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Wireless Communications Channels
Lecture 14: Revision

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Propagation mechanisms:

Free space attenuation

- ❑ Reflection and transmission
- ❑ Diffraction
- ❑ Diffuse scattering
- ❑ Waveguiding

Free space loss: Friis' law

Received power, with antenna gains G_{TX} and G_{RX}:

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

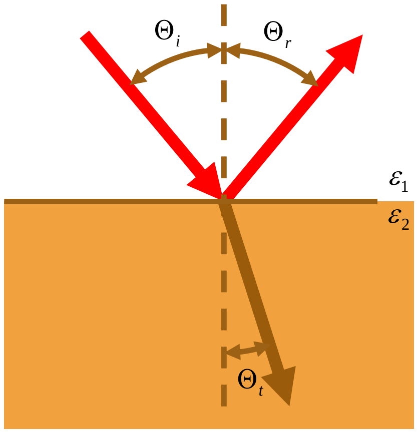
Free space loss factor

RX power goes down as a function of frequency, for a fixed distance.

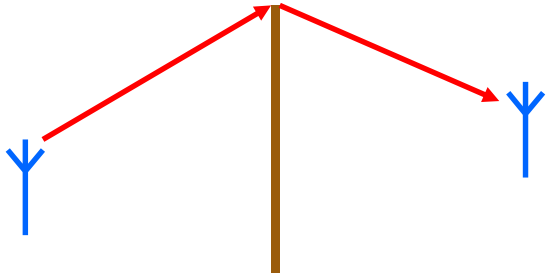
$$P_{RX|dB}(d) = P_{TX|dB} + G_{TX|dB} - L_{free|dB}(d) + G_{RX|dB}$$

$$= P_{TX|dB} + G_{TX|dB} - 10\log_{10}\left(\frac{4\pi d}{\lambda}\right)^2 + G_{RX|dB}$$

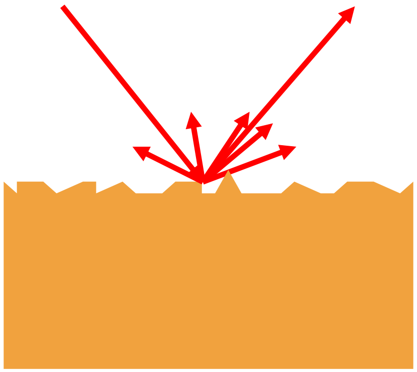
Fundamental propagation mechanisms



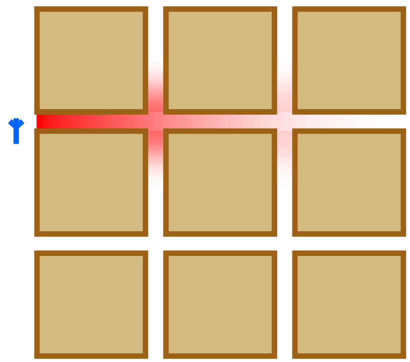
Reflection and transmission



Diffraction



Scattering



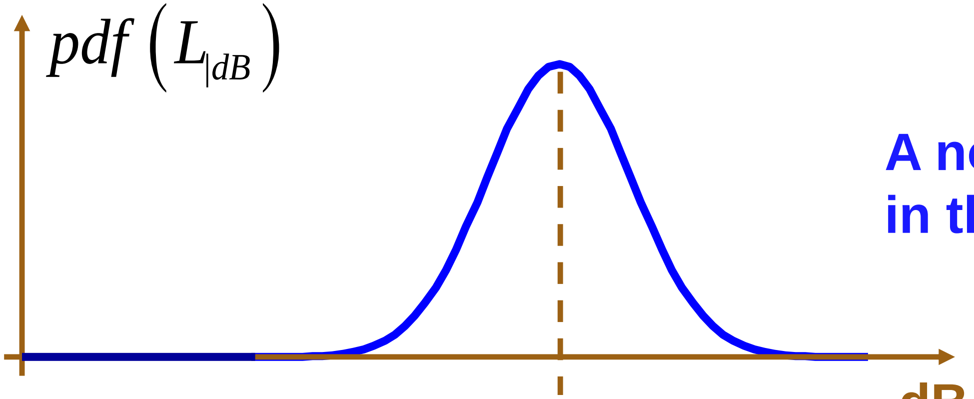
Waveguiding

Fading – Statistical description of the wireless channel

- **Large scale fading**
- **Small scale fading:**
  - without dominant component
  - with dominant component

Large-scale fading: Log normal distribution

Confirmed by propagation channel measurements over the past 50 years.

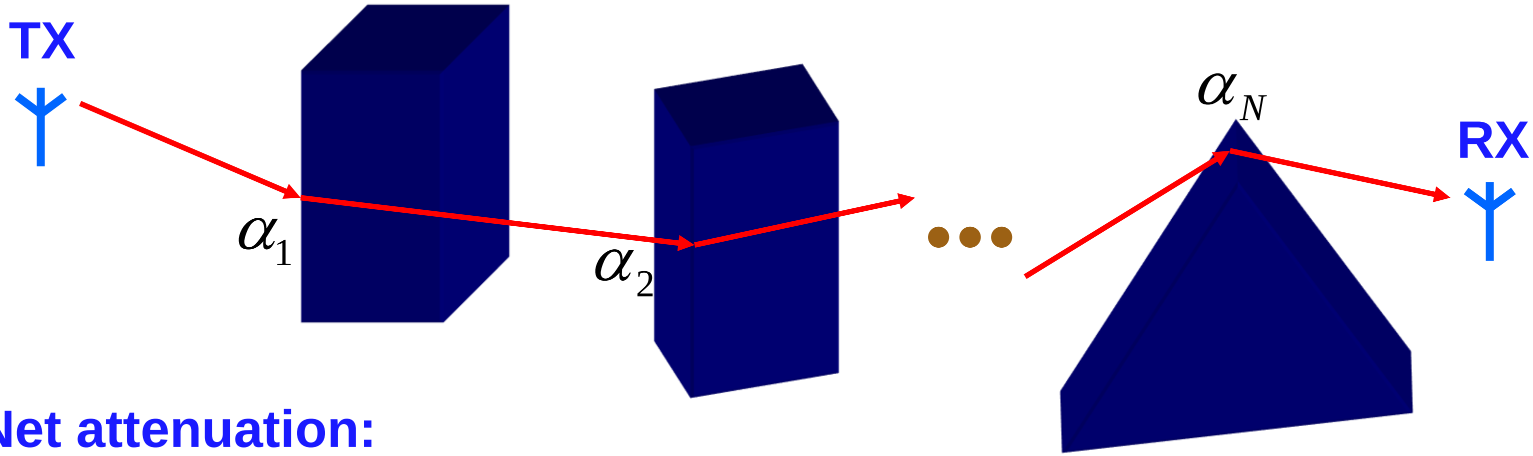


A normal distribution in the dB domain.

