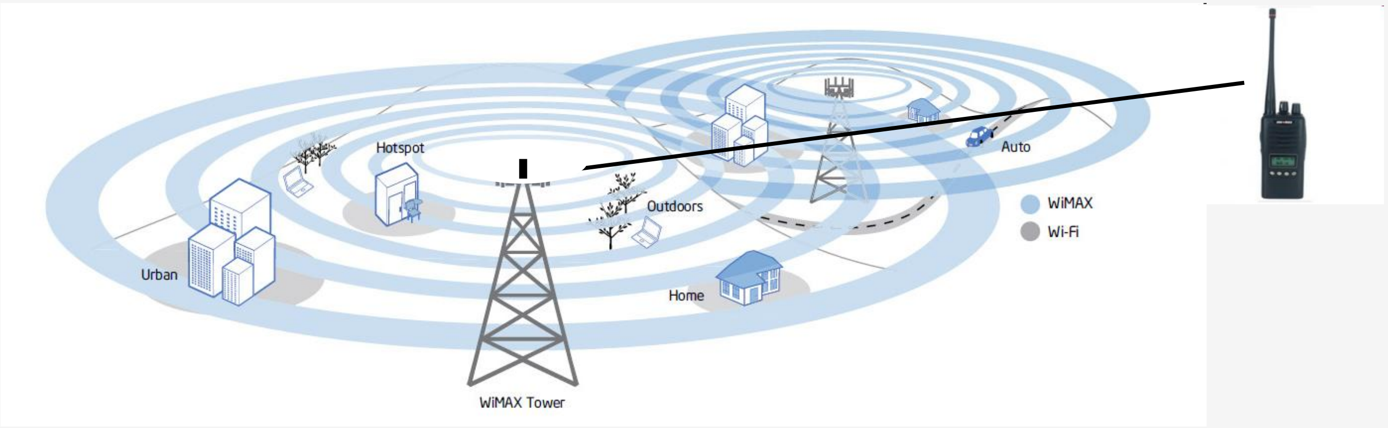


3. Standardize channel models *de-facto* or through official bodies: COST, IEEE, ETSI, 3GPP…

Why do we need channel models ?

❑ Example - back to basics: GSM (operator's need)

- ❑ The main need: to model the attenuation (path loss) vs. distance, for « typical » environments and varying BST height



Why do we need channel models ?

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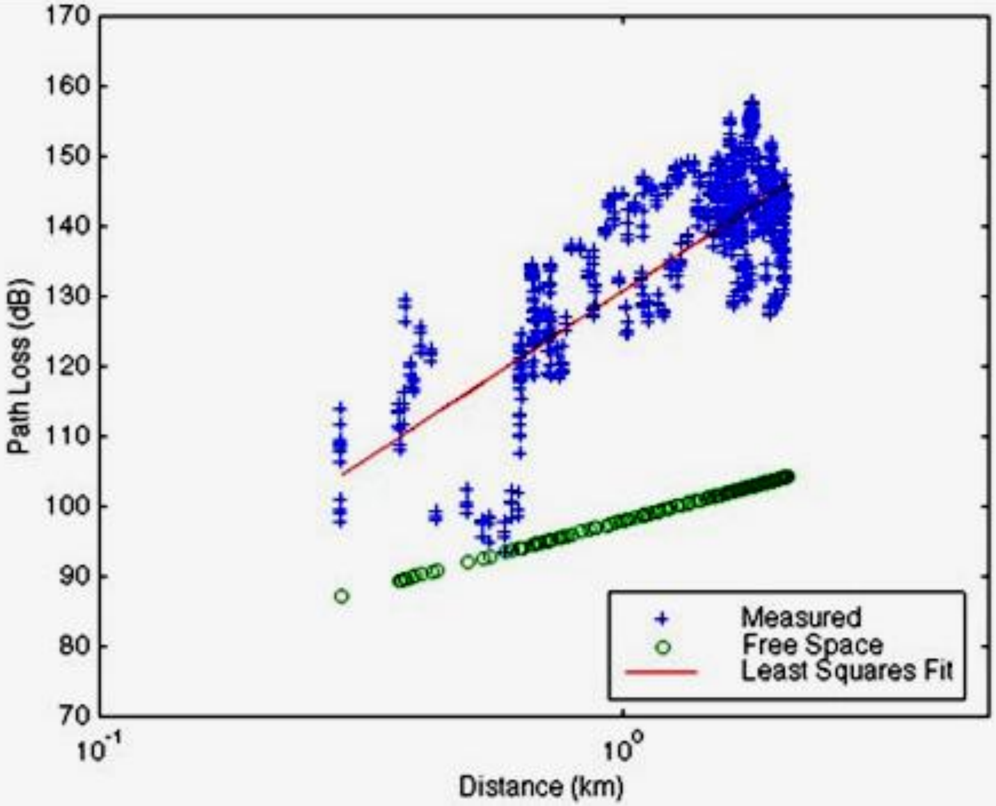

Why do we need channel models ?

❑ Example - back to basics: GSM (operator's need)

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COST-Hata model for suburban or rural environments:

$$L = 46.3 + 33.9 \log f - 13.82 \log h_B - a(h_R) + [44.9 - 6.55 \log h_B] \log d + C \quad \text{(dB)}$$

$$a(h_R) = (1.1 \log f - 0.7) h_R - (1.56 \log f - 0.8)$$

$$C = \begin{cases} 0\ dB \text{ for medium cities and suburban areas} \\ 3\ dB \text{ for metropolitan areas} \end{cases}$$

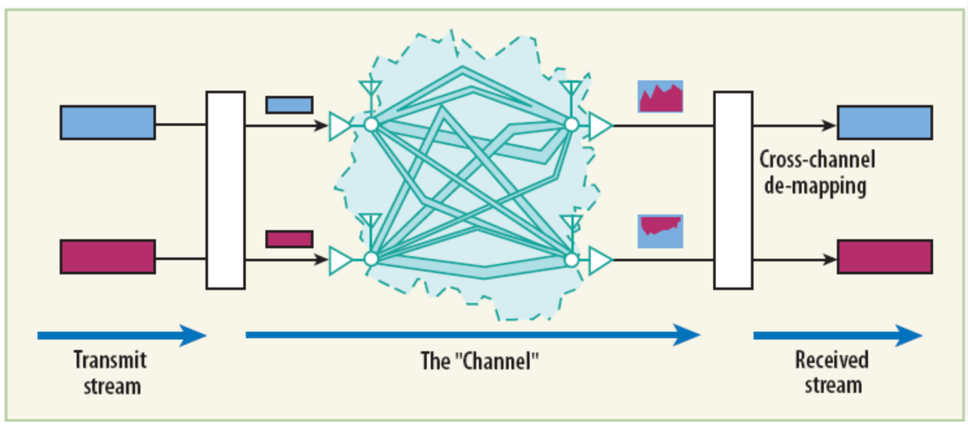
(1500-2000 MHz, 1-20 km)

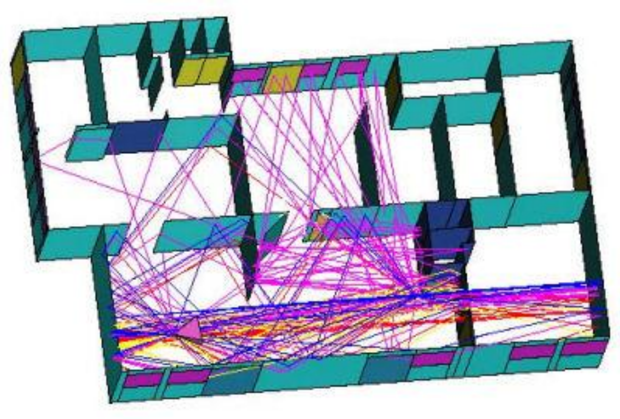
This is typical of an "empirical" path loss model

Why do we need channel models ?

❑ Example: MIMO WLAN - IEEE 802.11n (manufacturer's need)

- ❑ MIMO channels deeply involve the « space variant » characteristics of the channel (and the multi-antenna system)

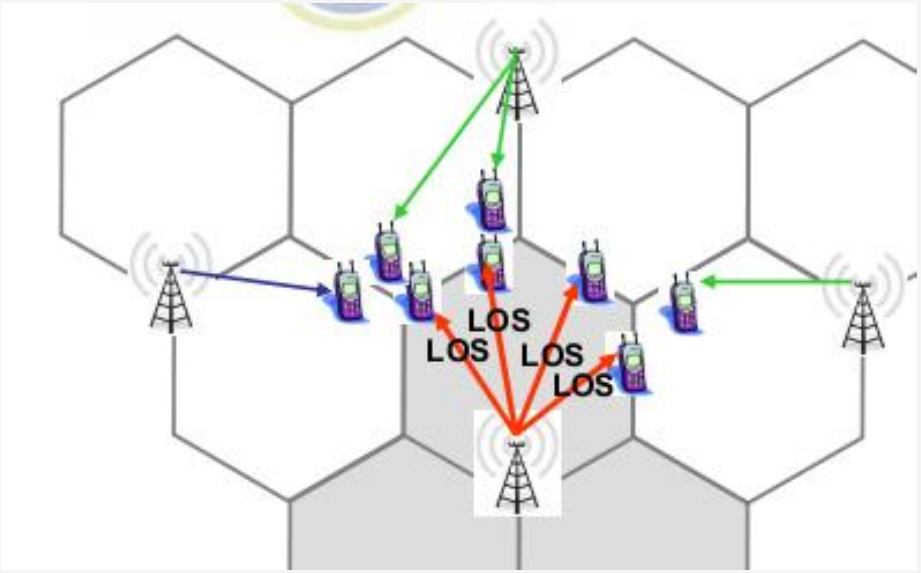




Why do we need channel models ?

- **Example: LTE / LTE-A (manufacturer & operator's need)**
  - A more complicated networking scheme, implying a sophistication of channel models

Cell-Edge Beamforming



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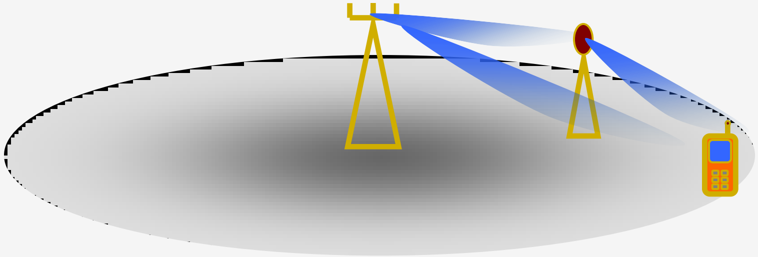
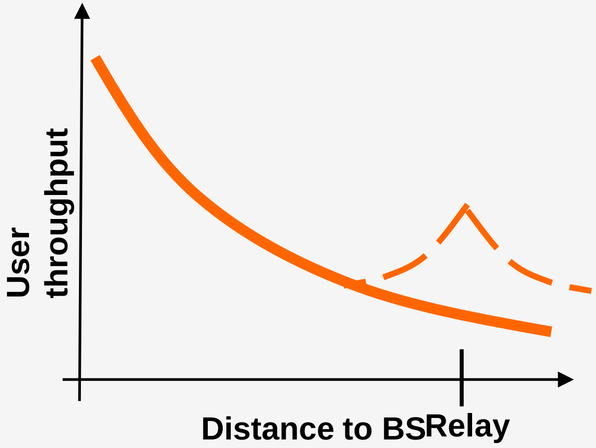
Relaying

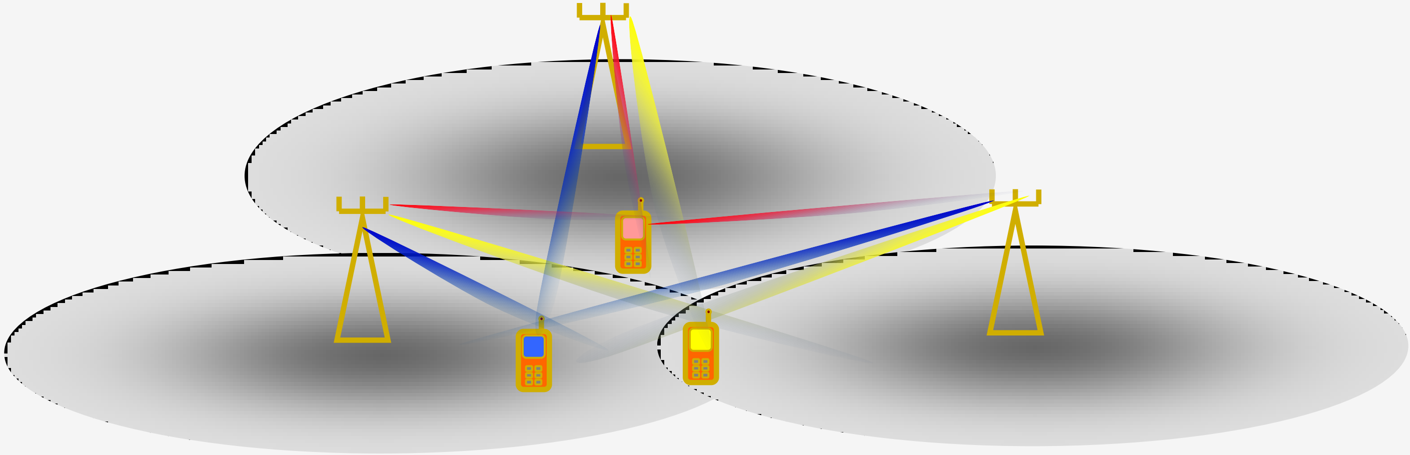




Why do we need channel models ?

