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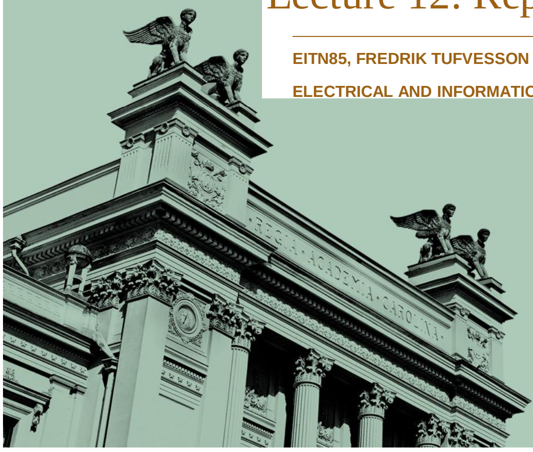
Wireless Communication Channels
Lecture 12: Repetition

EITN85, FREDRIK TUFVESSON

ELECTRICAL AND INFORMATION TECHNOLOGY



Why channel modelling?

The performance of a radio system is ultimately determined by the radio channel

The channel models basis for

- system design
- algorithm design
- antenna design etc.

Trend towards more interaction system-channel

- MIMO
- UWB
- radio based positioning

Without reliable channel models, it is hard to design radio systems that work well in *real* environments.

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THE RADIO CHANNEL
It is more than just a loss

- Some examples:
  - behavior in time/place?
  - behavior in frequency?
  - directional properties?
  - bandwidth dependency?
  - behavior in delay?

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THE RADIO CHANNEL
Some properties

- **Path loss**
  - **Roughly, received power decays exponentially with distance**

$$\text{Received power} \propto \text{Transmitted power} \times \text{Distance}^{-\text{Propagation exponent}}$$

- **Large-scale fading**
  - **Large objects, compared to a wavelength, in the signal path obstruct the signal**

- **Small-scale fading**
  - **Objects reflecting the signal causes multipath propagation from transmitter to receiver**

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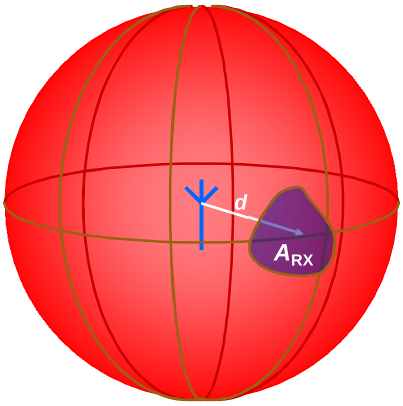
Free-space loss



If we assume RX antenna to be isotropic:

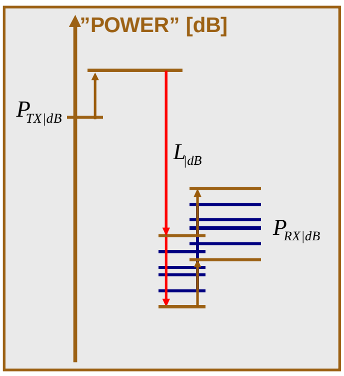
$$P_{RX} = \left(\frac{\lambda}{4\pi d}\right)^2 P_{TX}$$

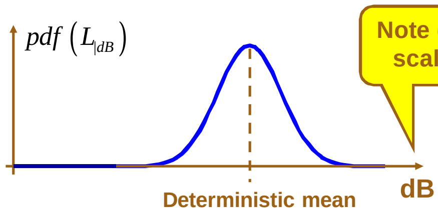
Attenuation between two isotropic antennas in free space is (free-space loss):

$$L_{free}(d) = \left(\frac{4\pi d}{\lambda}\right)^2$$

Large-scale fading
Log-normal distribution

Measurements confirm that in many situations, the large-scale fading of the received signal strength has a normal distribution in the dB domain.





Note dB scale

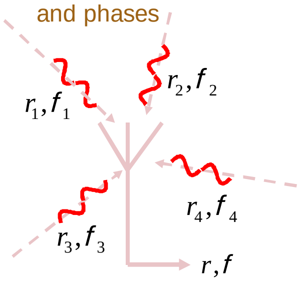
Deterministic mean value of path loss, $L_{0|dB}$

$$pdf(L_{|dB}) = \frac{1}{\sqrt{2\pi}\sigma_{F|dB}} \exp\left(-\frac{(L_{|dB} - L_{0|dB})^2}{2\sigma_{F|dB}^2}\right)$$

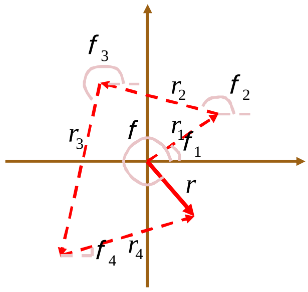
Standard deviation $\sigma_{F|dB} \approx 4 - 10$ dB

Small-scale fading
Many incoming waves

Many incoming waves with independent amplitudes and phases

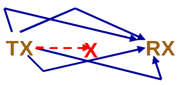


Add them up as phasors



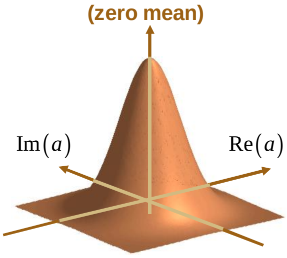
$$r\exp(jf) = r_1\exp(jf_1) + r_2\exp(jf_2) + r_3\exp(jf_3) + r_4\exp(jf_4)$$