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

Large-scale fading: Why log-normal?

Many diffraction points adding extra attenuation to the pathloss.
This is, however, only one of several possible explanations.



Net attenuation:

$$L_{tot} = L(d) \times \alpha_1 \times \alpha_2 \times \ldots \times \alpha_N$$

$$L_{tot|dB} = L(d)_{|dB} + \alpha_{1|dB} + \alpha_{2|dB} + \ldots + \alpha_{N|dB}$$

If these are considered random and independent, we should get a normal distribution in the dB domain.

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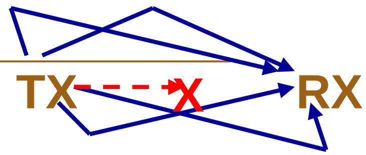
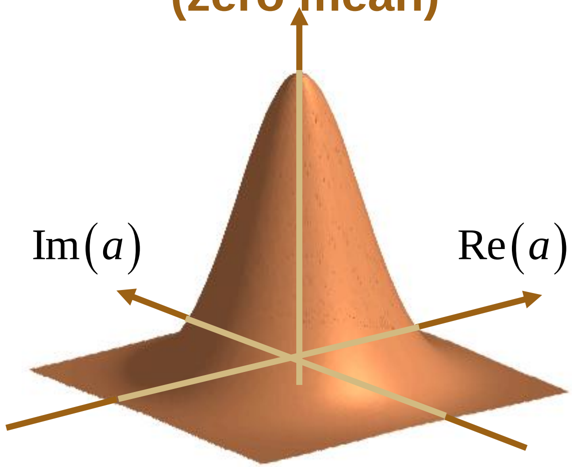
Small-scale fading
Rayleigh fading



No dominant component (non line-of-sight)

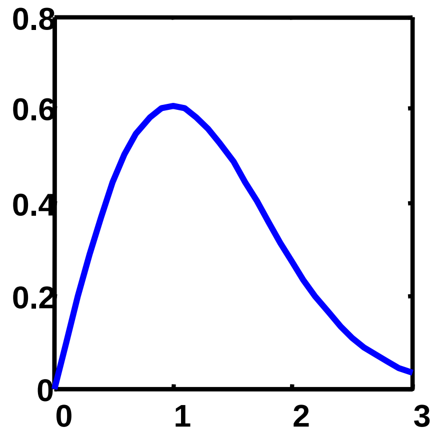
Tap distribution
2D Gaussian
(zero mean)



$$r = |a|$$

Amplitude distribution

Rayleigh

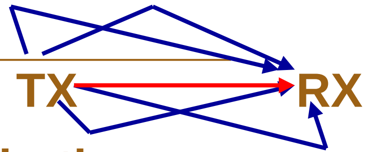


$$pdf\,(r) = \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right)$$

No line-of-sight component

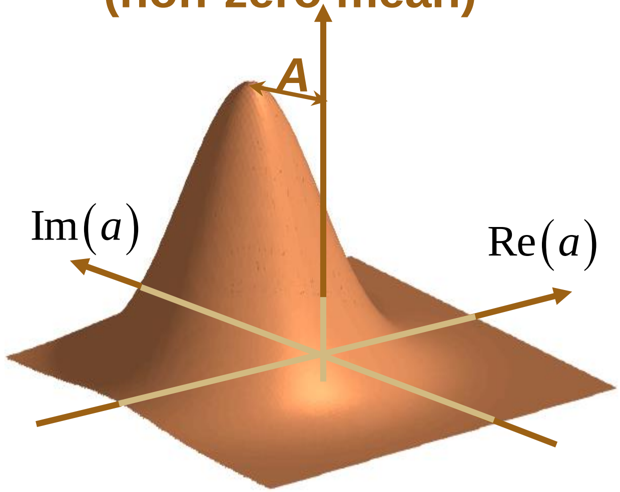
Small-scale fading
Ricean fading

A dominant component (line of sight)



Tap distribution

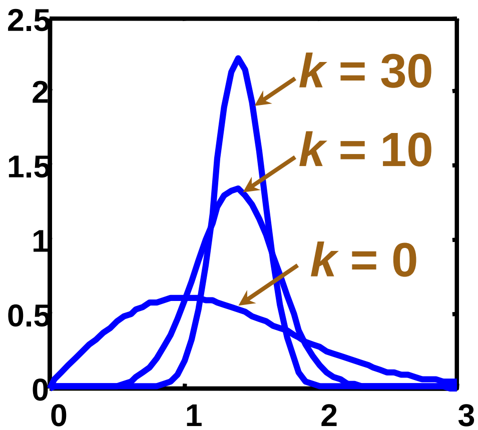
2D Gaussian (non-zero mean)



$$r = |\alpha|$$

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*.

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WSSUS model

- The channel is **Wide-Sense Stationary (WSS),** meaning
  a. $\mathrm{E(h(t))}$ = constant, for all t, the expectation of the channel is constant over time
  b. $R_h(t_1, t_2) = R_h(t_1 - t_2)$, the **correlation** of the channel is **invariant** over time.

- 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.)
  a. $R_h(t_1, t_2; \tau_1, \tau_2) = R_h(t_1 - t_2; \tau_1)\delta(\tau_1 - \tau_2)$