- ❑ **Example: LTE / LTE-A (manufacturer & operator's need)**
  - ❑ A more complicated networking scheme, implying a sophistication of channel models

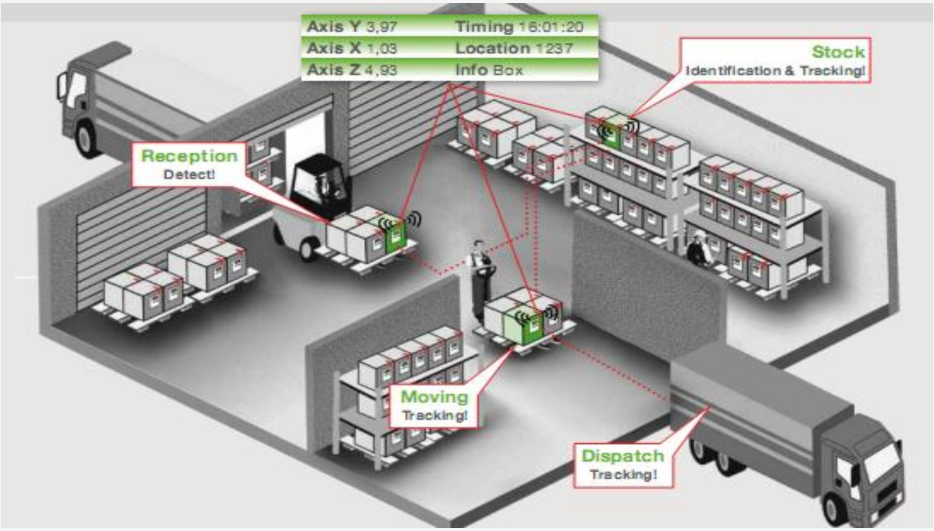
Coordinated Multipoint Tx and Rx

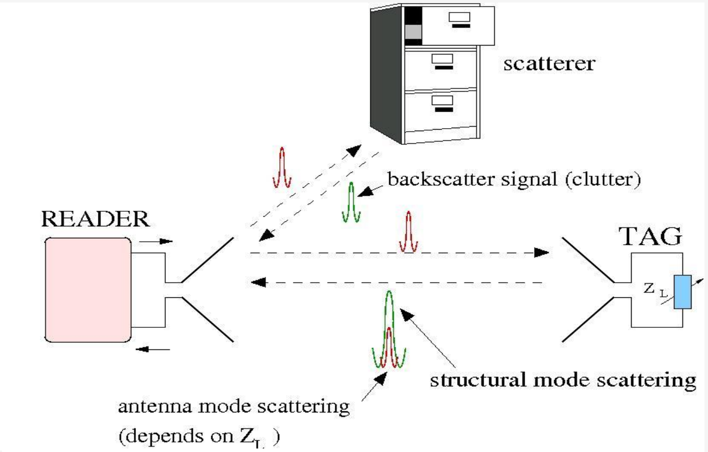


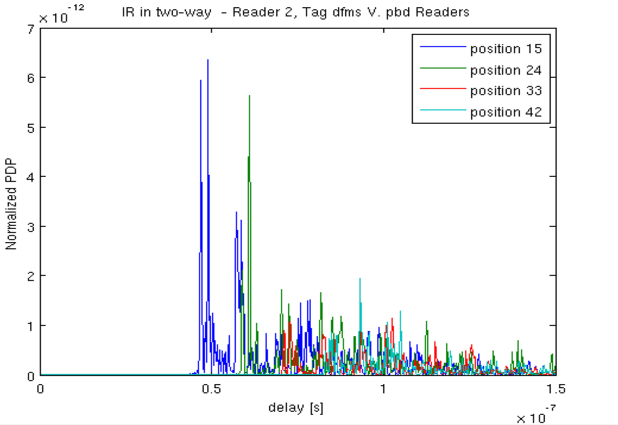
Why do we need channel models ?

❑ Example: UWB – RFID (researcher’s game: ongoing)

- ❑ In every wireless communications research project, one needs to make channel measurement campaigns !

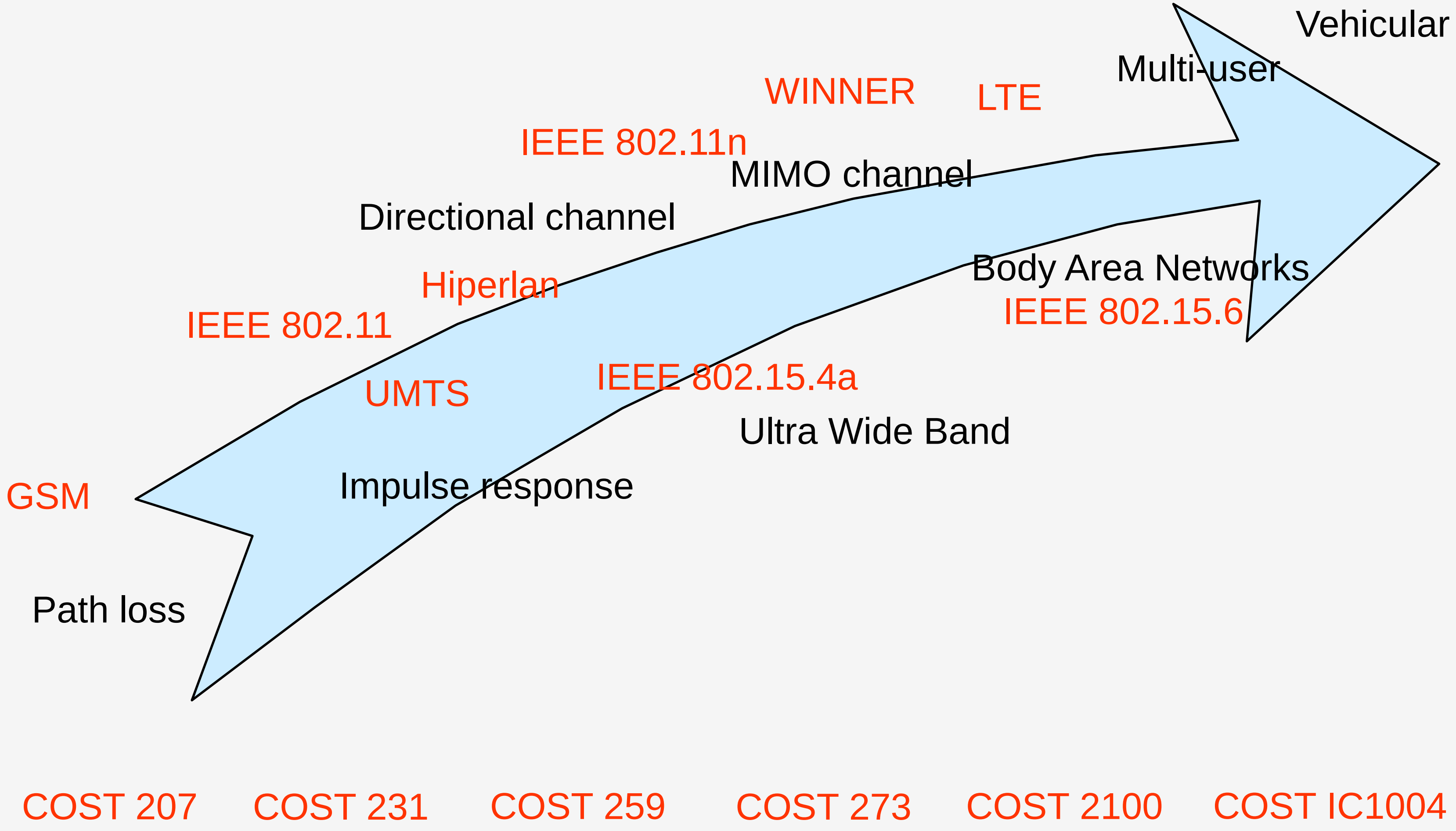






Why do we need channel models ?

- ❑ **Trend**



GSM

Path loss

IEEE 802.11

UMTS

Impulse response

Hiperlan

Directional channel

IEEE 802.15.4a

Ultra Wide Band

IEEE 802.11n

MIMO channel

WINNER

LTE

Body Area Networks

IEEE 802.15.6

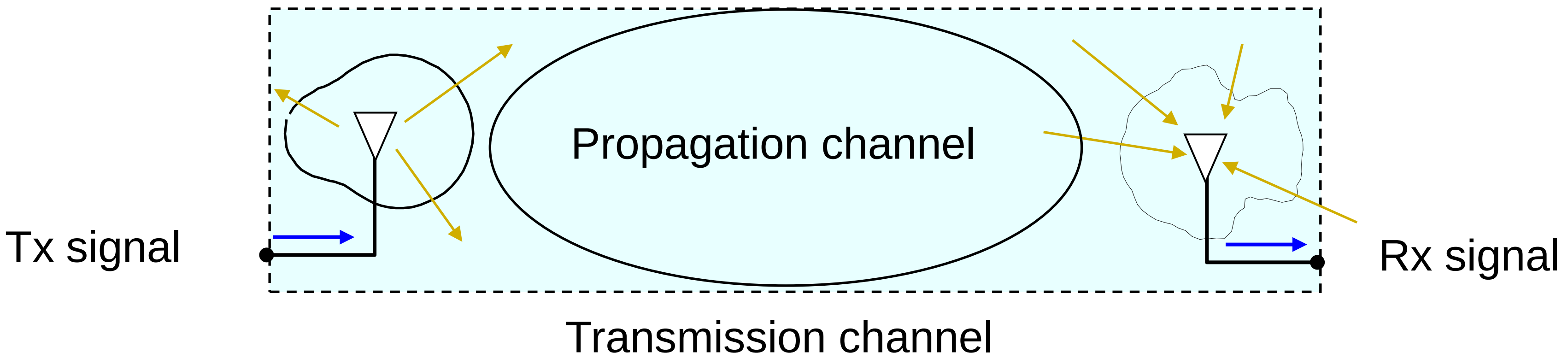
Multi-user

Vehicular

COST 207 COST 231 COST 259 COST 273 COST 2100 COST IC1004

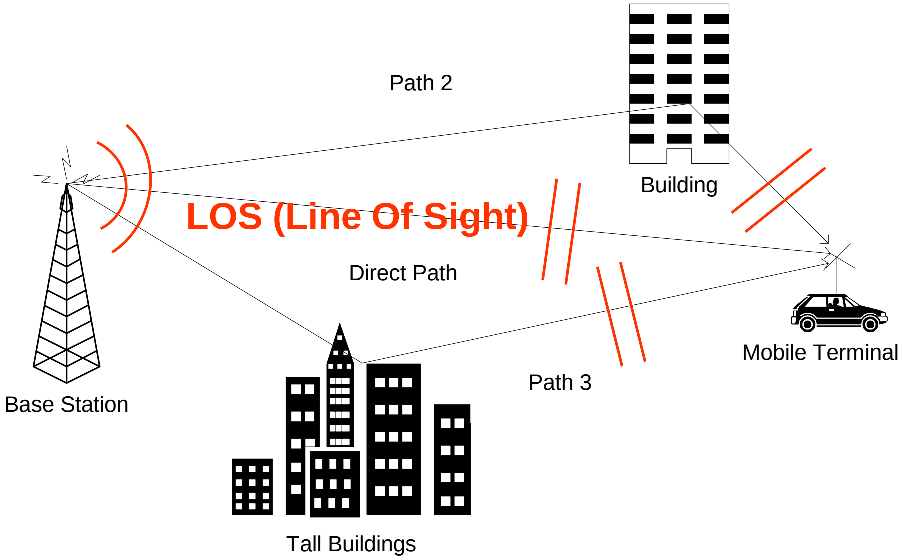
Basics

Basics



- ❑ The **transmission channel** comprises antennas and all objects contributing or hampering propagation between input/output ports
- ❑ The **propagation channel** excludes the antennas and expresses all wave propagation phenomena between Tx and Rx
- ❑ Both channels are considered to be **linear (time variant) filters characterized by their impulse response**

Basics

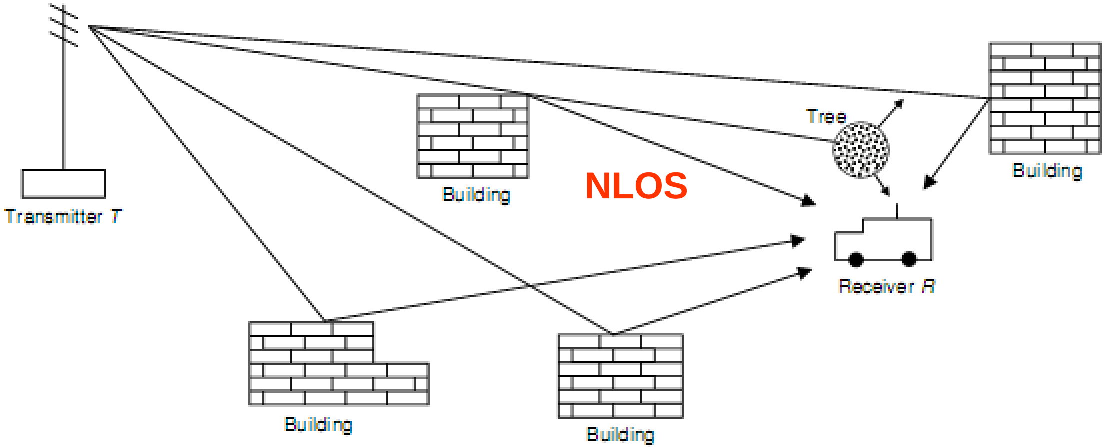


- ☐ **Spherical waves** at Tx
- ☐ **Planar waves** at Rx and in-between

These are approximations !