Small-scale fading
Rayleigh fading



No dominant component (no line-of-sight)

Tap distribution 2D Gaussian (zero mean)

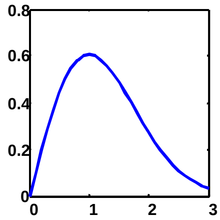


No line-of-sight component

$r = |a|$

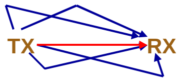
Amplitude distribution

Rayleigh



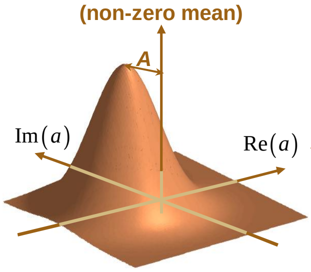
$$pdf(r) = \frac{r}{s^2}\exp\left(-\frac{r^2}{2s^2}\right)$$

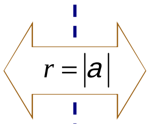
Small-scale fading
Rice fading



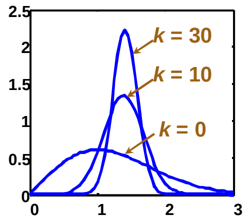
A dominant component (line of sight)

Tap distribution 2D Gaussian (non-zero mean)





Amplitude distribution Rice



$$pdf(r) = \frac{r}{\sigma^2}\exp\left(-\frac{r^2 + A^2}{2\sigma^2}\right) I_0\left(\frac{rA}{\sigma^2}\right)$$

Line-of-sight (LOS) component with amplitude *A*.

$$k = \frac{\text{Power in LOS component}}{\text{Power in random components}} = \frac{A^2}{2\sigma^2}$$

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Both small-scale and large-scale fading

Large-scale fading - lognormal fading gives a certain mean Small scale fading – Rayleigh distributed given a certain mean

The two fading processes adds up in a dB-scale

Suzuki distribution:

$$pdf(r) = \int_0^{\infty} \frac{\pi r}{2\sigma^2} e^{-\frac{\pi r^2}{4\sigma^2}} \frac{20}{\ln(10)} \frac{1}{\sigma\sigma_F\sqrt{2\pi}} e^{-\frac{20\log(\sigma)-\mu}{2\sigma_F^2}}$$

log-normal mean

log-normal std

small-scale std for complex components

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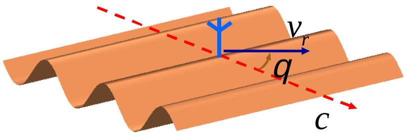
Small-scale fading
Doppler shifts



Receiving antenna moves with speed v_r at an angle θ relative to the propagation direction of the incoming wave, which has frequency f_0.

Frequency of received signal:

$$f = f_0 + \nu$$

where the Doppler shift is

$$\nu = -f_0 \frac{v_r}{c} \cos(\theta)$$

The maximum Doppler shift is

$$\nu_{\max} = f_0 \frac{v}{c}$$

Small-scale fading
The Doppler spectrum

Uncorrelated scattering with uniform angular distribution

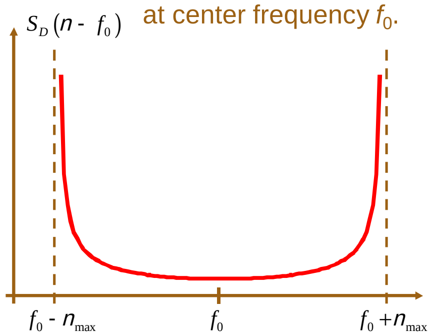
Doppler spectrum by Fourier transformation of the time correlation of the signal:

$$S_D(\nu) = \int r(\Delta t)\, e^{-j2\pi\nu\Delta t}\, d\Delta t$$

$$\propto \frac{1}{\pi\sqrt{\nu_{\max}^2 - \nu^2}}$$

for $-\nu_{\max} < \nu < \nu_{\max}$

Doppler spectrum at center frequency f_0.

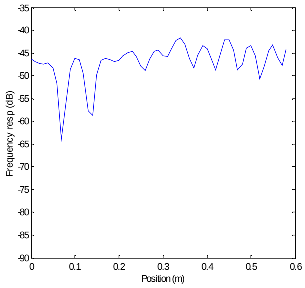


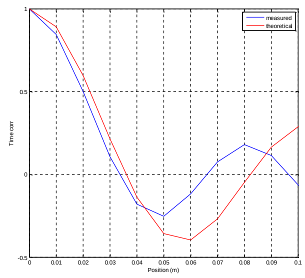
What does this mean in practice?

Condensed parameters
The time correlation

A property closely related to the Doppler spectrun is the time correlation of the channel. It is in fact the inverse Fourier transform of the Doppler spectrum:

$$\rho_t(\Delta t) = \int_{-\infty}^{\infty} P_B(\nu)\exp(j2\pi\nu\Delta t)\,d\nu$$





Compare $1/(2*p*v_{max})=0.014$ s

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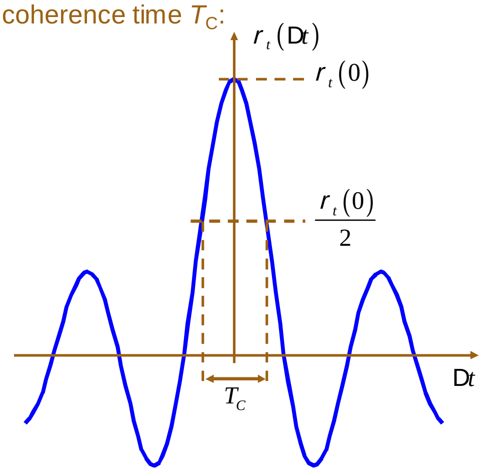
Condensed parameters
Coherence time

Given the time correlation of a channel, we can define the coherence time T_C:



What does the coherence time tell us?