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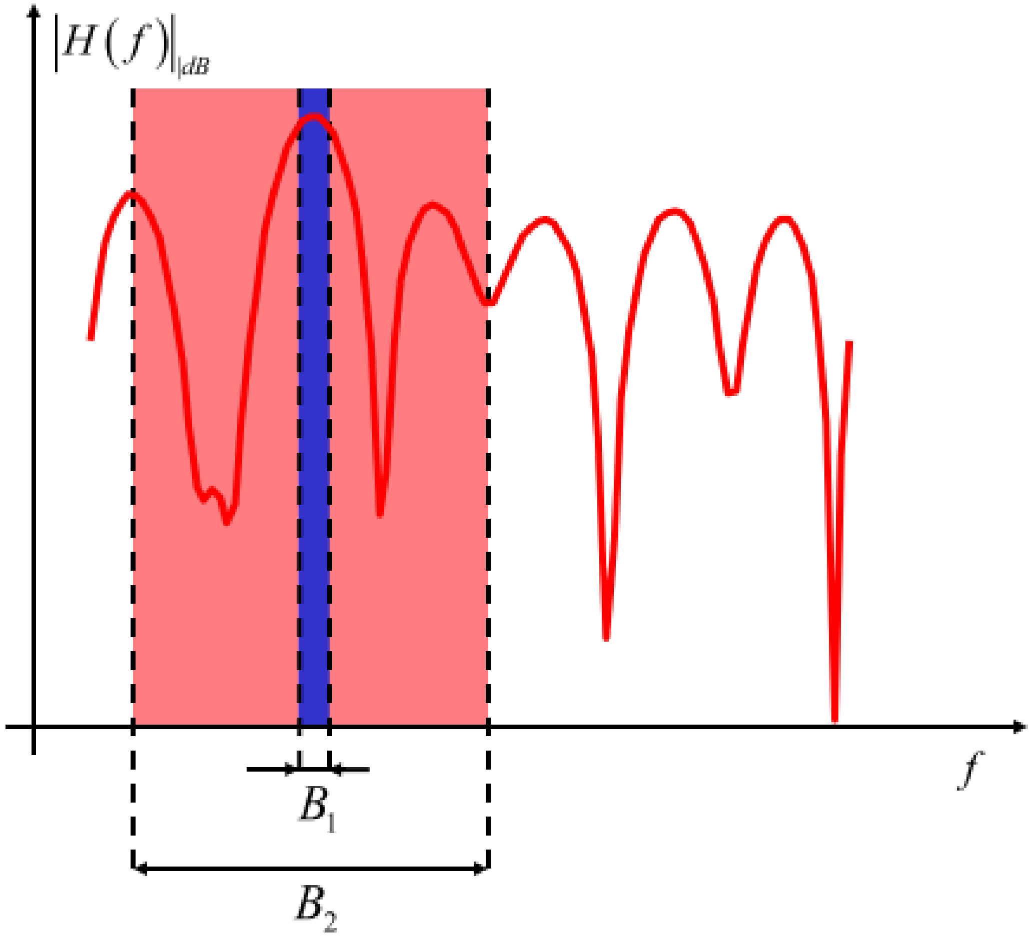
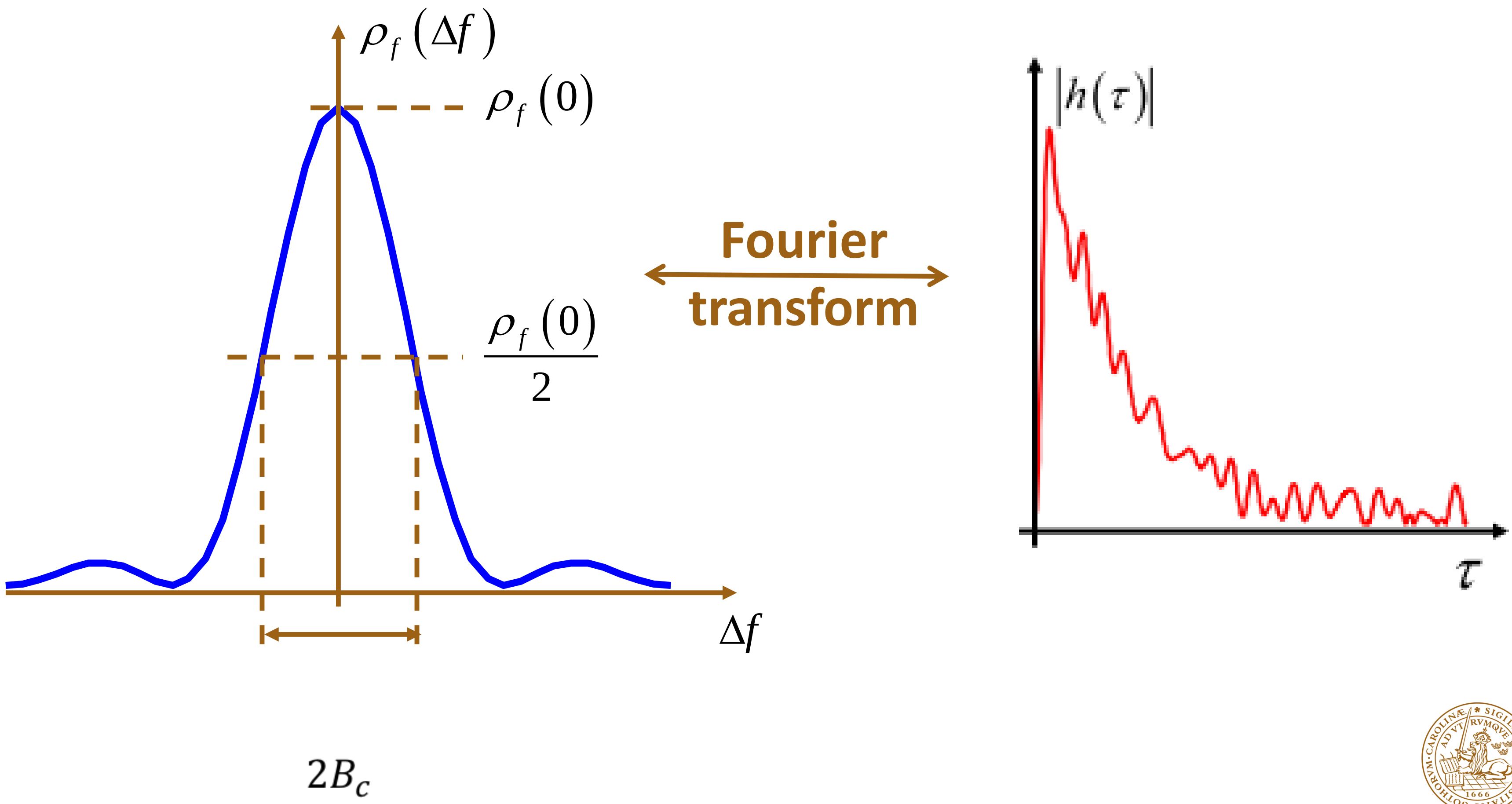
frequency flat vs frequency selective