(may not be verified…)

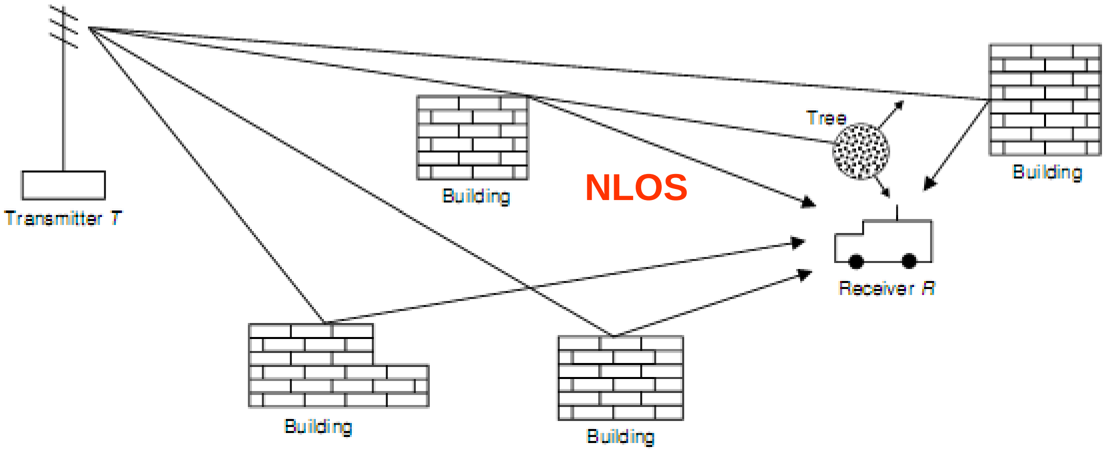
Basics



- ☐ **Direct propagation (LOS path)**
- ☐ **Specular reflection**
- ☐ **Diffraction**
- ☐ **Diffuse scattering**
- ☐ **Refraction/transmission**

} scatterers

Basics



- **The simple multipath based discrete channel model of the impulse response:**

$$h(t,\tau)=\sum_i A_i(t)\delta(\tau-\tau_i(t)) \qquad H(t,F)=\sum_i A_i(t)\exp(-2j\pi F\tau_i(t))$$

Time — Delay

Time — Frequency

At baseband, $A_i(t)$ is complex valued

Basics

❑ What (may) need be modeled

- ❑ The multipath amplitudes
- ❑ The multipath angles (at Tx/Rx)
- ❑ The multipath delays
- ❑ The time dependence of these parameters

(comes from Tx/Rx mobility, or mobility of the environment)

For various environments, Tx/Rx distances, locations…

Narrowband channels

Narrowband channels

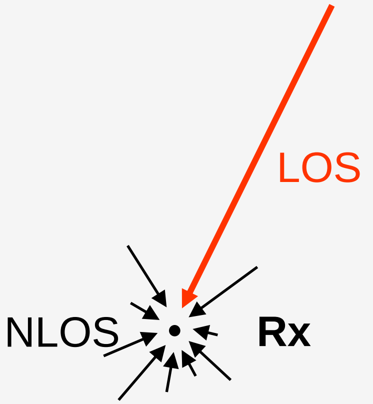
LOS/NLOS small scale fading

- ❑ **Received signal**:

$$r(t) = I(t)\cos(2\pi F_c t) - Q(t)\sin(2\pi F_c t)$$

$$I(t) = S_{LOS}\exp\left(j\varphi_{LOS}\right) + \sum_n S_n \exp\left(j\varphi_n\right)\Big|_t$$

$$Q(t) = S_{LOS}\exp\left(j\psi_{LOS}\right) + \sum_n S_n \exp\left(j\psi_n\right)\Big|_t$$



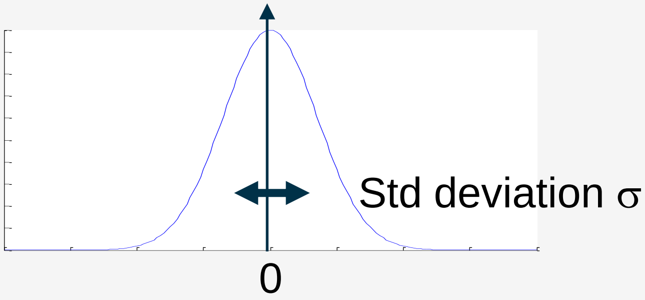
- ❑ **Assumption**:
  - ❑ S_{LOS} behaves as a deterministic variable (DV)
  - ❑ S_n and θ_n, φ_n behaves as random variables (RV)
  - ❑ Central-limit theorem ⇒ *I(t)*, *Q(t)* are non-centered, identically distributed Gaussian RV

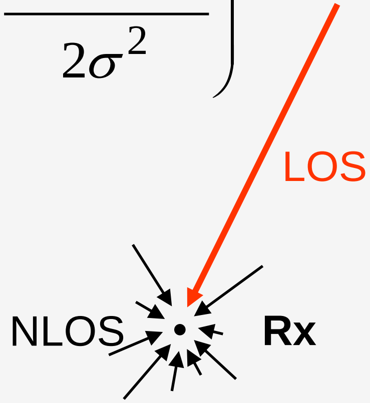
Narrowband channels

LOS/NLOS small scale fading

❑ **Statistics**:

- Random part of *I*, *Q*: $$PDF(I \text{ or } Q) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{I^2 \text{ or } Q^2}{2\sigma^2}\right)$$

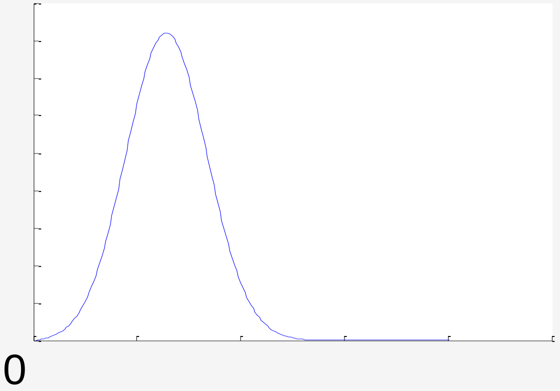




- Envelope |*r*|

Rice distribution:

$$PDF = \frac{|r|}{\sigma^2}\exp\left(-\frac{|r|^2+S_0^2}{2\sigma^2}\right) I_0\left(\frac{|r|S_0}{\sigma^2}\right)$$



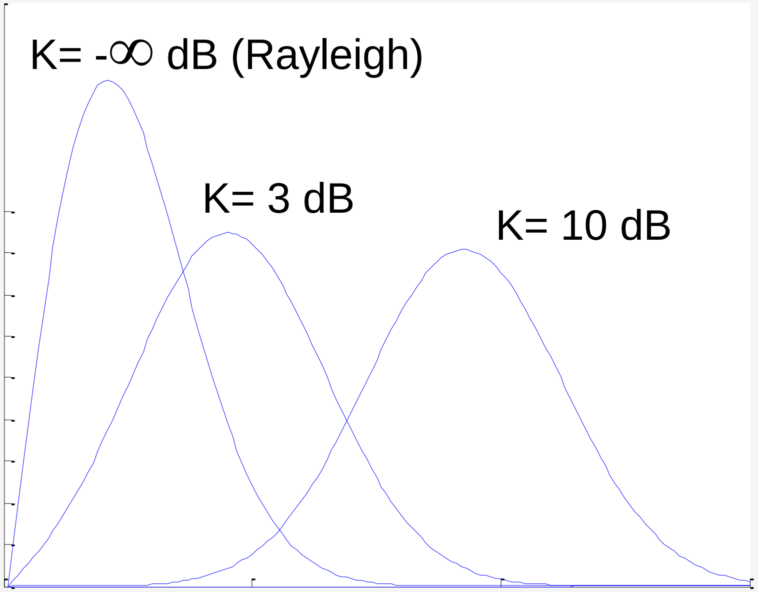
K factor: ratio of deterministic to random mean powers

$$K = \frac{S_0^2}{2\sigma^2}$$

Narrowband channels

LOS/NLOS small scale fading

- **Statistics**:
  - Rice distribution: $PDF = \frac{|r|}{\sigma^2} \exp\left(- \frac{|r|^2 + S_0^2}{2\sigma^2} \right) I_0\left(\frac{|r| S_0}{\sigma^2} \right)$



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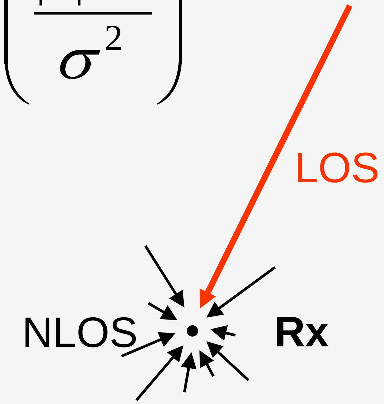
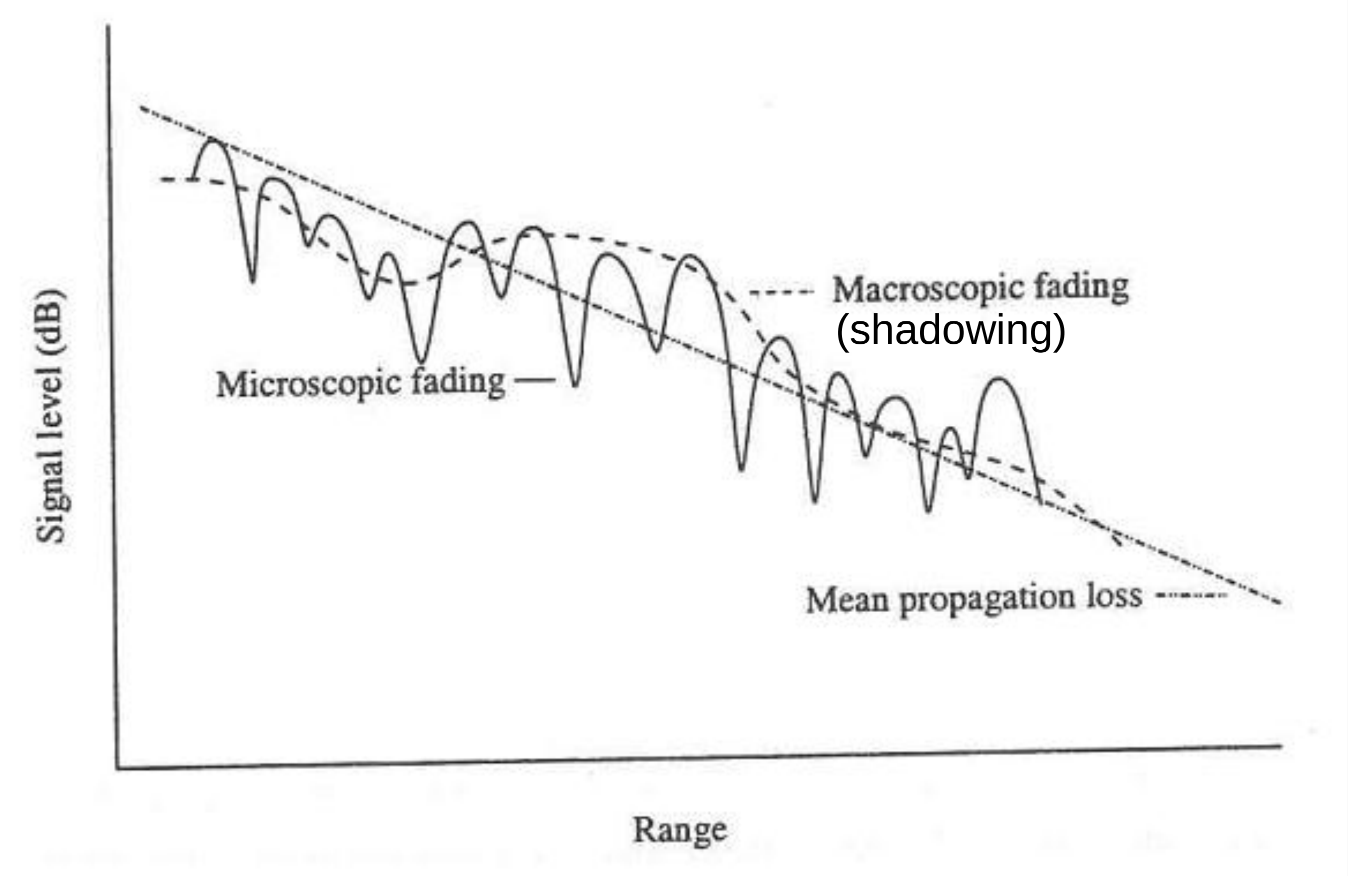


Narrowband channels

The three spatial scales of fading

- ☐ **Small distance/medium distance/long distance fading**



Narrowband channels

Path loss

❑ Long distance fading

- ❑ Friis formula (free space): $$\frac{P_r}{P_t} = G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 \propto d^{-2}$$

$$G_r, G_t = 1 \quad \Rightarrow \quad P_r = \frac{P_t}{L} \quad L_{dB} = 32.4 + 20\log(d_{km}) + 20\log(F_{MHz})$$

Going from 1 GHz to 10 GHz ⇒ 20 dB higher attenuation !

- ❑ Is this **frequency dependence** maintained in NLOS channels ?

Yes ! Frequency variations *roughly speaking* obey F^{-2} in NLOS

- ❑ Is this **distance dependence** maintained in NLOS channels ?