It shows us over how long time we can assume that the channel is fairly constant.

E.g. radio systems transmitting data in frames much shorter than T_C will not experience any fading within a single frame.

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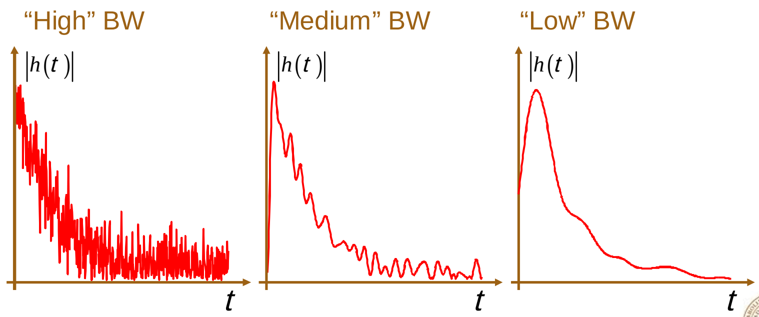
Narrow- versus wide-band Channel impulse response

The same radio propagation environment is experienced differently, depending on the system bandwidth.



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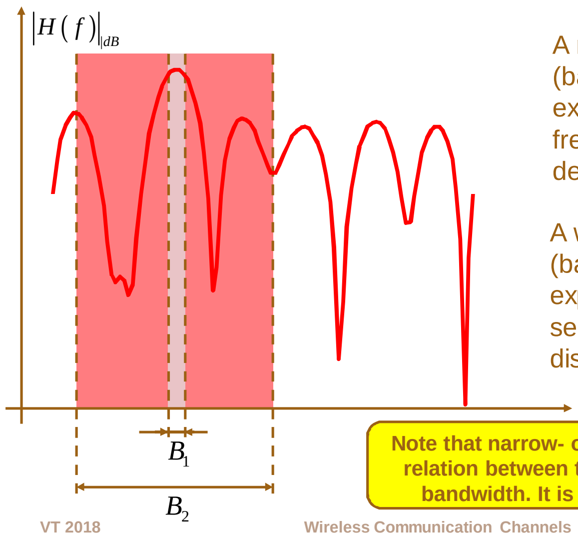
Narrow- versus wide-band Channel frequency response



A narrow-band system (bandwidth B_1) will not experience any significant frequency selectivity or delay dispersion.

A wide-band system (bandwidth B_2) will however experience both frequency selectivity and delay dispersion.

Note that narrow- or wide-band depends on the relation between the channel and the system bandwidth. It is not an absolute measure.

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Condensed parameters
Power-delay profile (cont.)

We can "reduce" the PDP into more compact descriptions of the channel:

Total power (time integrated):

$$P_m = \int_{-\infty}^{\infty} P(\tau)\,d\tau$$

Average mean delay:

$$T_m = \frac{\int_{-\infty}^{\infty} \tau P(\tau)\,d\tau}{P_m}$$

Average rms delay spread:

$$S = \sqrt{\frac{\int_{-\infty}^{\infty} \tau^2 P(\tau)\,d\tau}{P_m} - T_m^2}$$

For our tapped-delay line channel:

$$P_m = \sum_{i=1}^{N} 2\sigma_i^2$$

$$T_m = \frac{\sum_{i=1}^{N} \tau_i 2\sigma_i^2}{P_m}$$

$$S = \sqrt{\frac{\sum_{i=1}^{N} \tau_i^2 2\sigma_i^2}{P_m} - T_m^2}$$

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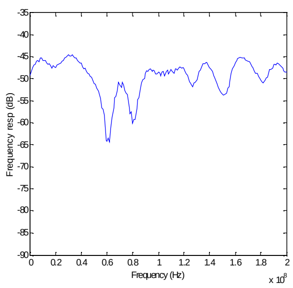
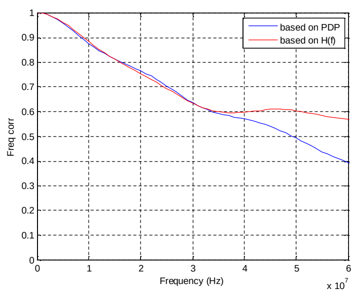
Condensed parameters
Frequency correlation

A property closely related to the power-delay profile (PDP) is the frequency correlation of the channel. It is in fact the Fourier transform of the PDP:

$$\rho_f(\Delta f) = \int_{-\infty}^{\infty} P(\tau)\exp(-j2\pi\Delta f \tau)\,d\tau$$





Compare $1/(2\pi\tau_{rms})=9.8$ MHz

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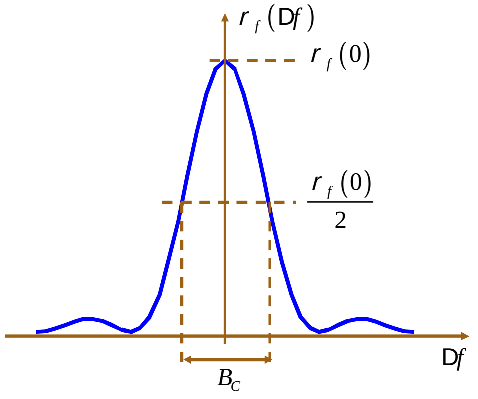
Condensed parameters
Coherence bandwidth

Given the frequency correlation of a channel, we can define the coherence bandwidth B_C:



What does the coherence bandwidth tell us?