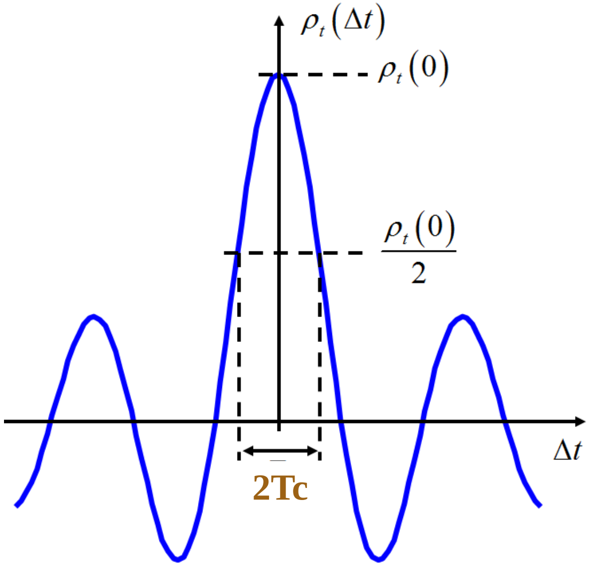


Power delay profile vs. frequency correlation function



Doppler spectrum vs. the time correlation function

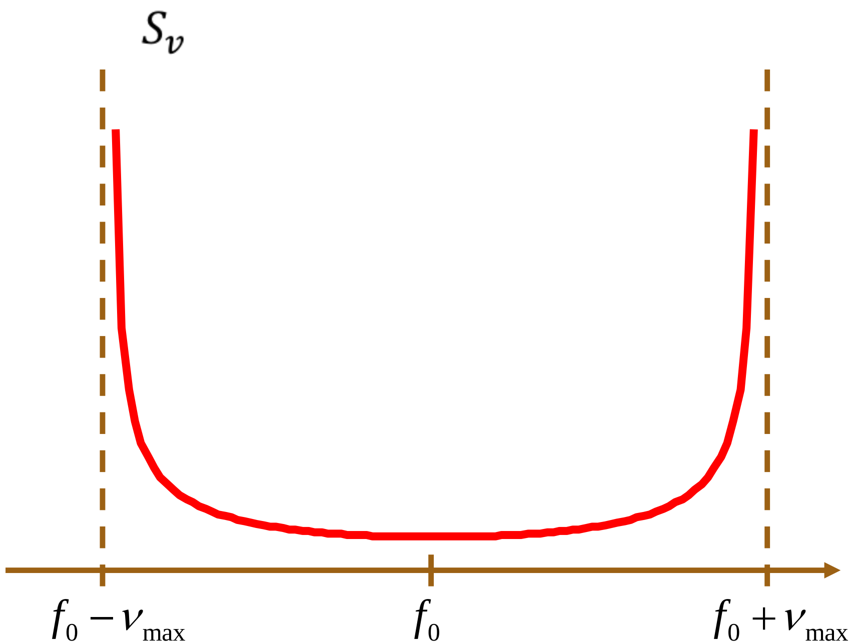
Doppler spectrum and the time correlation of the signal are related to each other by Fourier transformation



time correlation function

Fourier

transforms



Doppler power spectrum

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Widely used ”rules-of-thumb”

$$Tc \approx \frac{1}{D_s}$$

$$Bc \approx \frac{1}{S_\tau}$$

$$Tc = \frac{9}{16\pi D_s}$$

time over which the time correlation function is above 0.5

$$Bc = \frac{1}{5S_\tau}$$

band over which the frequency correlation function is above 0.5

$$T_c = \frac{0.423}{D_s}$$

less restrictive and widely used

$$Bc = \frac{1}{50S_\tau}$$

band over which the frequency correlation function is above 0.9

Channel models

- Different modelling methods
  - Stored channel impulse responses
  - Deterministic channel models
  - Stochastic channel models
- Wideband models
- Directional channel models
- Multiple antenna (MIMO) models

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Wideband models

Tapped delay line model often used

$$h(t,\tau)=\sum_{i=1}^{N}\alpha_i(t)\exp\left(j\theta_i(t)\right)\delta(\tau-\tau_i)$$

Often Rayleigh-distributed taps, but might include LOS and different distributions of the tap values

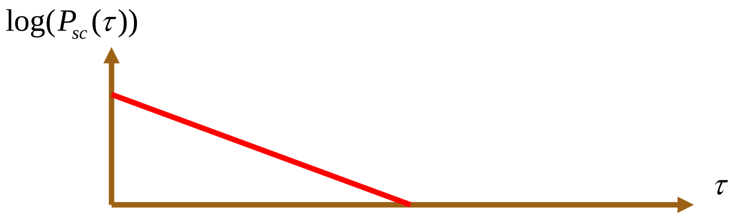
Mean tap power determined by the power delay profile

Power delay profile

Often described by a single exponential decay

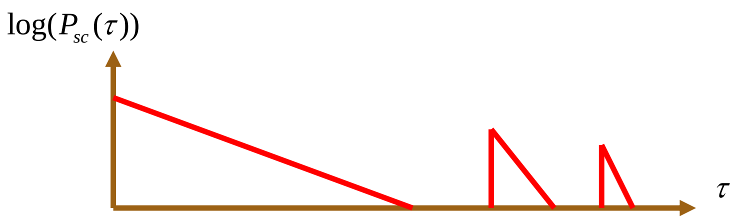
$$P_{sc}(\tau) = \begin{cases} exp(-\tau / S_\tau) & \tau \geq 0 \\ 0 & otherwise \end{cases}$$

delay spread



though often there is more than one "cluster"

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



Double directional impulse response

TX position

RX position

number of multipath components for these positions

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

direction-of-arrival

delay

direction-of-departure

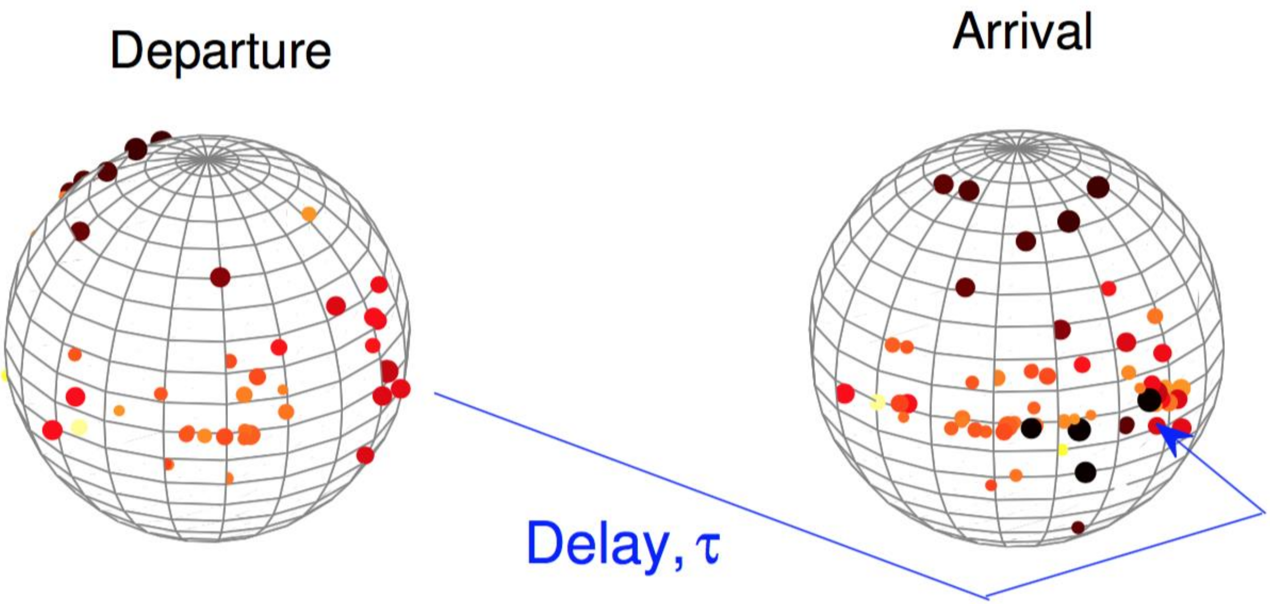
$$h_\ell(t,\vec{r}_{\mathrm{TX}},\vec{r}_{\mathrm{RX}},\tau,\Omega,\Psi) = |a_\ell| e^{j\varphi_\ell}\delta(\tau-\tau_\ell)\delta(\Omega-\Omega_\ell)\delta(\Psi-\Psi_\ell)$$