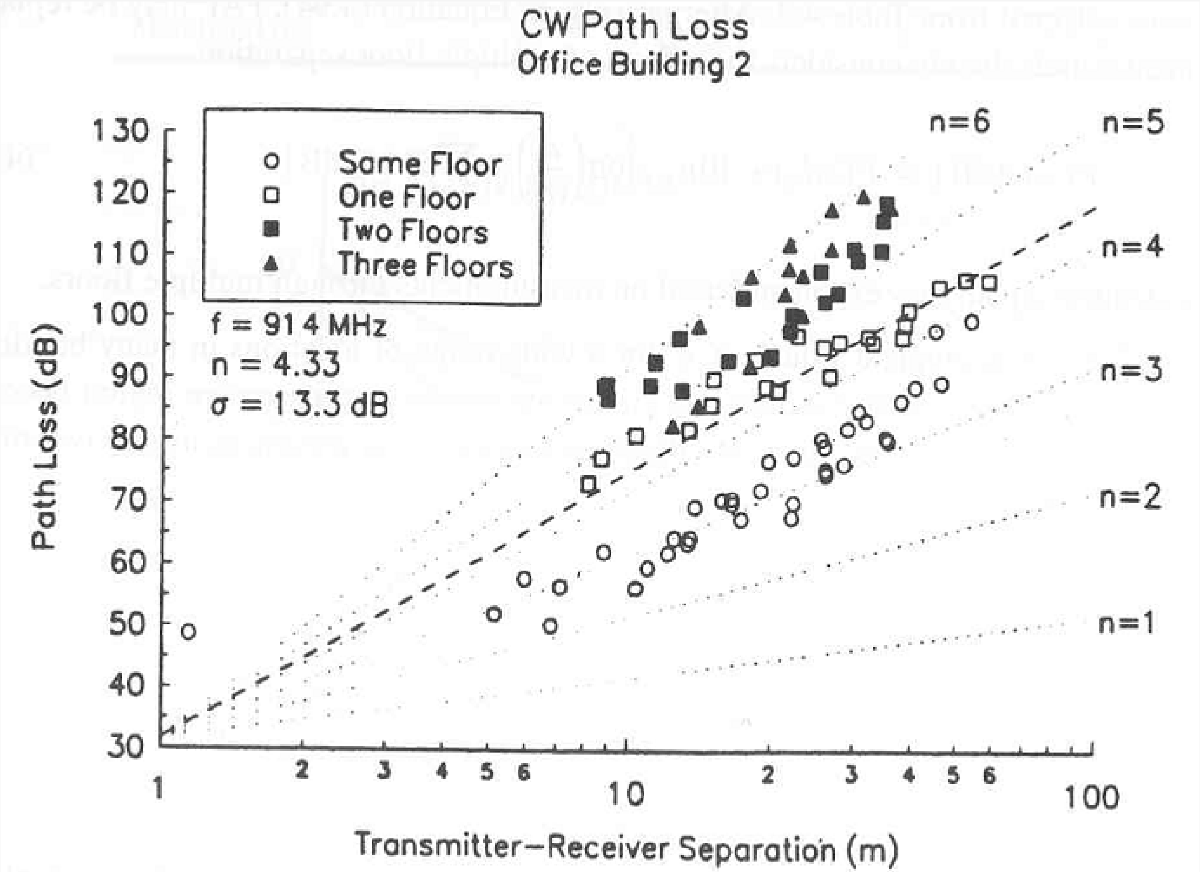
No ! The path loss exponent *n* often exceeds 2

$$\frac{L(d)}{L(d_0)} \propto \left(\frac{d}{d_0}\right)^n$$

Narrowband channels

Path loss

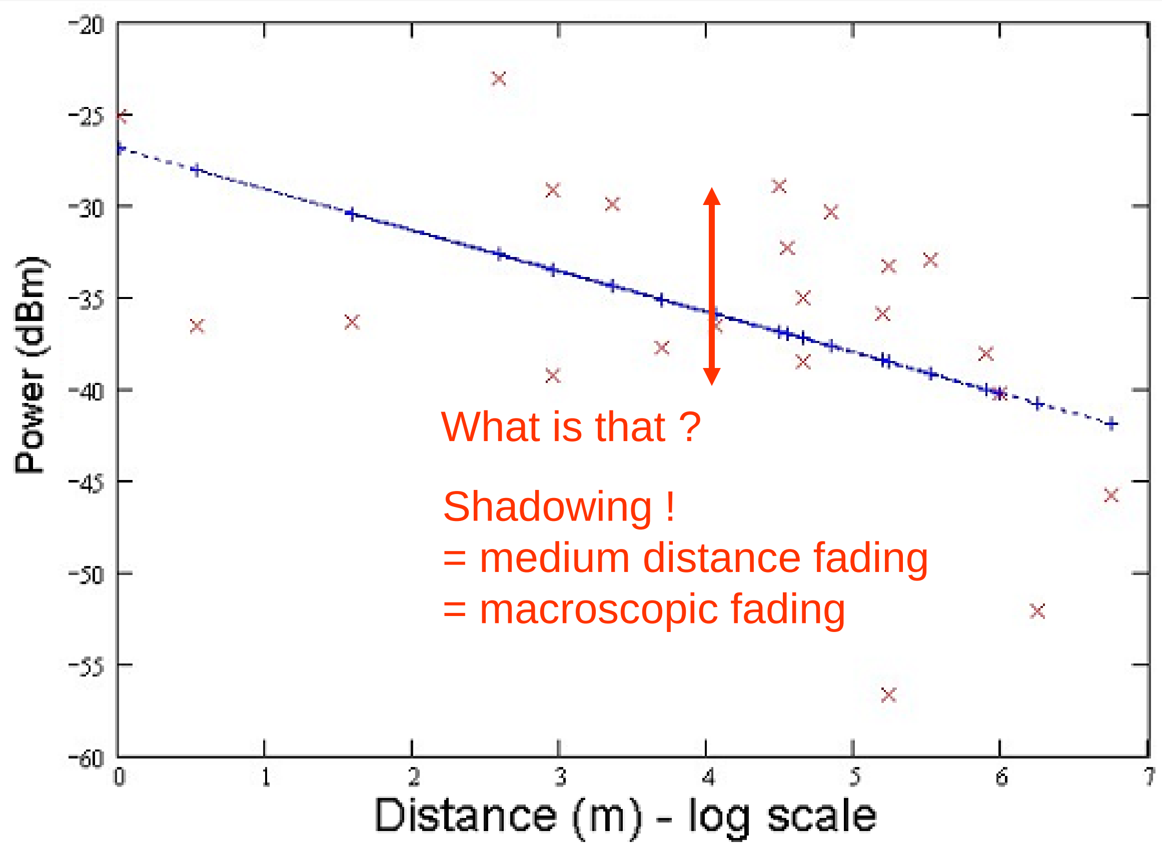
- **Long distance fading**



Narrowband channels

Shadowing

- **Medium distance fading**



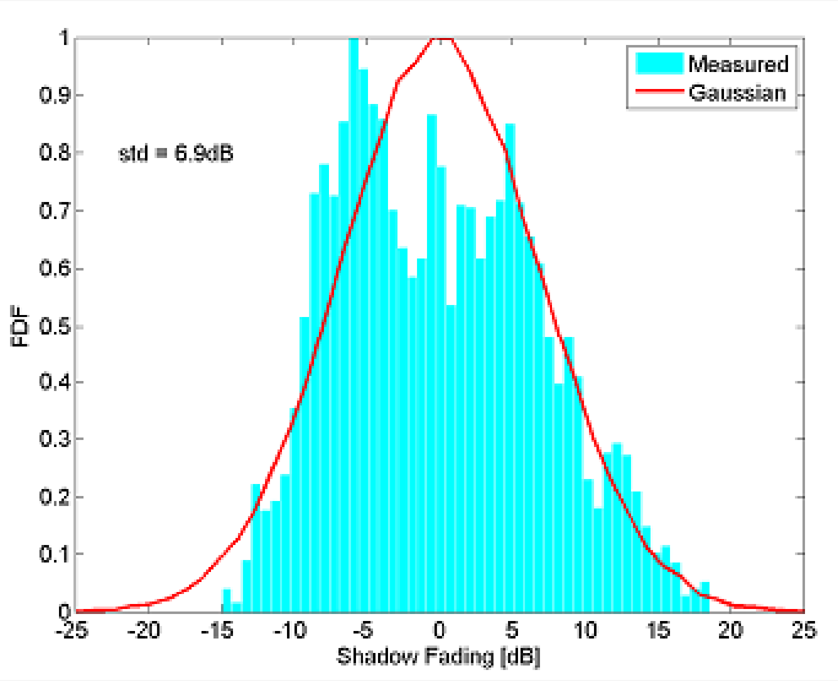
What is that ?

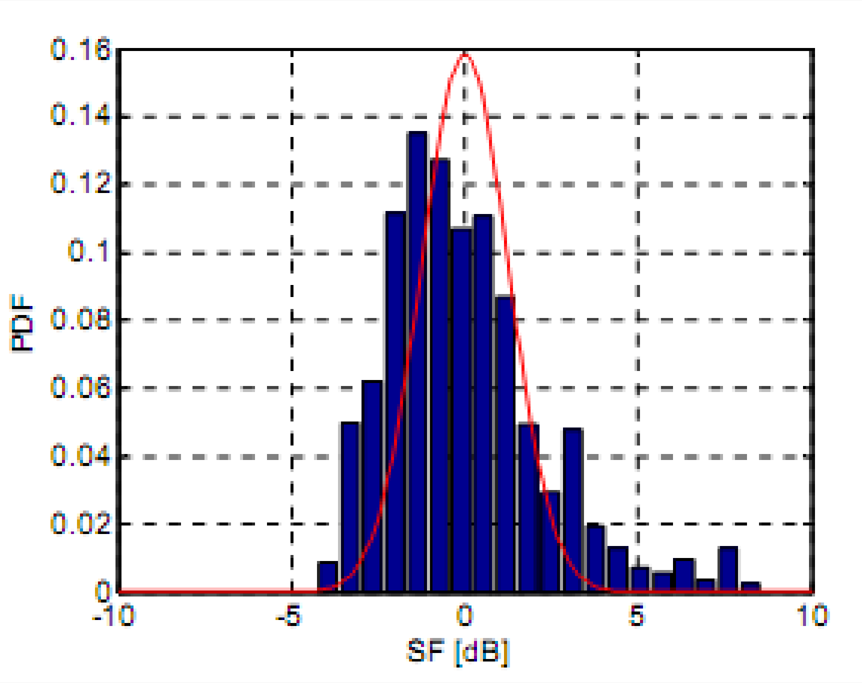
Shadowing !
= medium distance fading
= macroscopic fading

Narrowband channels

Shadowing

- ❑ **Medium distance fading**





Gaussian in dB = lognormal fading

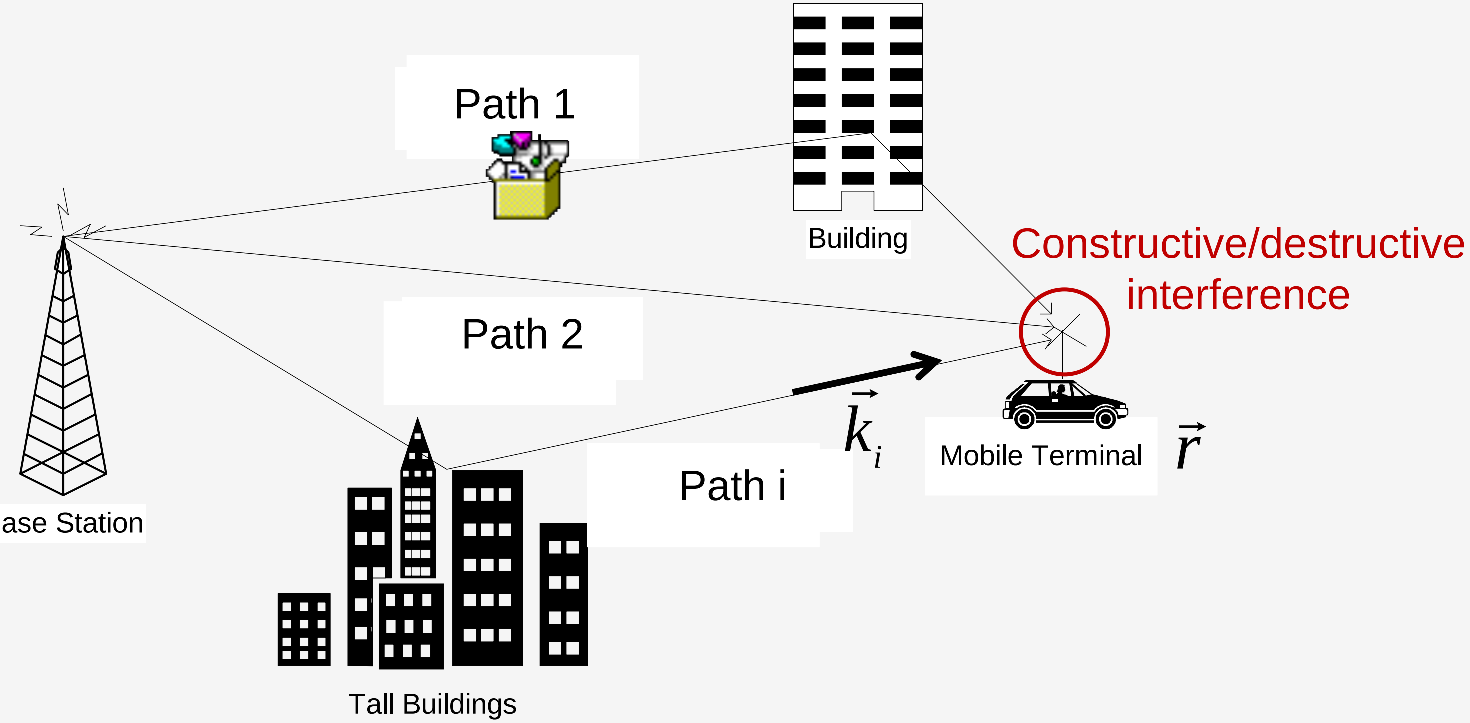
Wideband channels

Wideband channels

☐ Small scale / short term / wideband fading

Constructive/destructive interference between multipaths

$$H(t,F,\vec{r}) = \sum_i A_i(t)\exp\left(-2j\pi F\tau_i(t,\vec{r})\right) \qquad \tau_i(t,\vec{r}) = \tau_i\left(t,\vec{0}\right) - \frac{\vec{k}_i\vec{r}}{2\pi F}$$