It shows us over how large a bandwidth we can assume that the channel is fairly constant.

Radio systems using a bandwidth much smaller than B_C will not notice the frequency selectivity of the channel.

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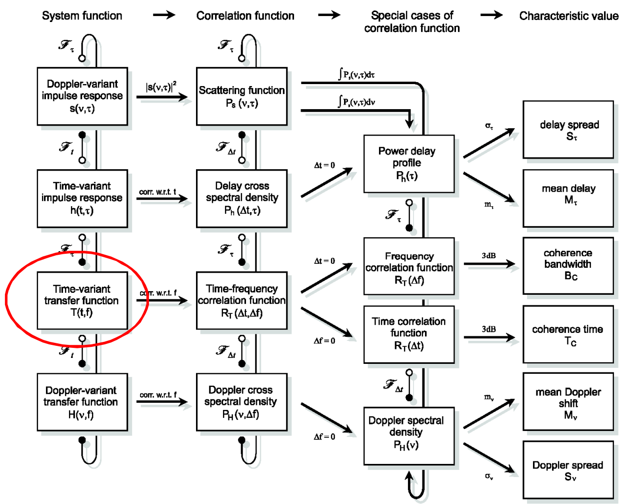
Channel measures



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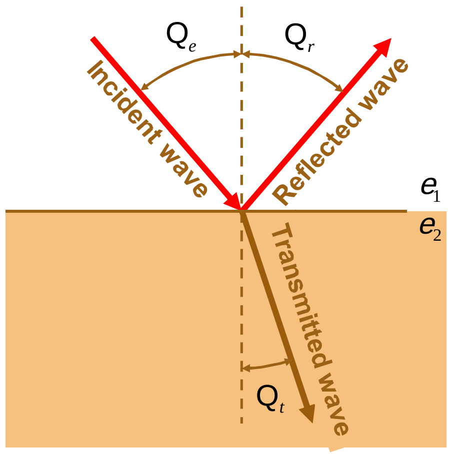
Reflection and transmission



reflected angle

$$\Theta_e = \Theta_r .$$

transmitted angle

$$\frac{\sin\Theta_t}{\sin\Theta_e} = \frac{\sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2}}$$

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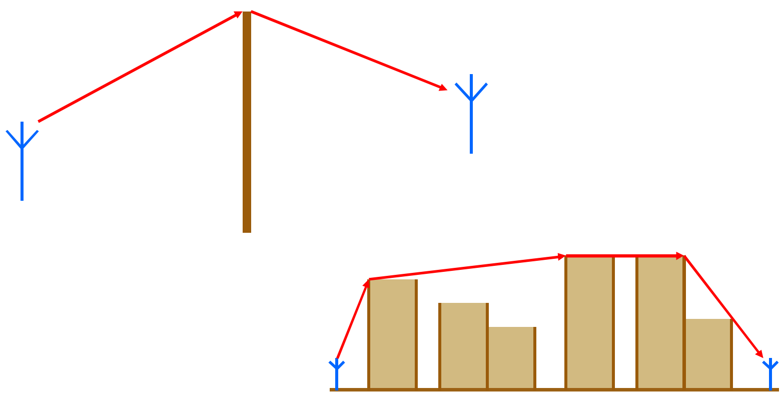
Diffraction



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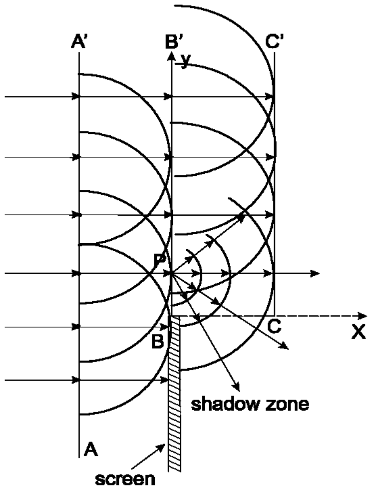
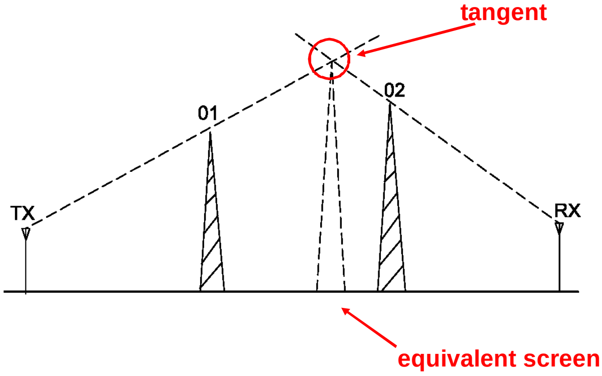
Diffraction, Huygen's principle