Double directional impulse response with slightly different notation:

$$h_p(\tau, \phi^{\mathrm{Rx}}, \theta^{\mathrm{Rx}}, \phi^{\mathrm{Tx}}, \theta^{\mathrm{Tx}}) = \sum_{n=1}^{N} \alpha_n \delta\left(\tau - \tau_n\right)$$

$$\times\, \delta\left(\phi^{\mathrm{Rx}} - \phi_n^{\mathrm{Rx}}\right) \delta\left(\theta^{\mathrm{Rx}} - \theta_n^{\mathrm{Rx}}\right) \delta\left(\phi^{\mathrm{Tx}} - \phi_n^{\mathrm{Tx}}\right) \delta\left(\theta^{\mathrm{Tx}} - \theta_n^{\mathrm{Tx}}\right)$$

Time and location is omitted here!



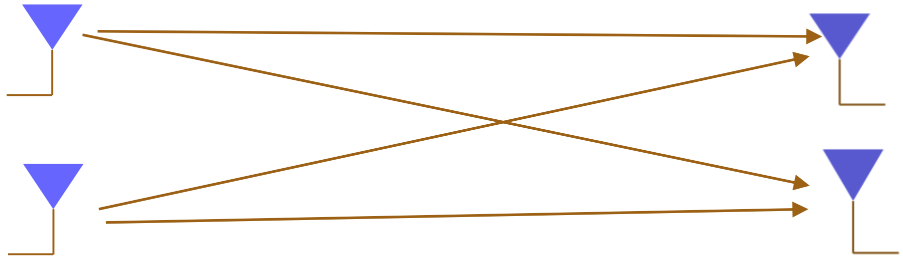
The MIMO channel

channel matrix

$$\boldsymbol{H}(\tau) = \begin{bmatrix} h_{11}(\tau) & h_{12}(\tau) & \cdots & h_{1M_{\mathrm{Tx}}}(\tau) \\ h_{21}(\tau) & h_{22}(\tau) & \cdots & h_{2M_{\mathrm{Tx}}}(\tau) \\ \vdots & \vdots & \ddots & \vdots \\ h_{M_{\mathrm{Rx}}1}(\tau) & h_{M_{\mathrm{Rx}}2}(\tau) & \cdots & h_{M_{\mathrm{Rx}}M_{\mathrm{Tx}}}(\tau) \end{bmatrix}$$

signal model

$$\boldsymbol{y}(t) = \sum_{\tau=0}^{D-1} \boldsymbol{H}(\tau) \cdot \boldsymbol{x}(t-\tau)$$



Deterministic modeling methods

Solve Maxwell's equations with boundary conditions

Problems:

- Data base for environment
- Computation time

"Exact" solutions

- Method of moments
- Finite element method
- Finite-difference time domain (FDTD)

High frequency approximation

- All waves modeled as rays that behave as in geometrical optics
- Refinements include approximation to diffraction, diffuse scattering, etc.

Channel sounding

- **Time domain measurements:**
  - Impulse sounder
  - Correlative sounder
- **Frequency domain measurements:**
  - Vector network analyzer
- **Directional measurements:**
  - Directional antennas
  - Real antenna arrays
  - Multiplexed arrays
  - Virtual arrays

Properties of an ideal sounding signal

- ❑ **Large bandwidth:** inversely proportional to the shortest temporal changes in the signal, which determines delay resolution.

- ❑ **Large time-bandwidth product:** Sounding signal should have a duration longer than inverse of bandwidth. They also need to have good autocorrelation properties.

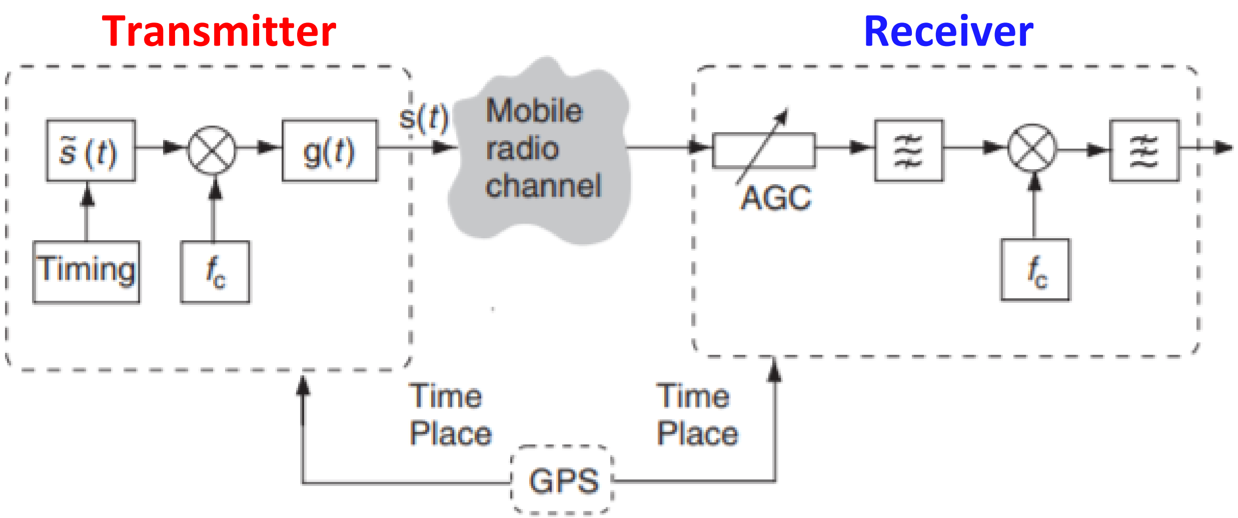
- ❑ **Signal duration:** The sounding signal should also not be too long, in particular exceeding the channel coherence time. Pulse repetition time longer than a single pulse duration and maximum access delay of channel.

- ❑ **Power spectral density:** Sounding signal power spectral density should be uniform across bandwidth of interest. This yields same quality of channel estimates across the range of bands interested.

- ❑ **Peak-to-average power:** Relatively high for high amplifier efficiency.