Wideband channels

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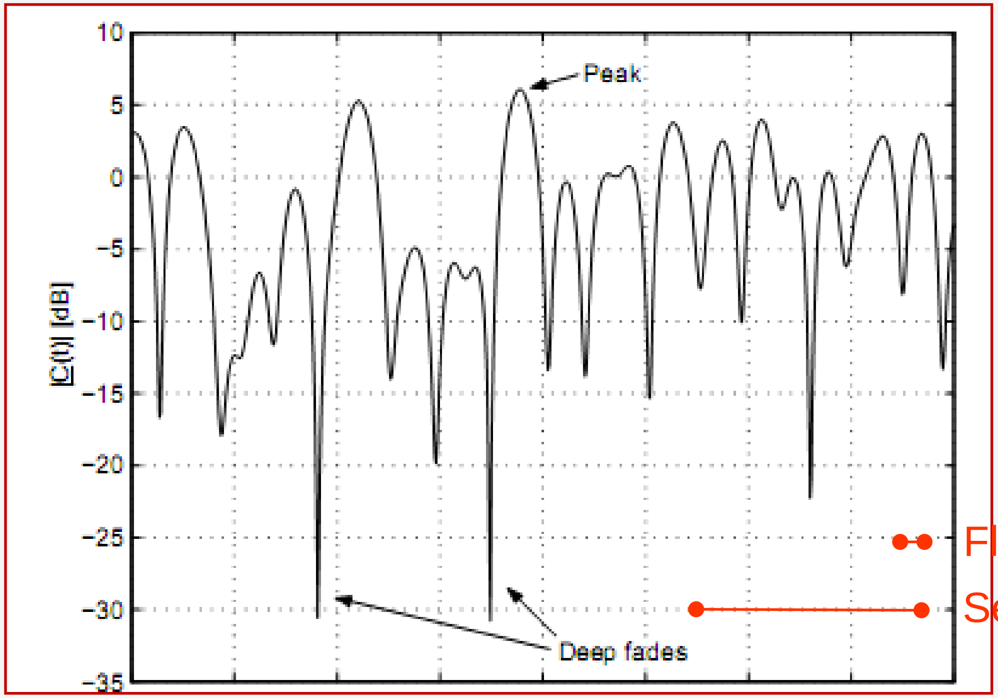
↔ Coherence band width



●● Flat (narrowband) fading

●——● Selective (wideband) fading

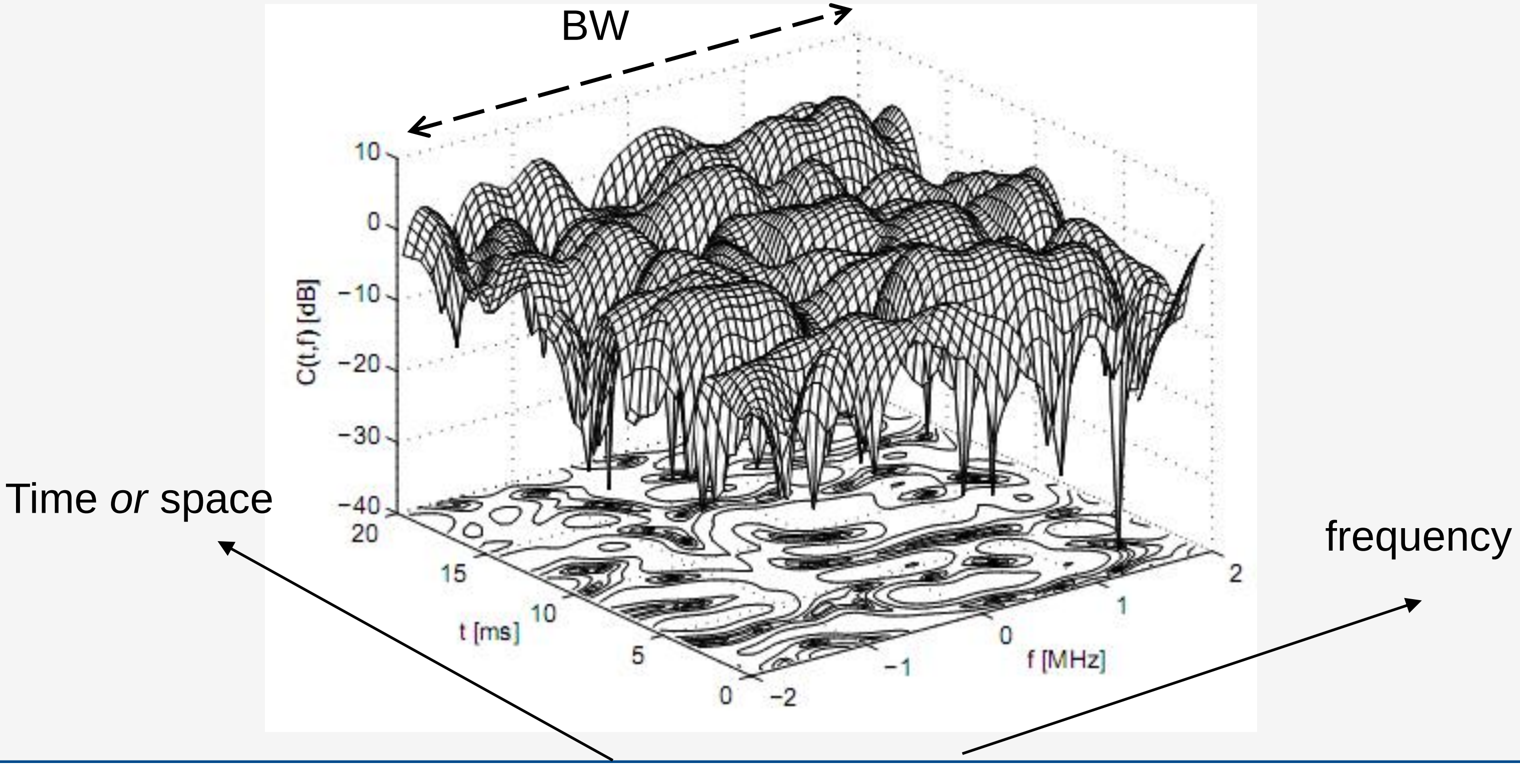
Frequency

Wideband channels

❑ Small scale / short term / wideband fading

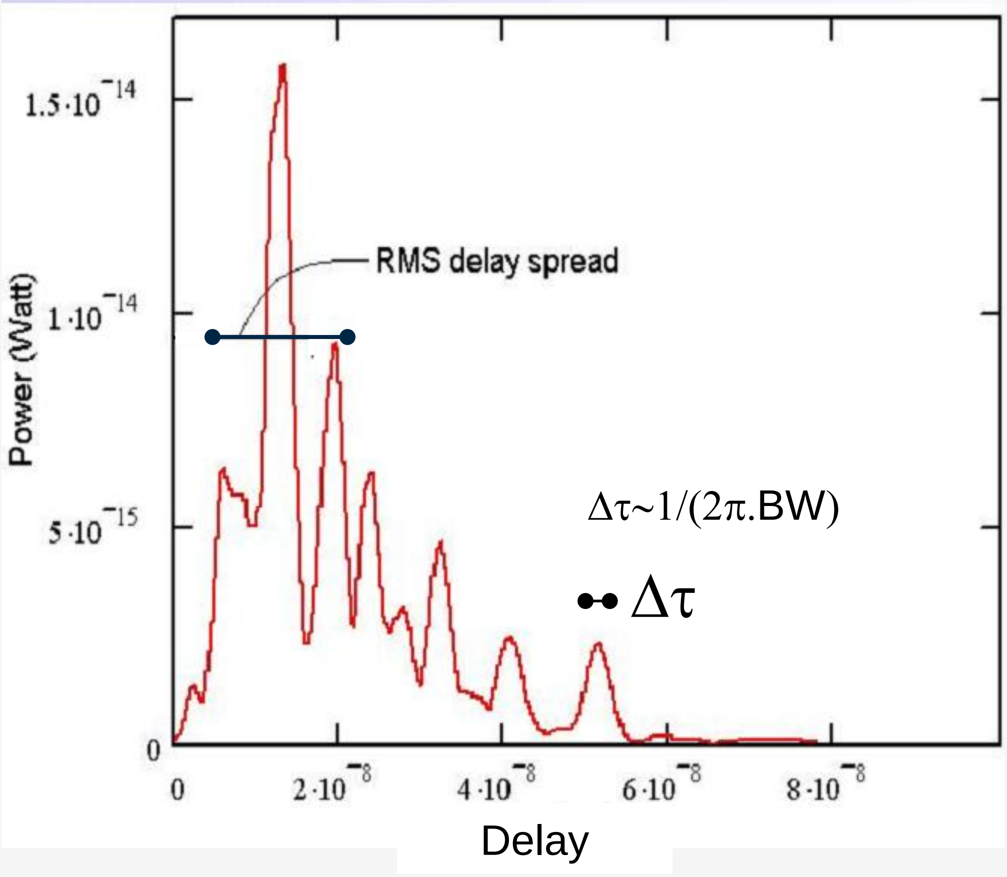
Constructive/destructive interference between multipaths

$$H(t,F,\vec{r}) = \sum_i A_i(t)\exp\left(-2j\pi F\tau_i(t,\vec{r})\right) \qquad \tau_i(t,\vec{r}) = \tau_i\left(t,\vec{0}\right) - \frac{\vec{k}_i\vec{r}}{2\pi F}$$



Wideband channels

☐ Frequency ⇔ Delay (Fourier): impulse response



$\Delta\tau \sim 1/(2\pi.BW)$

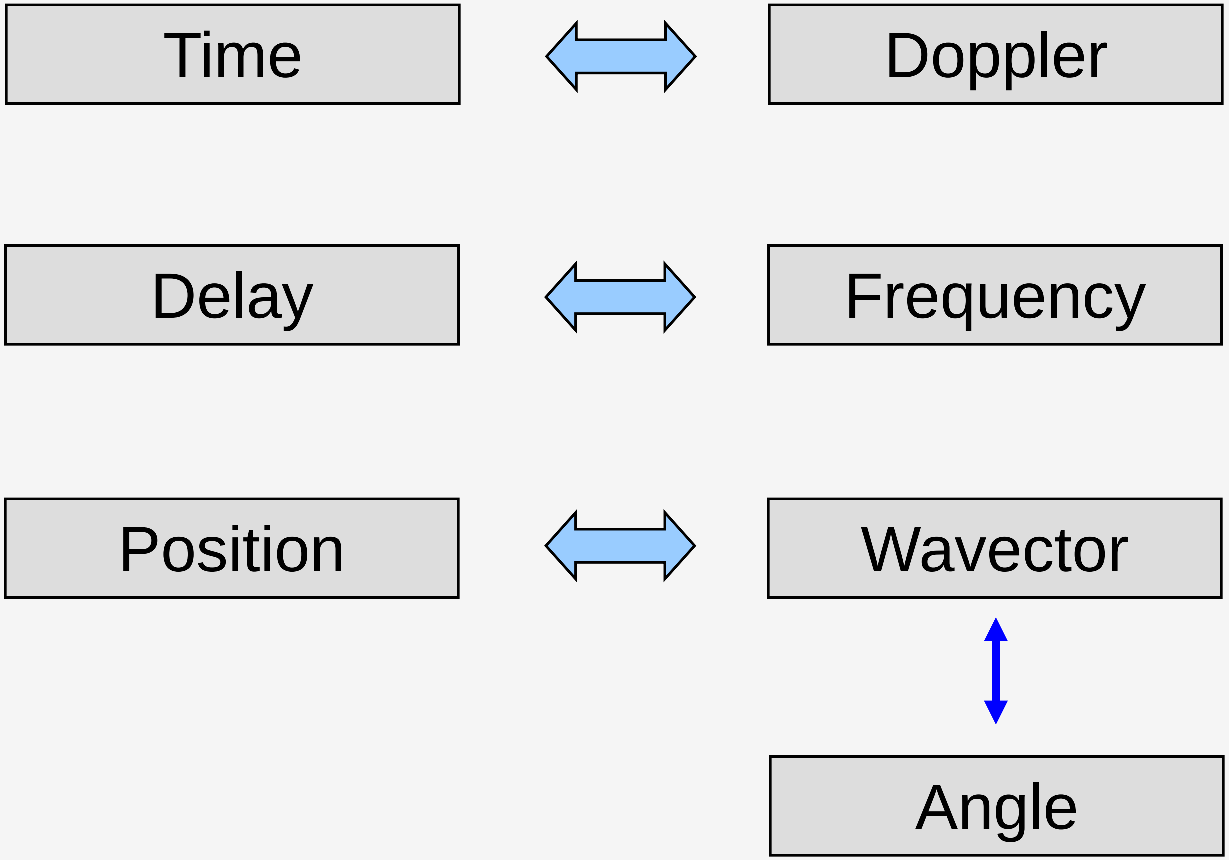
$$\overline{\tau} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)}$$