Each point of a wavefront can be considered as a source of a spherical wave

➡ Bending around corners and edges

Diffraction – Bullington's method



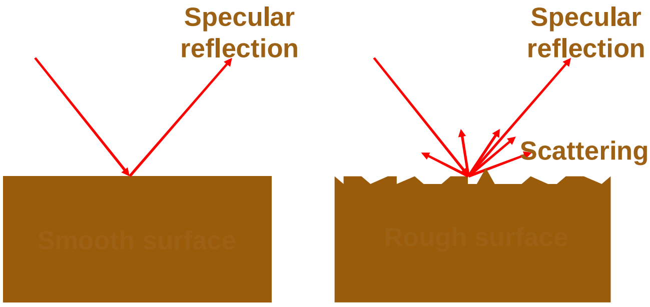
Replace all screens with one equivalent screen

Height determined by the steepest angle

Simple but a bit optimistic

$$E_{\text{total}} = \exp(-jk_0 x)\left(\frac{1}{2} - \frac{\exp(-j\pi/4)}{\sqrt{2}} F(\nu_F)\right) \qquad \nu_F = \alpha_k \sqrt{\frac{2d_1 d_2}{\lambda(d_1+d_2)}}$$

Scattering



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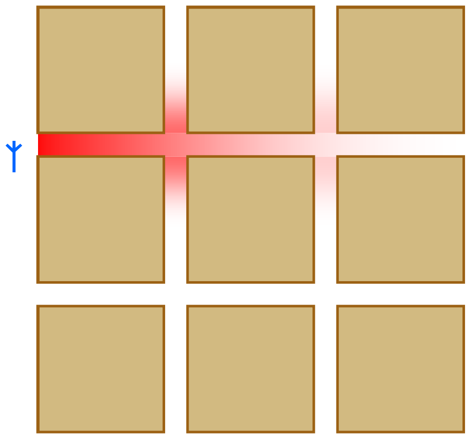
Waveguiding



Waveguiding effects often result in lower propagation exponents

n=1.5-5

This means lower path loss along certain street corridors

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The WSSUS model Assumptions

A very common wide-band channel model is the WSSUS-model.

Recalling that the channel is composed of a number of different contributions (incoming waves), the following is assumed:

The channel is Wide-Sense Stationary (WSS), meaning that the time correlation of the channel is invariant over time. (Contributions with different Doppler frequency are uncorrelated.)

The channel is built up by Uncorrelated Scatterers (US), meaning that the frequency correlation of the channels is invariant over frequency. (Contributions with different delays are uncorrelated.)

Modelling methods

Stored channel impulse responses

- realistic
- reproducible
- hard to cover all scenarios

Deterministic channel models

- based on Maxwell's equations
- site specific
- computationally demanding

Stochastic channel models

- describes the distribution of the field strength etc
- mainly used for design and system comparisons

The Okumura-Hata model
How to calculate prop. loss

$$L_{O-H} = A + B\log\left(d_{|km}\right) + C$$

$$A = 69.55 + 26.16\log\left(f_{0|MHz}\right) - 13.82\log\left(h_b\right) - a\left(h_m\right)$$

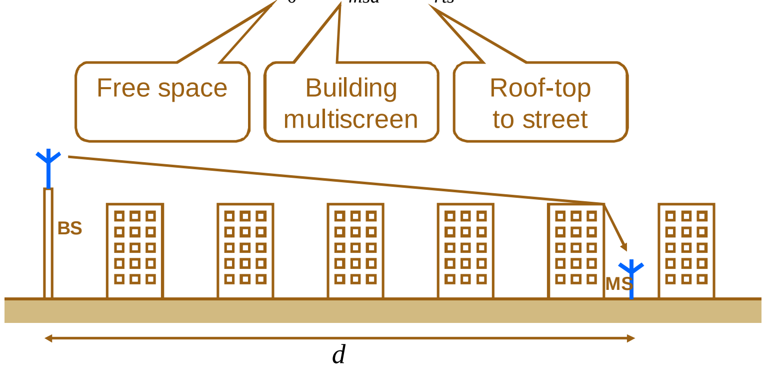
$$B = 44.9 - 6.55\log\left(h_b\right)$$

h_b and h_m in meter

	$a(h_m) =$	$C =$
Metropolitan areas	$8.29\left(\log(1.54h_m)\right)^2 - 1.1$ for $f_0 \le 200$ MHz $3.2\left(\log(11.75h_m)\right)^2 - 4.97$ for $f_0 \ge 400$ MHz	0
Small/medium-size cities	$\left(1.1\log\left(f_{0\vert MHz}\right) - 0.7\right)h_m - \left(1.56\log\left(f_{0\vert MHz}\right) - 0.8\right)$	0
Suburban environments	$\left(1.1\log\left(f_{0\vert MHz}\right) - 0.7\right)h_m - \left(1.56\log\left(f_{0\vert MHz}\right) - 0.8\right)$	$-2\left[\log\left(f_{0\vert MHz}/28\right)\right]^2 - 5.4$
Rural areas	$\left(1.1\log\left(f_{0\vert MHz}\right) - 0.7\right)h_m - \left(1.56\log\left(f_{0\vert MHz}\right) - 0.8\right)$	$-4.78\left[\log\left(f_{0\vert MHz}\right)\right]^2 + 18.33\log\left(f_{0\vert MHz}\right) - 40.94$

The COST 231-Walfish-Ikegami model
How to calculate prop. loss

$$L = L_0 + L_{msd} + L_{rts}$$



Motley-Keenan indoor model

For indoor environments, the attenuation is heavily affected by the building structure, walls and floors play an important rule

$$PL = PL_0 + 10n\log(d/d_0) + F_{\text{wall}} + F_{\text{floor}}$$

distance dependent path loss

sum of attenuations from walls, 1-20 dB/wall

sum of attenuation from the floors (often larger than wall attenuation)