Generic sounder structure

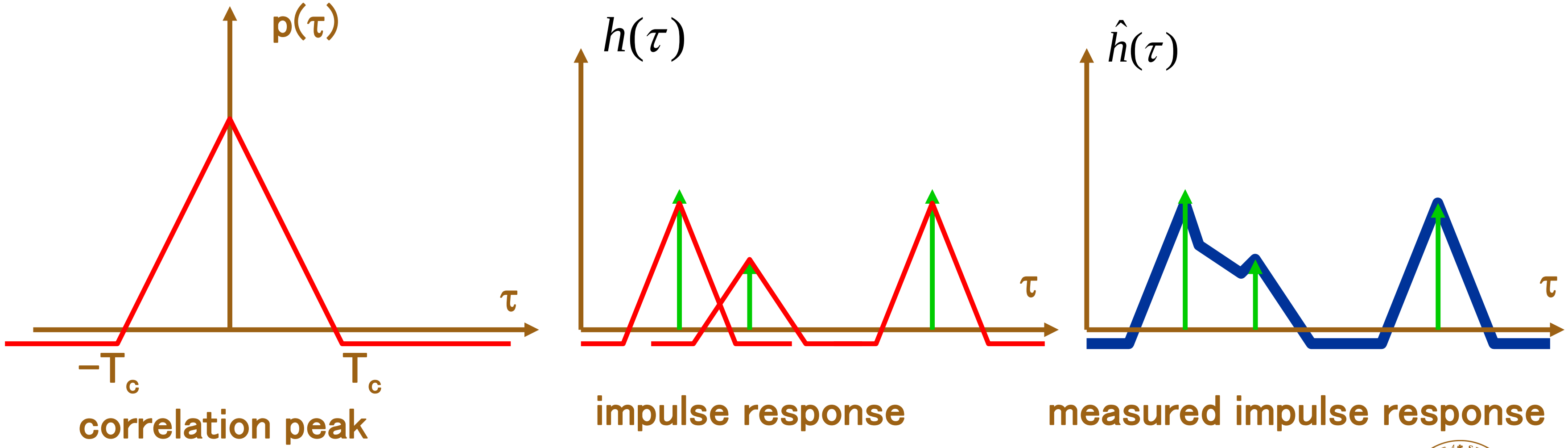
<u>Principle</u>: The TX sends out a signal that excits – **"sounds"** the channel. Output of channel **"listened"** by the RX and **"stored"**. From **knowledge** of TX and RX signal, the time variant impulse can be extracted.



Conceptually most simple!

Correlative sounder

- Transmit a pseudo-noise sequence and correlate with the same sequence at the receiver:
  - Compare conventional CDMA systems
  - Correlation peak for each delayed multipath component



Frequency domain measurements

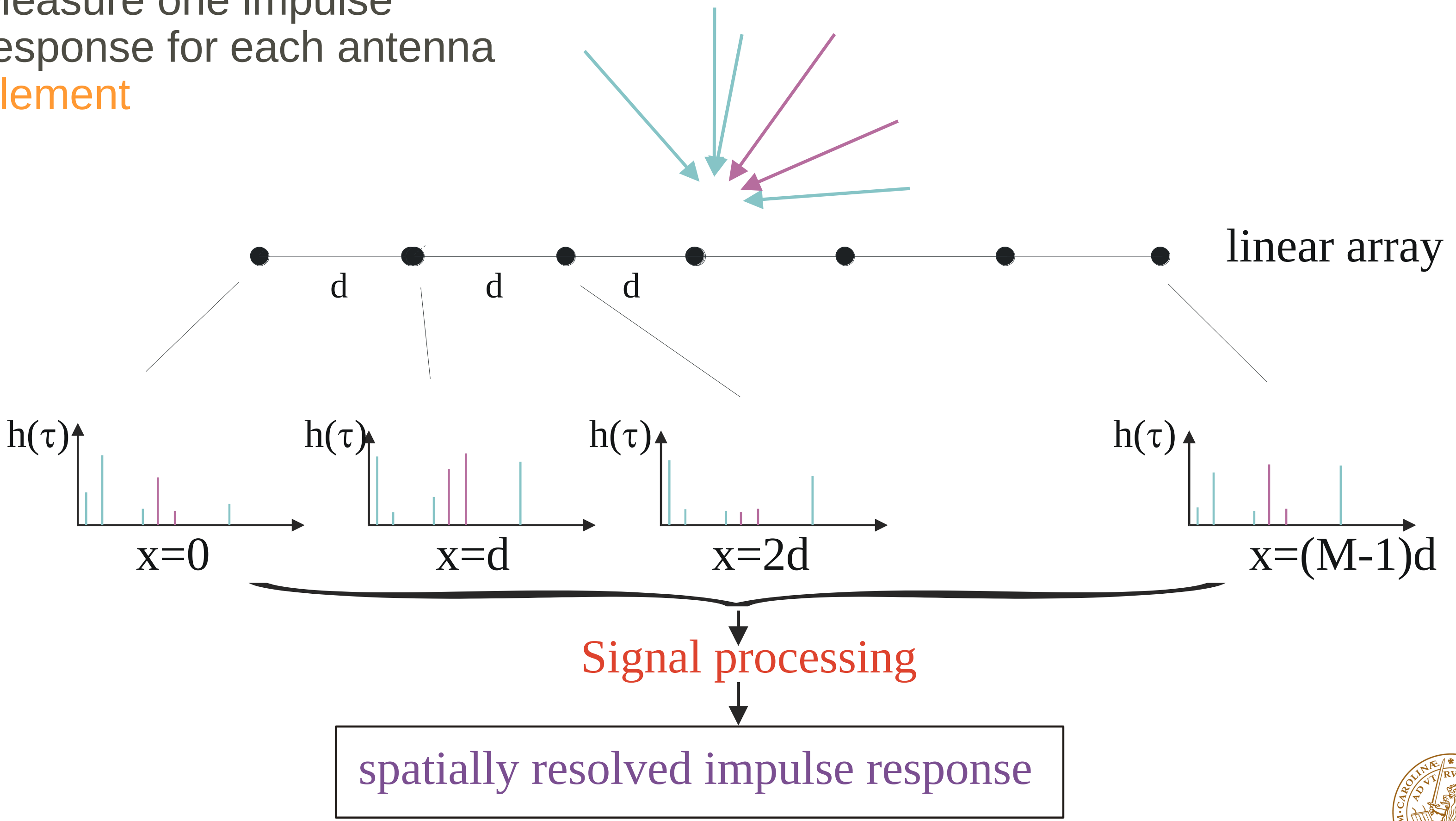
Use a vector network analyzer or similar to determine the transfer function of the channel