$$\tau^2 = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)}$$

$$\tau_{\text{rms}} = \sqrt{\tau^2 - (\overline{\tau})^2}$$

Wideband channels

- **Fourier pairs**



Time

Doppler

Delay

Frequency

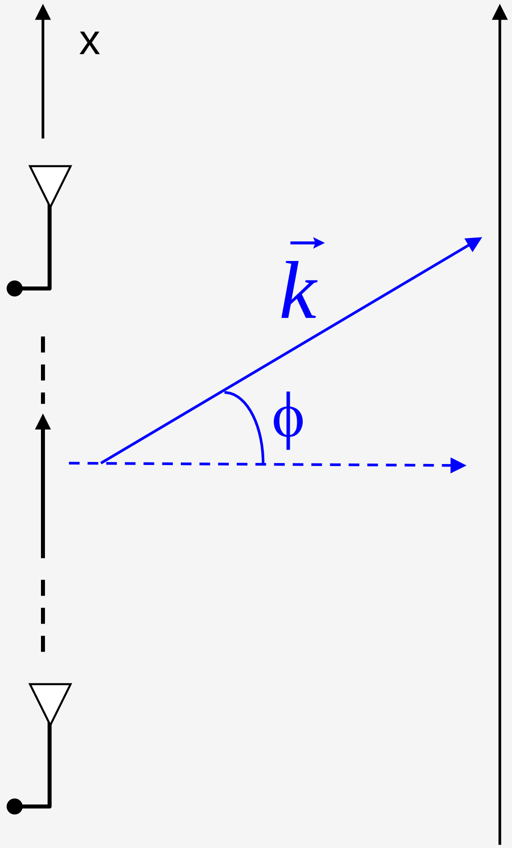
Position

Wavector

Angle

Wideband channels

❑ Fourier pairs

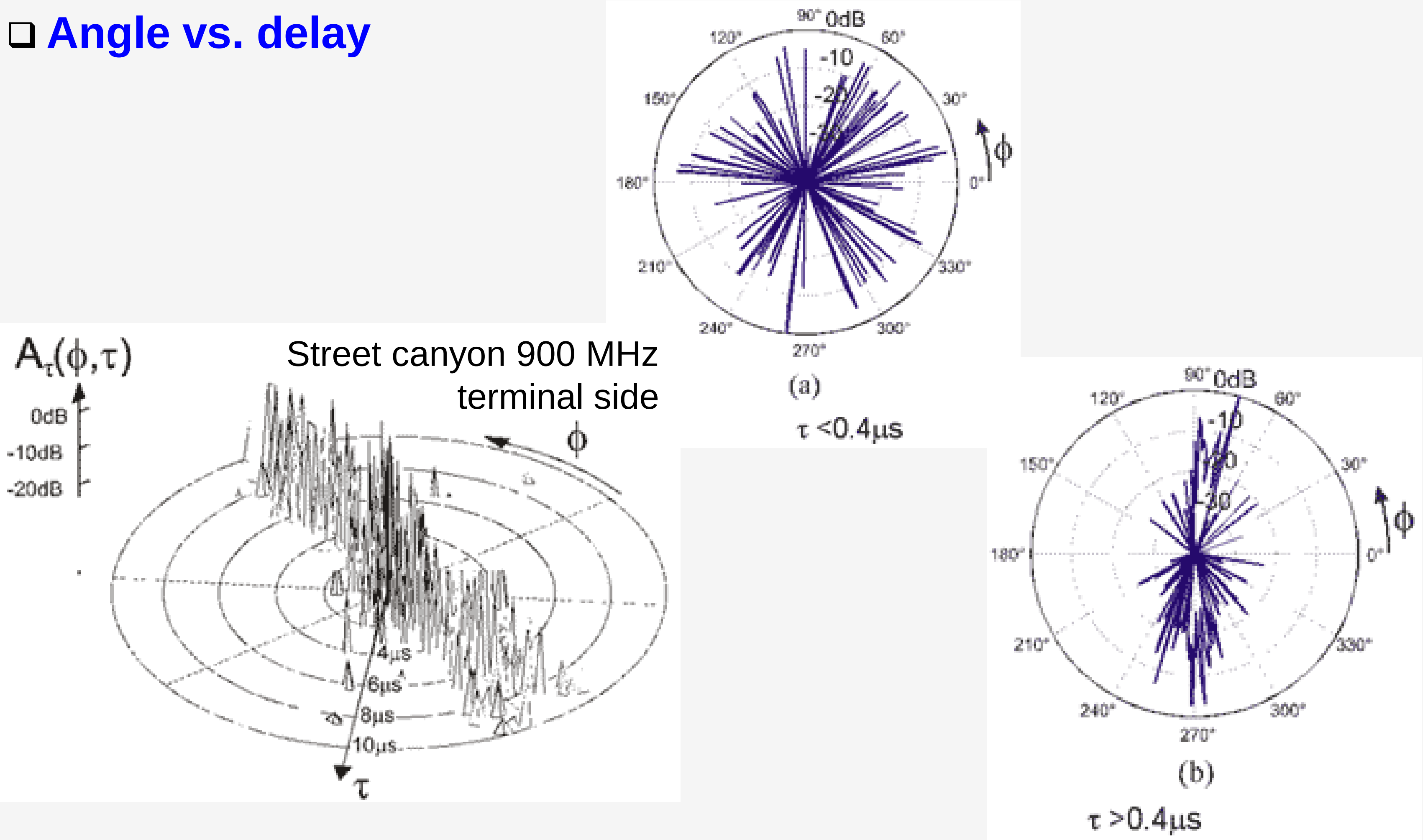


$$\exp(jk_x x) = \exp(jkx\sin(\phi))$$

- ❑ The directional spectrum is obtained from the spatial structure of the signal

Wideband channels

❑ Angle vs. delay



Street canyon 900 MHz
terminal side

(a)

$\tau < 0.4\mu s$

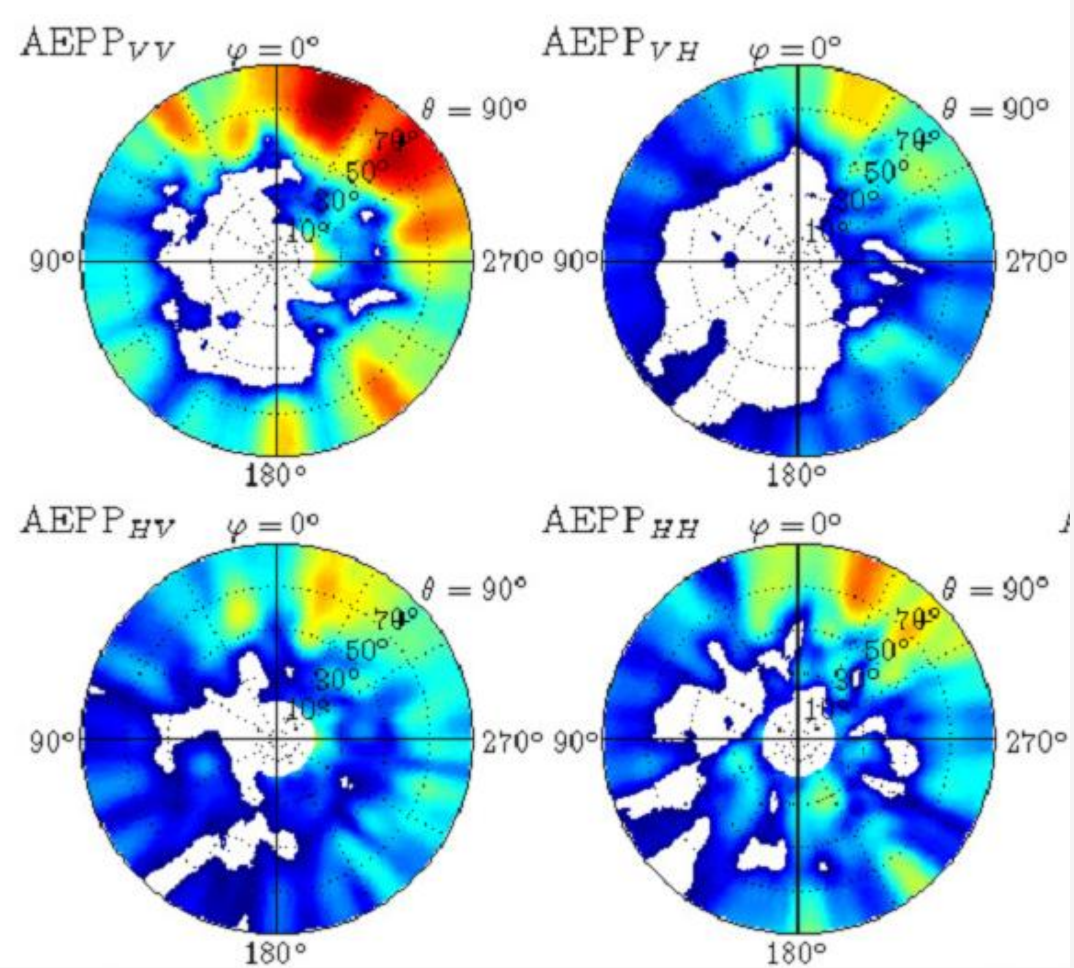
(b)

$\tau > 0.4\mu s$

Wideband channels

- ☐ **Angle vs. delay**

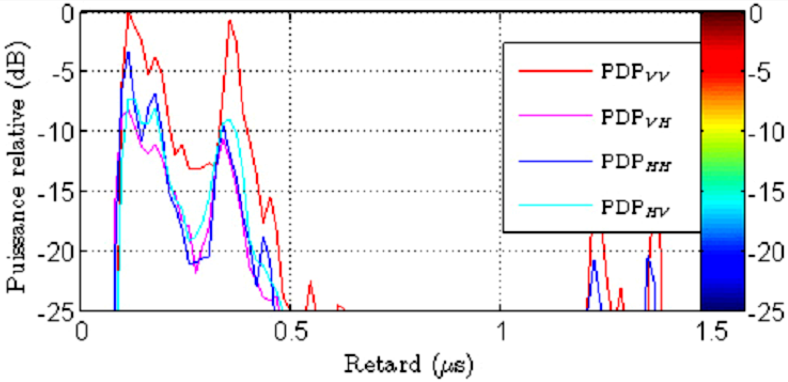
Dunand & Conrat, 2008

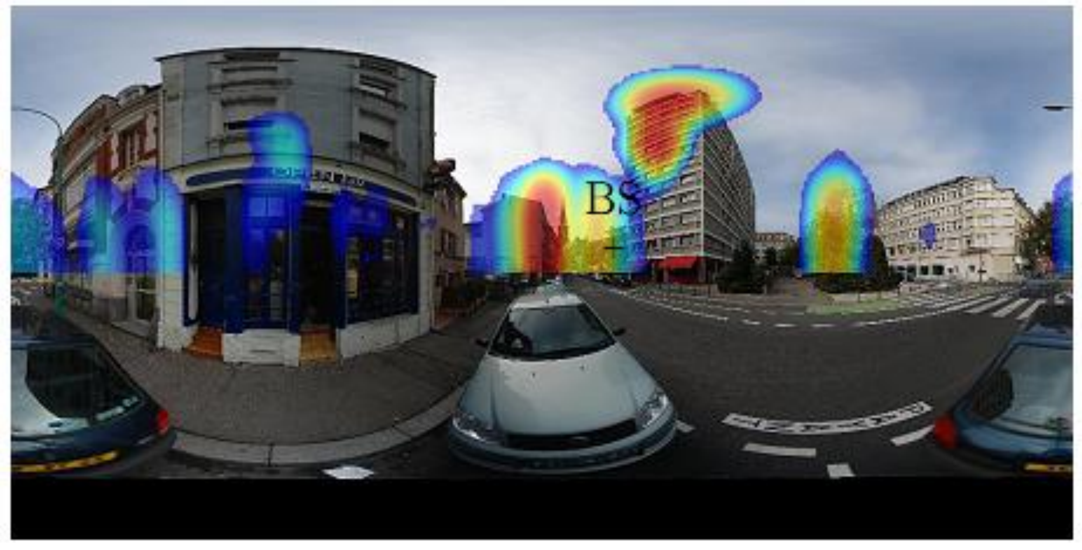


Wideband channels

- ☐ **Angle vs. delay**

Dunand & Conrat, 2008

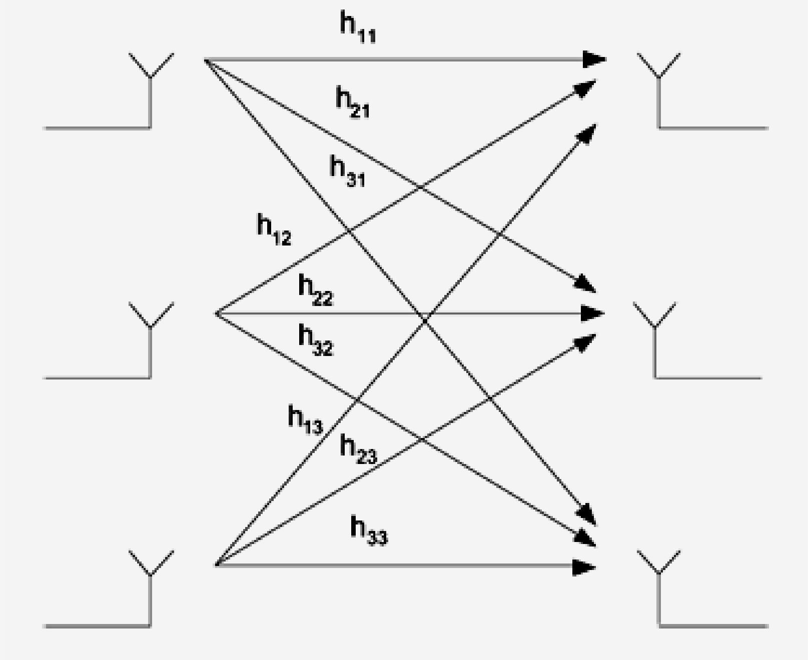




MIMO channels

MIMO channels

❑ **The impulse response becomes a matrix !**



$$\mathbf{H}(\tau)=\begin{bmatrix} h_{11}(\tau) & h_{12}(\tau) & \cdots & h_{1M}(\tau) \\ h_{21}(\tau) & h_{22}(\tau) & \cdots & h_{2M}(\tau) \\ \vdots & \vdots & \ddots & \vdots \\ h_{N1}(\tau) & h_{N2}(\tau) & \cdots & h_{NM}(\tau) \end{bmatrix}$$