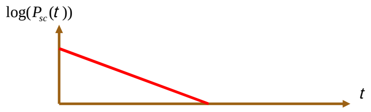
site specific, since it is valid for a particular case

Power delay profile

Often described by a single exponential decay

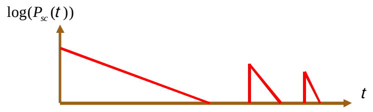
$$P_{sc}(\tau) = \begin{cases} \exp(-\tau/S_\tau) & \tau \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

delay spread



though often there is more than one “cluster”

$$P(\tau) = \begin{cases} \sum_k \frac{P_k^c}{S_{\tau,k}^c} P_{sc}(\tau - \tau_{0,k}^c) & \tau \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

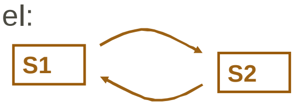


arrival time

If the bandwidth is high, the time resolution is large so we might resolve the different multipath components

Need to model arrival time

- The Saleh-Valenzuela model:
- The D-K-model:



arrival rate: $l_0(t)$ $Kl_0(t)$

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Saleh-Valenzuela Model

Originally not for UWB [A.M. Saleh, R.A. Valenzuela, 1987]

MPCs arrive in clusters

Impulse responses given by

$$h(t) = \sum_{l=0}^{\infty} \sum_{k=0}^{\infty} \beta_{kl} e^{j\theta_{kl}} \delta(t - T_l - \tau_{kl})$$

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

Path interarrival times given by Poisson-distributed arrival process

Different occurance rates for clusters (L) and rays (l)

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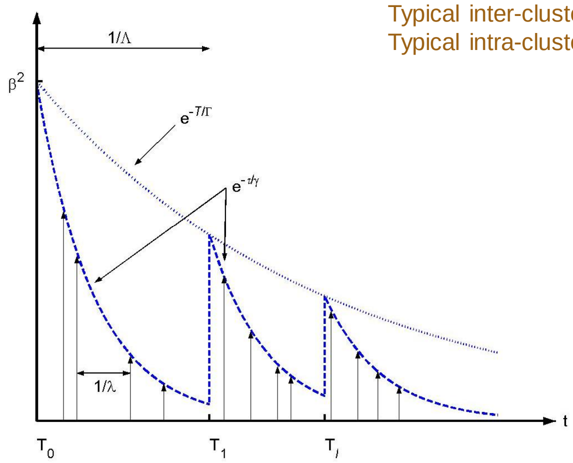
Saleh-Valenzuela Model (cont'd)

Typical inter-cluster decay: 10-30 ns
Typical intra-cluster decay: 1-60 ns



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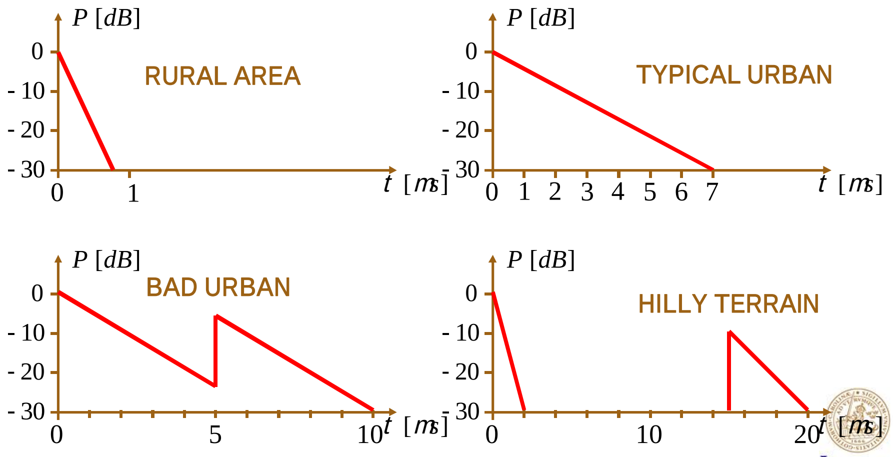
Wideband models
COST 207 model for GSM

Four specified power-delay profiles



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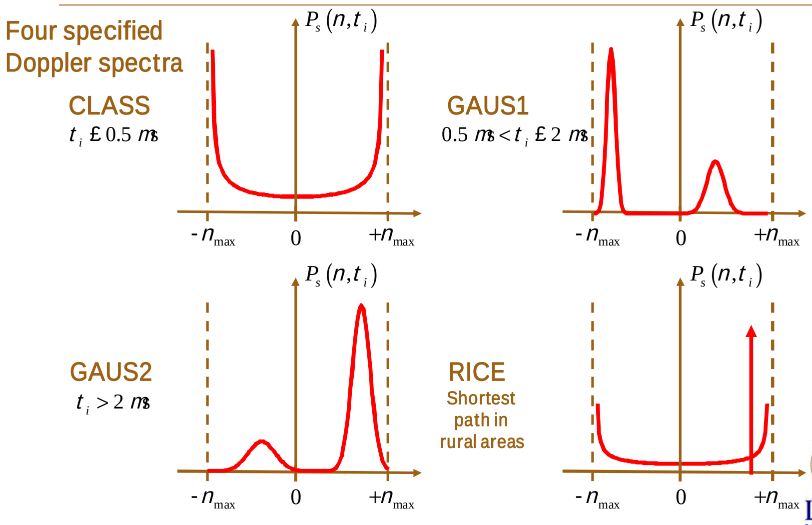
Wideband models
COST 207 model for GSM



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Narrowband vs. UWB Channel Models

Assumptions about standard wireless channels:

- “Narrowband” in the RF sense (bandwidth much smaller than carrier frequency
- WSSUS assumption
- Complex Gaussian fading (Rayleigh or Rice) in each delay tap

Specialties of UWB channel:

- Bandwidth comparable to carrier frequency
- Different frequency components can “see” different reflection/ diffraction coefficients of obstacles
- Few components per delay bin ® central limit theorem (Gaussian fading) not valid anymore

ð New channel models are needed!!