$$H_{meas}(f) = H_{TXantenna}(f) * \boxed{H_{channel}(f)} * H_{RXantenna}(f)$$

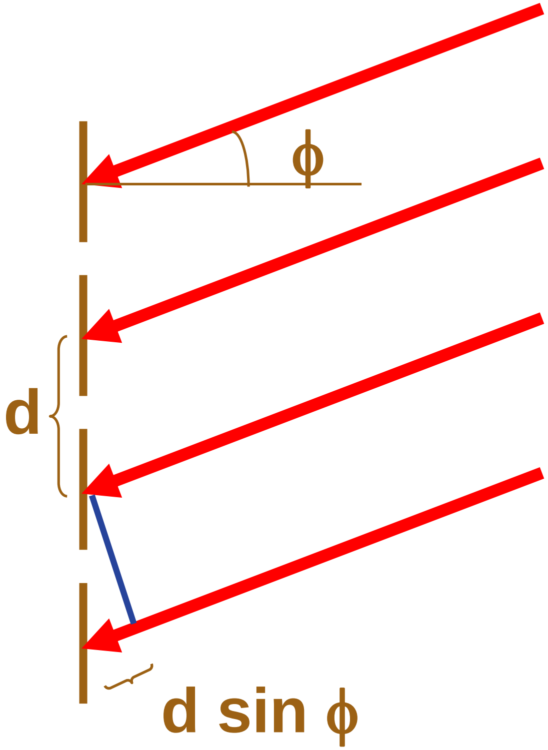
- Time domain properties via FFT
- Using a large frequency band it is possible to get good time resolution
- As for time domain measurements, we need to know the influence of the measurement system

Channel sounding: Multielement array

- Measure one impulse response for each antenna element



Directional analysis: DOA estimation



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

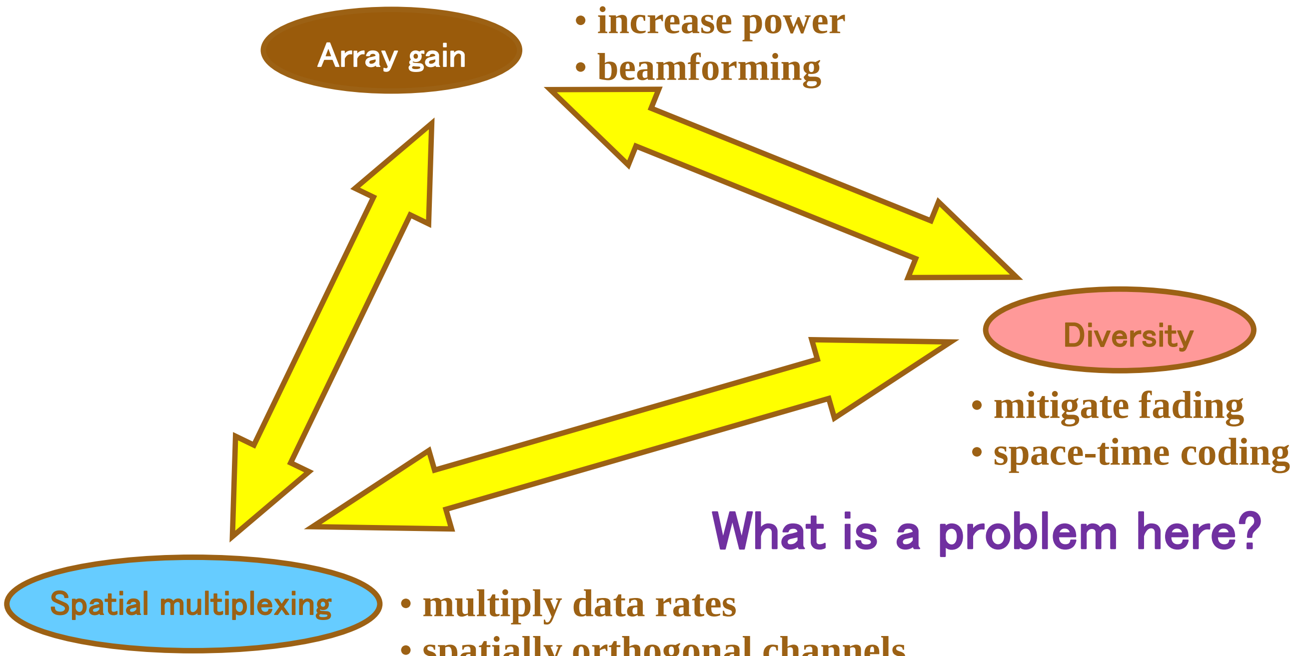
$$\vec{a}(\phi) = \begin{pmatrix} 1 \\ \exp(-jk_0 d\cos(\phi)) \\ \exp(-j2k_0 d\cos(\phi)) \\ \vdots \\ \exp(-j(M-1)k_0 d\cos(\phi)) \end{pmatrix}$$

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

Characterization of Antennas: Key Parameters

- **Directivity:** Total radiated power in a certain direction relative to the total transmitted power. Note that the gain and the directivity of an antenna are linked to each other.
- **Efficiency:** The efficiency of an antenna is a ratio of the power delivered to the antenna relative to the power radiated from the antenna.
- **Q-factor (a.k.a. quality factor):** Energy stored within the antenna compared to energy dissapated out of the antenna.
- **Mean effective gain:** Include influence of random channel. It is the average received power compared to average received power by isotropic antenna in real environment.

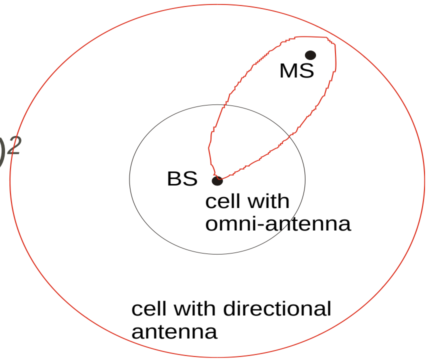
Goals of MIMO



What is a problem here?