- The relative variation of coefficients (with position, frequency, time) dramatically impacts the diversity/spatial multiplexing performance

- The multipath structure is responsible for this variation

MIMO channels

- ❑ **A non physical approach : based on the structure of the MIMO correlation matrix** $\mathbf{R}_{\mathsf{h}} = \mathrm{E}\{\mathbf{h}\mathbf{h}^H\}, \quad \text{with } \mathbf{h} = \mathrm{vec}(\mathbf{H})$

Kronecker approximation: $\mathbf{R}_{\mathsf{h}} \approx \frac{1}{\sqrt{\mathrm{tr}\{\mathbf{R}_{\mathsf{Rx}}\}}} \mathbf{R}_{\mathsf{Rx}} \otimes \mathbf{R}_{\mathsf{Tx}}^T$

The method lends itself to easy stochastic generation in a software tool: $\mathbf{H} = c \cdot \mathbf{R}_{\mathsf{Rx}}^{1/2}\, \mathbf{G}\, \mathbf{R}_{\mathsf{Tx}}^{1/2}, \quad \text{with } \mathbf{G} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$

Statistical modeling: define statistical distributions for the coefficients of the correlation matrices

⇨ **3GPP (LTE), IEEE 802.11n, IEEE 802.16…**

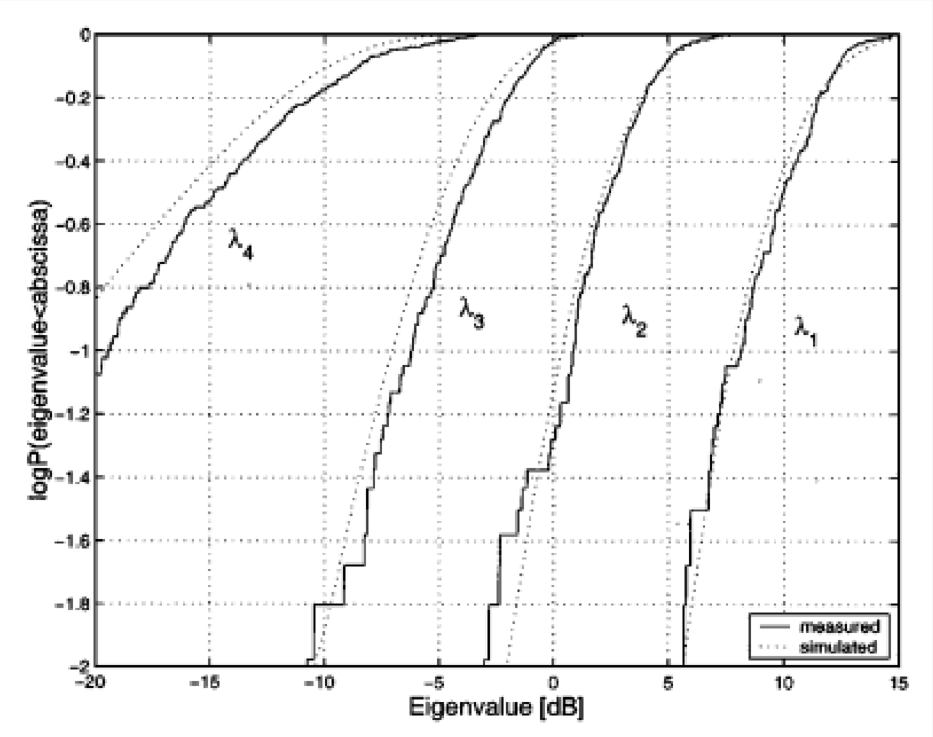
MIMO channels

- **A non physical approach : based on the structure of the MIMO correlation matrix** $\mathbf{R_h} = \mathrm{E}\{\mathbf{hh}^H\}$, with $\mathbf{h} = \mathrm{vec}(\mathbf{H})$

Kronecker approximation: $\mathbf{R_h} \approx \frac{1}{\sqrt{\mathrm{tr}\{\mathbf{R}_{\mathsf{Rx}}\}}} \mathbf{R}_{\mathsf{Rx}} \otimes \mathbf{R}_{\mathsf{Tx}}^T$

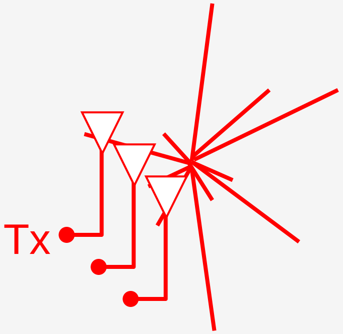
$$\boldsymbol{H} = \boldsymbol{U\Lambda V}^{\mathrm{H}}$$

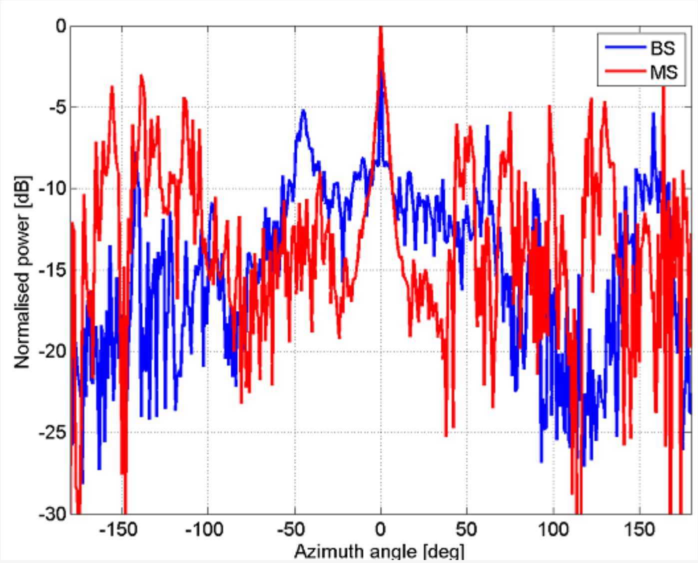
$$= \sum_{i=1}^{\min(n_{\mathrm{R}}, n_{\mathrm{T}})} \lambda_i \mathbf{u}_i \mathbf{v}_i^{\mathrm{H}}$$

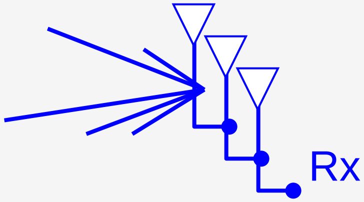


MIMO channels

❑ Double directional channels for MIMO channel modeling





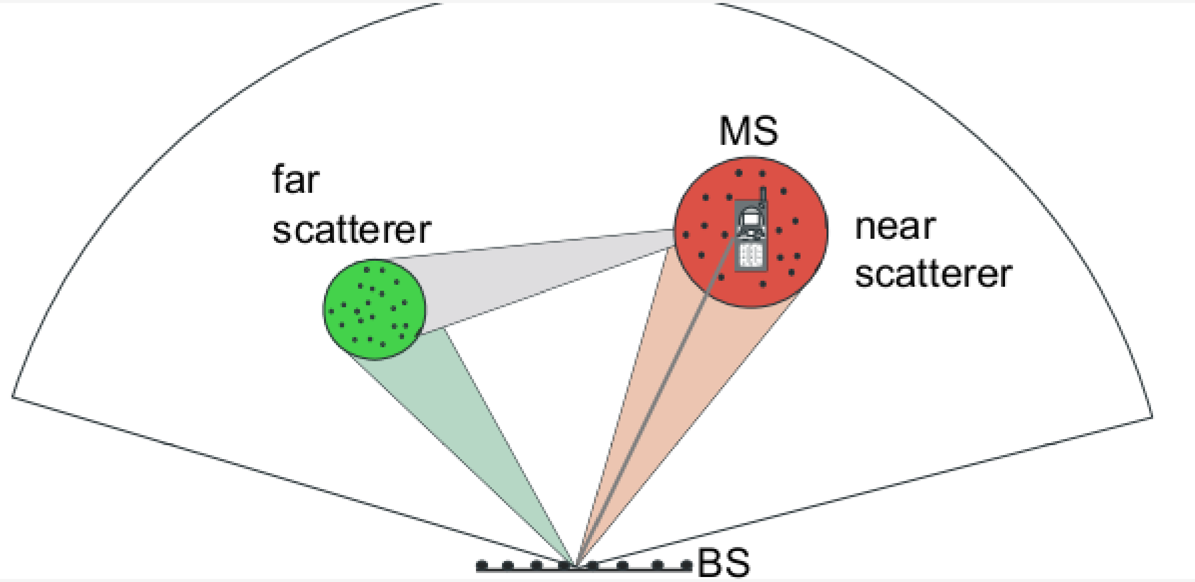


Statistical modeling: define statistical distributions for path amplitudes, path delays, path DoA, path DoD…

⇒ **3GPP, IEEE 802.11n, IEEE 802.16…**

MIMO channels

- ☐ **A semi-physical modeling approach : GSCM (Geometry-based Stochastic Channel Modeling)**



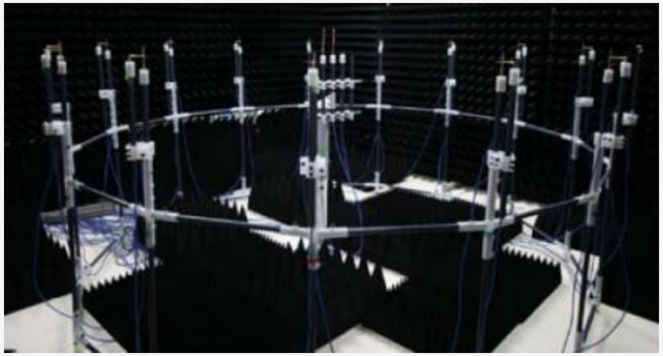
Statistical modeling: define statistical distributions for scatterers positions, characteristics…

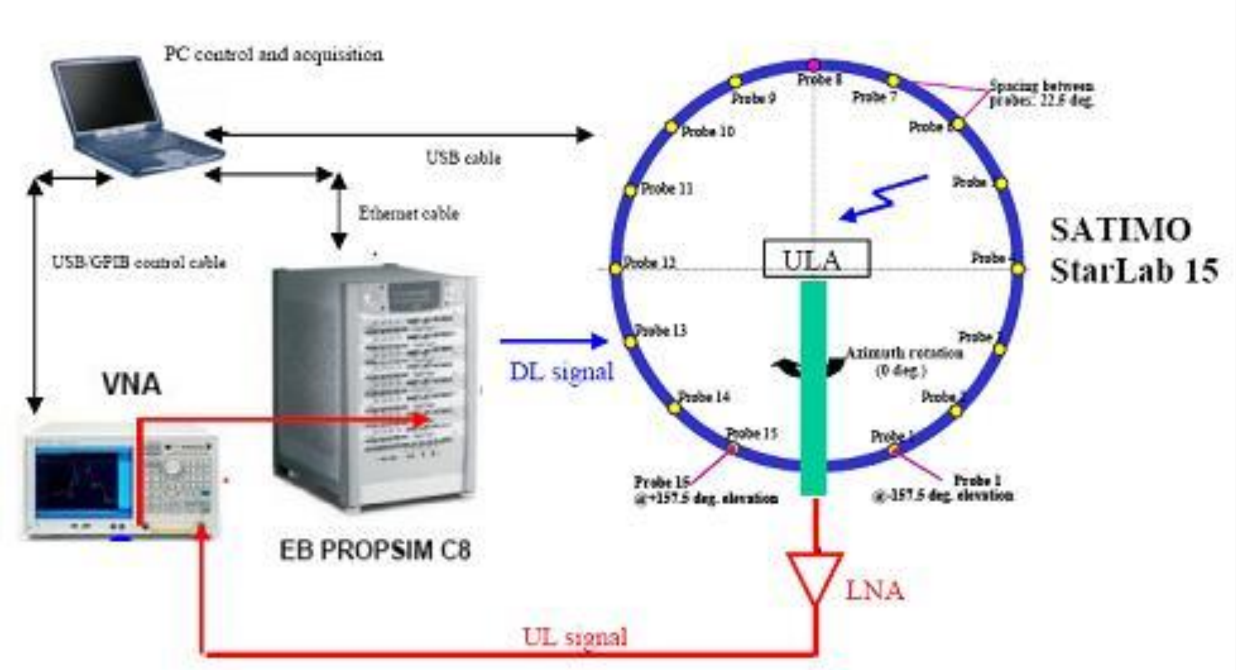
⇨ **COST 259, 273, 2100…**

MIMO channels

❑ What’s that for ?