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Why directional channel models?

The spatial domain can be used to increase the spectral efficiency of the system

- Smart antennas
- MIMO systems

Need to know directional properties

- How many significant reflection points?
- Which directions?

Model independent on specific antenna pattern

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Double directional impulse response

TX position — RX position — number of multipath components for these positions

$$h(t,\vec{r}_{\mathrm{TX}},\vec{r}_{\mathrm{RX}},\tau,\Omega,\Psi) = \sum_{\ell=1}^{N(\vec{r})} h_\ell(t,\vec{r}_{\mathrm{TX}},\vec{r}_{\mathrm{RX}},\tau,\Omega,\Psi)$$

delay — direction-of-departure — direction-of-arrival

$$h_\ell(t,\vec{r}_{\mathrm{TX}},\vec{r}_{\mathrm{RX}},\tau,\Omega,\Psi) = |a_\ell| e^{j\varphi_\ell}\delta(\tau-\tau_\ell)\delta(\Omega-\Omega_\ell)\delta(\Psi-\Psi_\ell)$$

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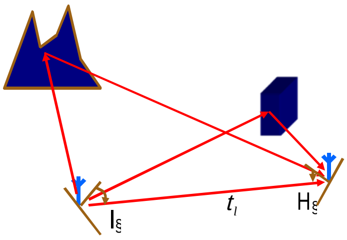
Angular spread

$$E\{s^*(\Omega,\Psi,\tau,\nu)s(\Omega',\Psi',\tau',\nu')\} = P_s(\Omega,\Psi,\tau,\nu)\delta(\Omega-\Omega')\delta(\Psi-\Psi')\delta(\tau-\tau')\delta(\nu-\nu')$$



double directional delay power spectrum

$$DDDPS(\Omega,\Psi,\tau) = \int P_s(\Psi,\Omega,\tau,\nu)d\nu$$

angular delay power spectrum

$$ADPS(\Omega,\tau) = \int DDDPS(\Psi,\Omega,\tau)G_{MS}(\Psi)d\Psi$$

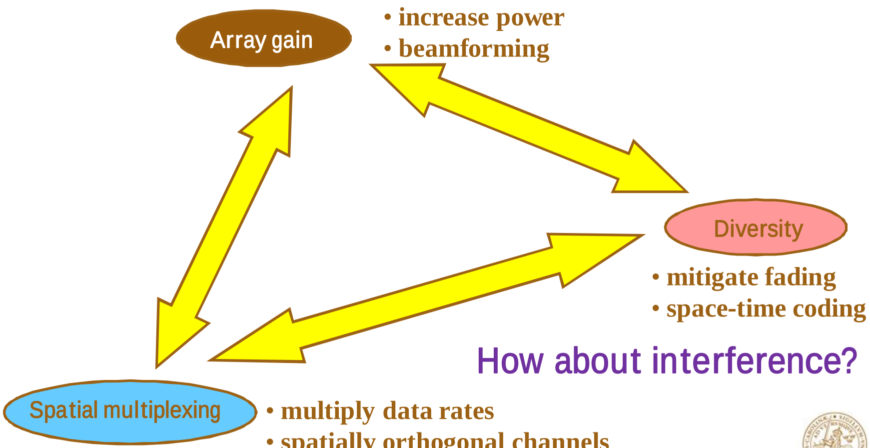
angular power spectrum

$$APS(\Omega) = \int APDS(\Omega,\tau)d\tau$$

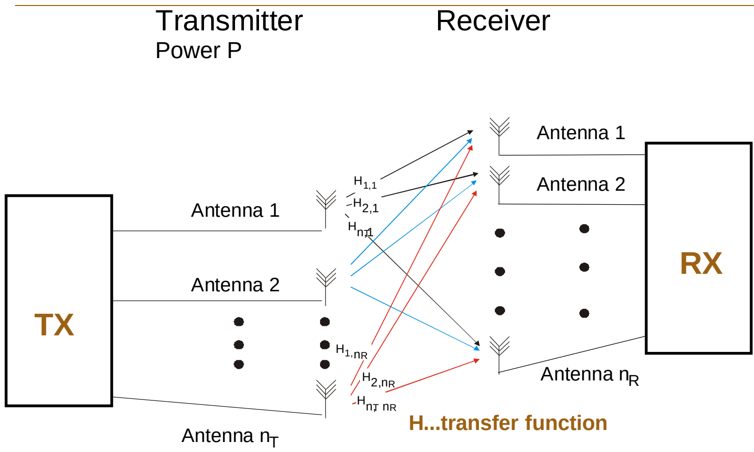
power

$$P = \int APS(\Omega)d\Omega$$

Goals of MIMO



Signal model



g...SNR at each receiver branch

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Capacity formula

Instantaneous channel characterized by matrix ***H***

- Shannon's formula (for two-dimensional symbols):

$$C = \log_2(1+\gamma |H|^2) bits/s/Hz$$

- Foschini's formula:

$$C = \log_2\left[\det\left[\boldsymbol{I}_{n_R} + \frac{\gamma}{n_T}\boldsymbol{H}\boldsymbol{H}^H\right]\right] bits/s/Hz$$