Benifits of MIMO Systems

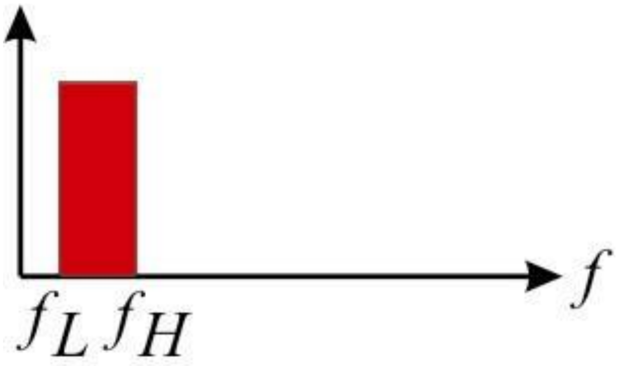
- Higher spectral efficiency and capacity (higher bits/seconds/Hz)
- Better utilization of spectrum, which is expensive; but number of base stations limited (unless we talk of massive MIMO where we can use hundereds of elements)
- Better transmission quality
- Increased coverage due to higher array gain!
  - Directional antennas have gain and received power: $P_R=G_T G_R P_T(\lambda/4\pi d)^2$
  - UE moves: follow UE with main beam of BS to steer the gain to UE
- Improved user position estimation



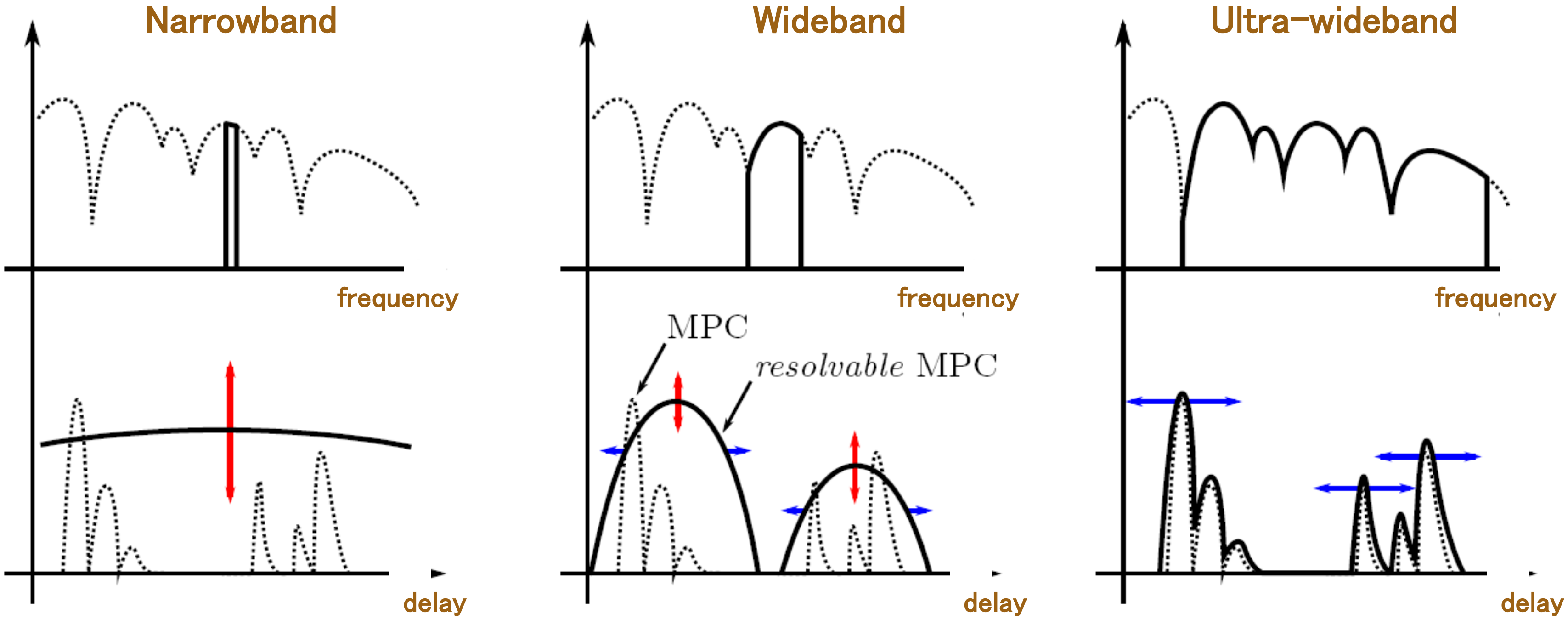
What is Ultra-Wideband (UWB)?

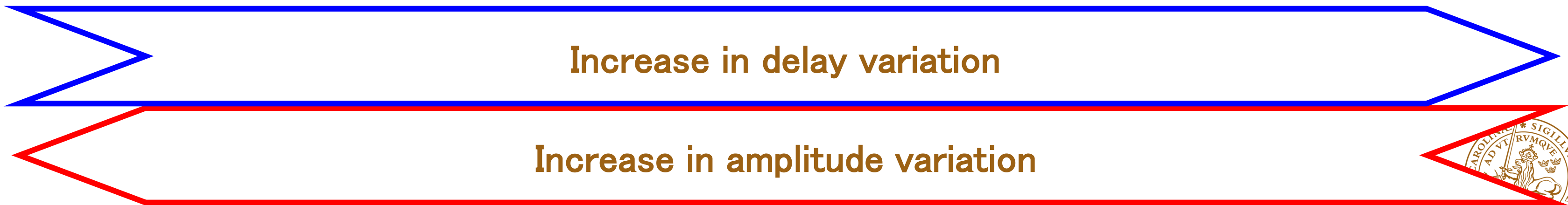
- Transmitted power is spread over an extremely large bandwidth

- Definition: Signals having
  $f_H - f_L > 500\ \mathrm{MHz}$



Implications of Higher Bandwidths





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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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cm-wave and mm-wave bands for 5G

The free space loss increases with freqeuncy!

Free space loss at 100 m for a frequency of 6 GHz: 88 dB

Free space loss at 100 m for a frequency of 60 GHz: 108 dB

A 20 dB increase in loss per decade of increase in freqeuncy.

How to deal with this?

cm-wave and mm-wave bands for 5G

Specific propagation related challenges:

1. Shadowing due to objects and humans.
2. Hand effects for handheld devices.
3. Transmission losses through building materials and objects.

Exam details

Place: E2349

March 14th 9-12am	March 14th 1-4pm	March 14th 4-7pm
Axel Sandqvist	Ajai panneer selvam	Zonghan Wang
Swaroop Nambala	Jon Aizkorreta Carro	Aysha Mariam Mohamed Ismail
Isa Clementsson	Nazyar Mehdishishavan	Bharath Manjunatha
Yuanqing Fu	Ilayda Yaman	ChunXu
	Jaeyoung Park	Dexin Kong
	Guillermo Jimenez	

Exam format

- Written: Five individual questions for 1 hour, 25 points
- Oral: individual questions + group discussion, 30 points
- 28-37 points ->3
- 38-47 points ->4
- >= 48 points ->5
- Questions range in varying levels of difficulty and complexity

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Exam content

- From lecture 1 to 13
- May include componets of Assignment 1 to 3
- May include material from examples in the textbook
- May include exercise class material
- May include conceptual questions
- The aim is for you to convince us that you have understood the material taught in the course

Tips

- If you donot understand the question, please ask me again
- For each question, i would like to see your thinking:
  - You need to demonstrate how you think about answering the question as a process
- Not all questions may have an answer or have a single answer.

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