- ❑ Example : standardization of OTA (Over The Air) test methods for MIMO terminals

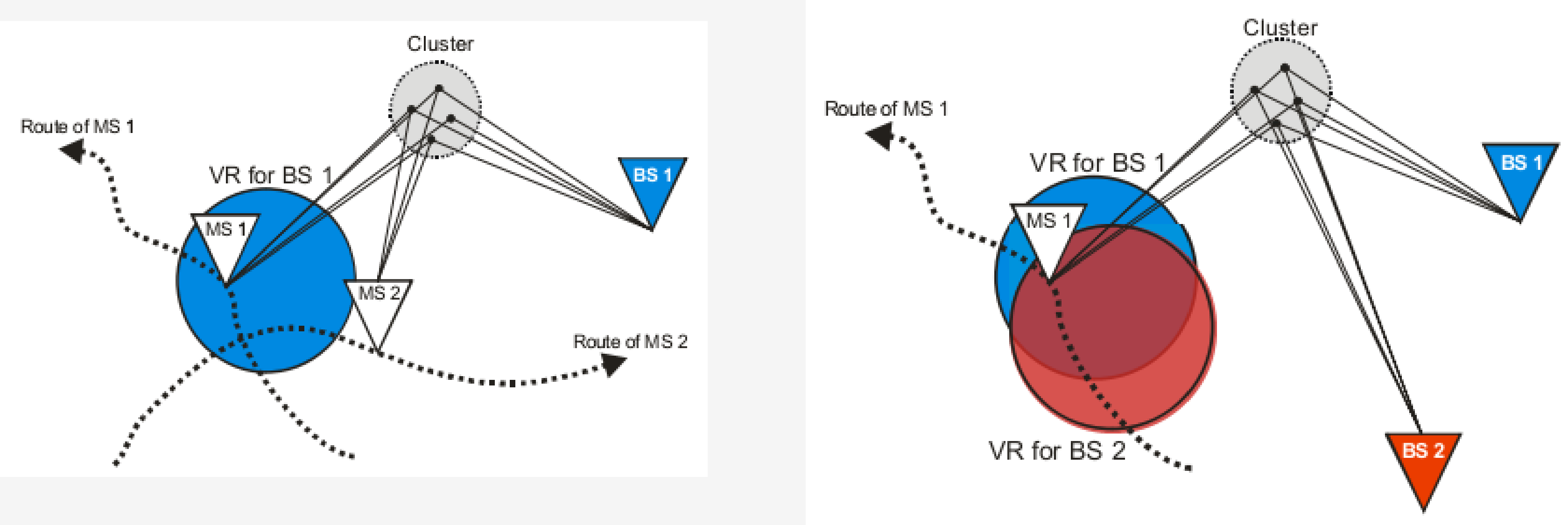




Multi-link channels

Multi-link channels

- **Multi-link channels are encountered in future networks**
  - Where BS can simultaneously be connected to several users
  - for which terminals may simultaneously be connected to several BS

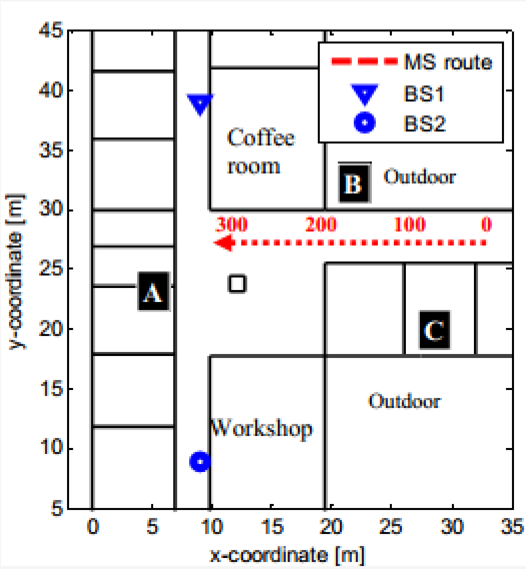


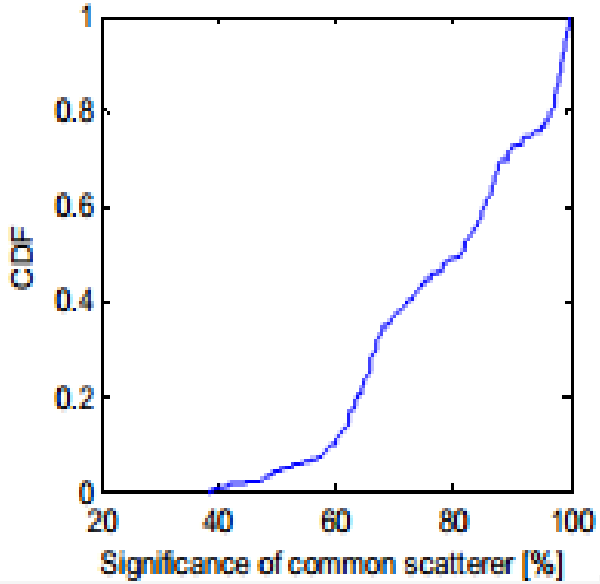
Multi-link channels

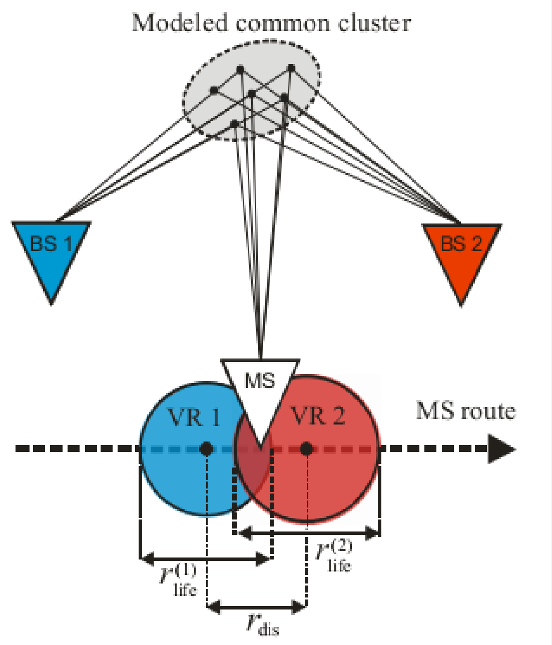
❑ Multi-link channels are encountered in future networks

- ❑ Where BS can simultaneously be connected to several users
- ❑ for which terminals may simultaneously be connected to several BS

⇨ channel modeling requires proper account of macroscopic spatial correlations



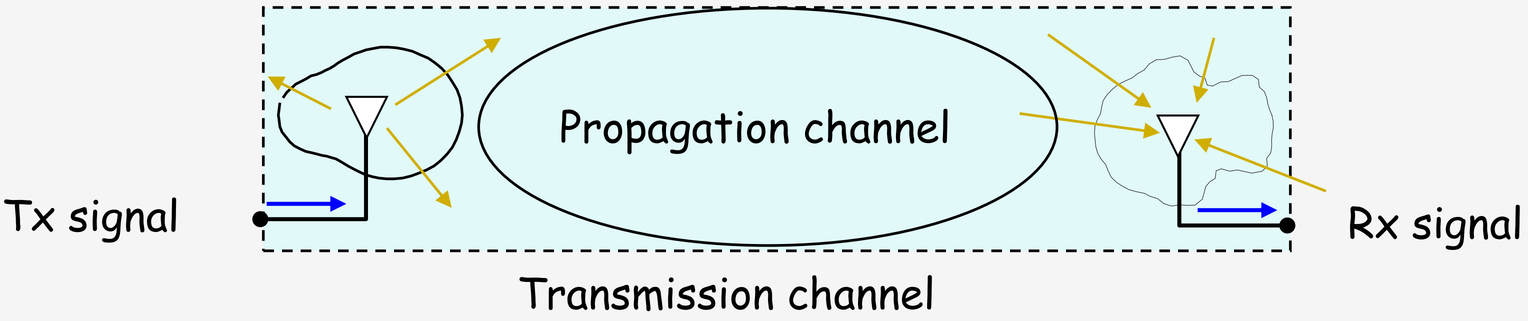




Perspectives & conclusion

Perspectives

- ☐ **Antennas are part of the radio channel !**



An instrumentation antenna
(for channel measurements)

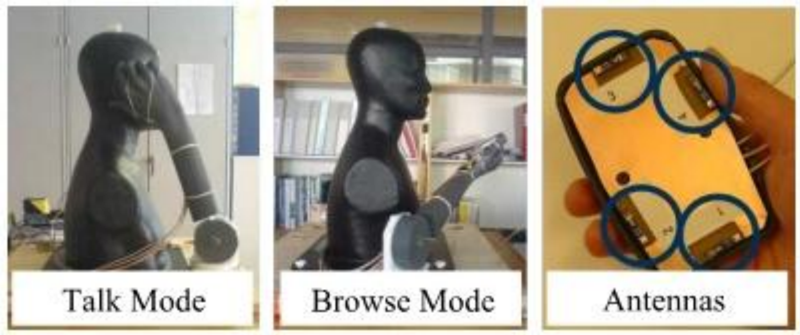
#

A use case

Perspectives

❑ Antennas are part of the radio channel !

The super-antenna concept: antenna + user in near field

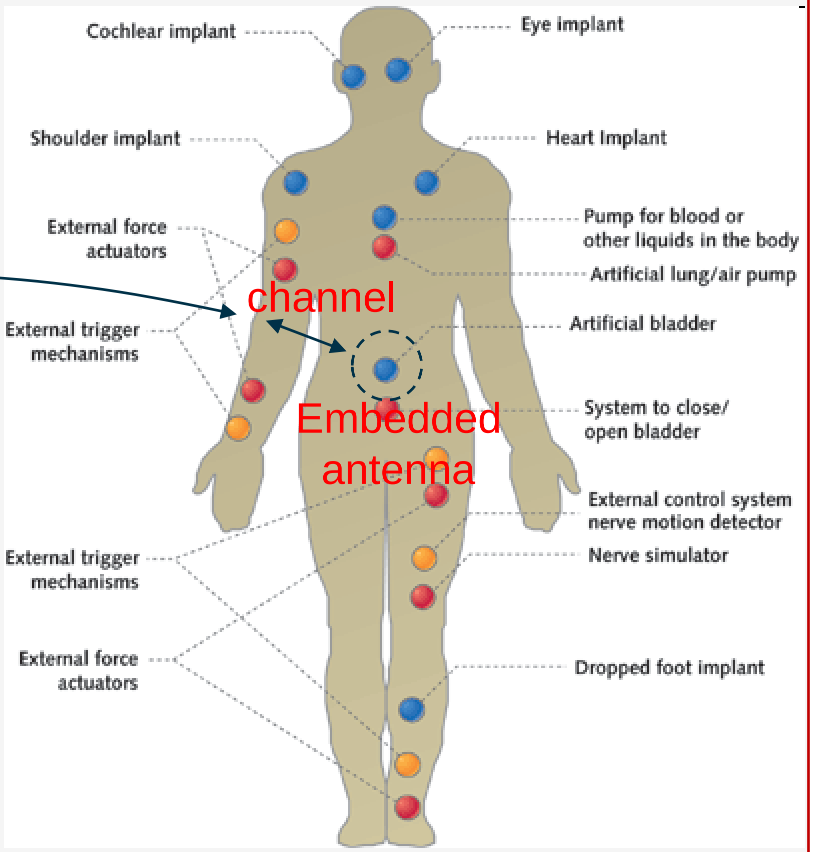


F. Harrysson et al., COST 2100 TD 07-379, Sep. 2007

Perspectives

☐ Antennas are part of the radio channel !

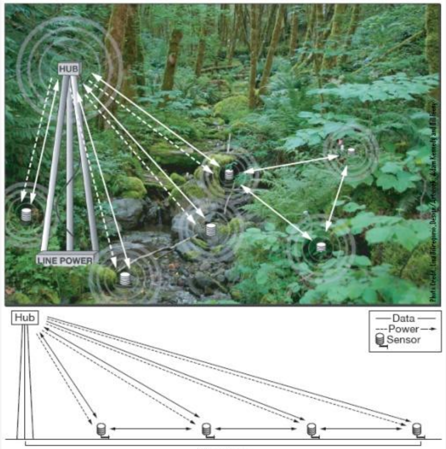
In-body antennas: ε ~50 σ ~2 S/m !

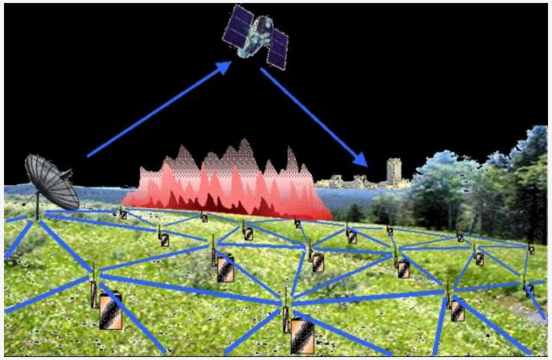


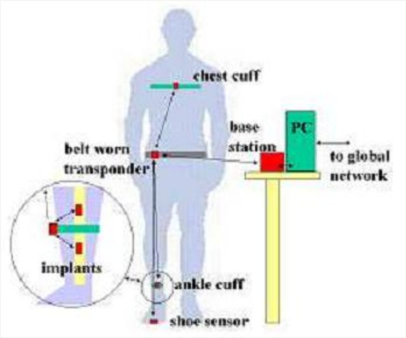
→ Composite antenna-channel problem

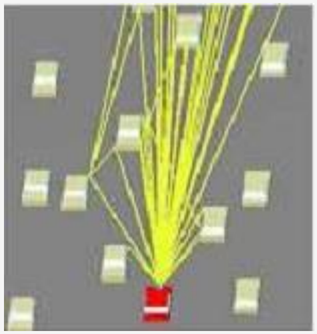
Perspectives

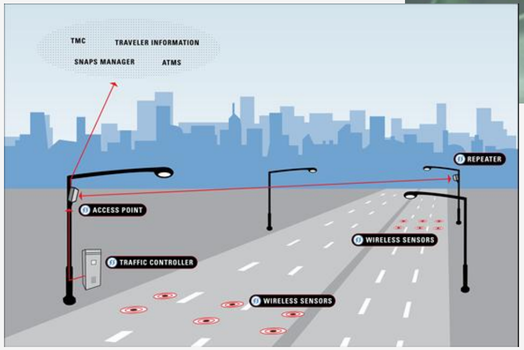
- ❑ A variety of propagation environments for new wireless use cases











Conclusion

- ❑ **The main message: radio channel modeling is a rich subject, combining propagation physics, data processing and a lucid view of systems/networks requirements**

- ❑ **The increasing sophistication of channel investigations and models stems from the complexification of wireless networks, from picocells to macrocells (even satellites) throughout**

- ❑ **It seems that researchers in this area are not yet jobless ☺**