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Channel measurements

In order to model the channel behavior we need to measure its properties

- Time domain measurements
  - » impulse sounder
  - » correlative sounder
- Frequency domain measurements
  - » Vector network analyzer

- Directional measurements
  - directional antennas
  - real antenna arrays
  - multiplexed arrays
  - virtual arrays

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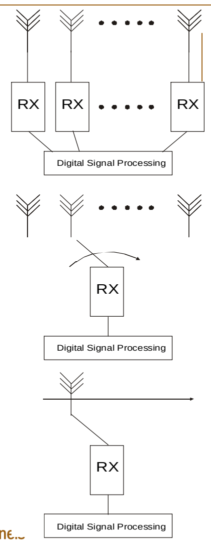
Real, multiplexed, and virtual arrays

- Real array: simultaneous measurement at all antenna elements

- Multiplexed array: short time intervals between measurements at different elements

- Virtual array: long delay

  no problem with mutual coupling



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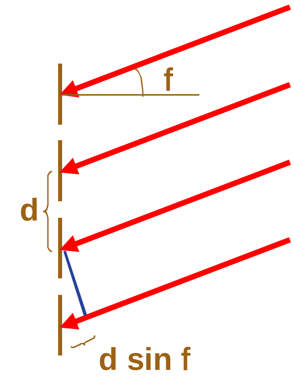
Directional analysis



The DoA can, e.g., be estimated by correlating the received signals with steering vectors.

$$\vec{a}(\phi) = \begin{pmatrix} 1 \\ \exp(-jk_0 d\cos(\phi)) \\ \exp(-j2k_0 d\cos(\phi)) \\ \vdots \\ \exp(-j(M-1)k_0 d\cos(\phi)) \end{pmatrix}$$

An element spacing of d=5.8 cm and an angle of arrival of f =20 degrees gives a time delay of $6.6\cdot 10^{-11}$ s between neighboring elements

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Techniques for wireless positioning

Three main measurement principles:

- Angle-of-arrival (AOA)
- Received signal strength (RSS)
- Propagation-time:
  - Time-of-arrival (TOA)
  - Roundtrip-time-of-flight (RTOF)
  - Time-difference-of-arrival (TDOA)

These differ both in terms of system requirements and in accuracy

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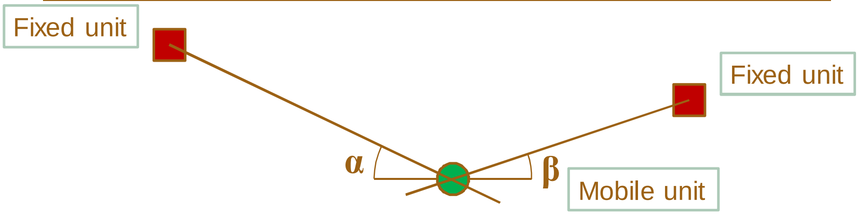
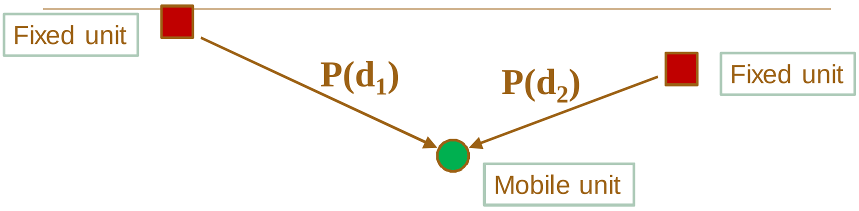
Angle-of-arrival (AOA) based positioning



- Based on bearing estimation followed by intersection of different direction pointers
- Requires antenna arrays or directive antennas at measuring side: requires complex hardware
- Accuracy limited by size of antenna array or directivity
- No requirements on synchronization

Received signal strength (RSS) based positioning



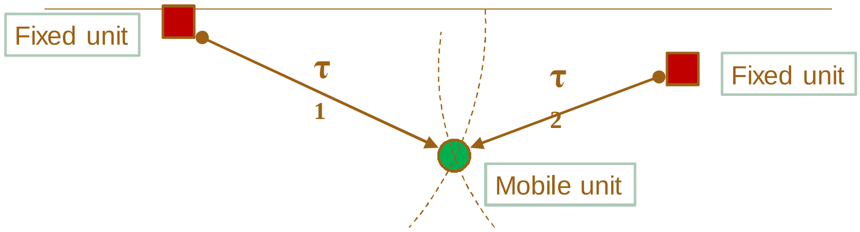
Based on propagation-loss equations

Propagation-loss is often more complex than free-space (1/d^2) loss, e.g., indoors:

- Advanced models required
- Fingerprinting (learn actual field strength from measuerements)

Feasible implementation: Most radio modules already provide an RSS indicator

Time-based positioning: Time-of-arrival (TOA)



Based on one-way propagation time

Requires precise synchronization of all involved units (time synchronization directly affects accuracy)

– *Ex. A 1 ns clock drift implies a distance error of 0.3 m*

Bandwidth dependent (accuracy inversely proportional to bandwidth)

Can provide higher accuracy than AOA and RSS methods

In practice, expensive or less inaccurate

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