EC 744 Wireless Communications
Spring 2007

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Wireless Channels, Cellular systems

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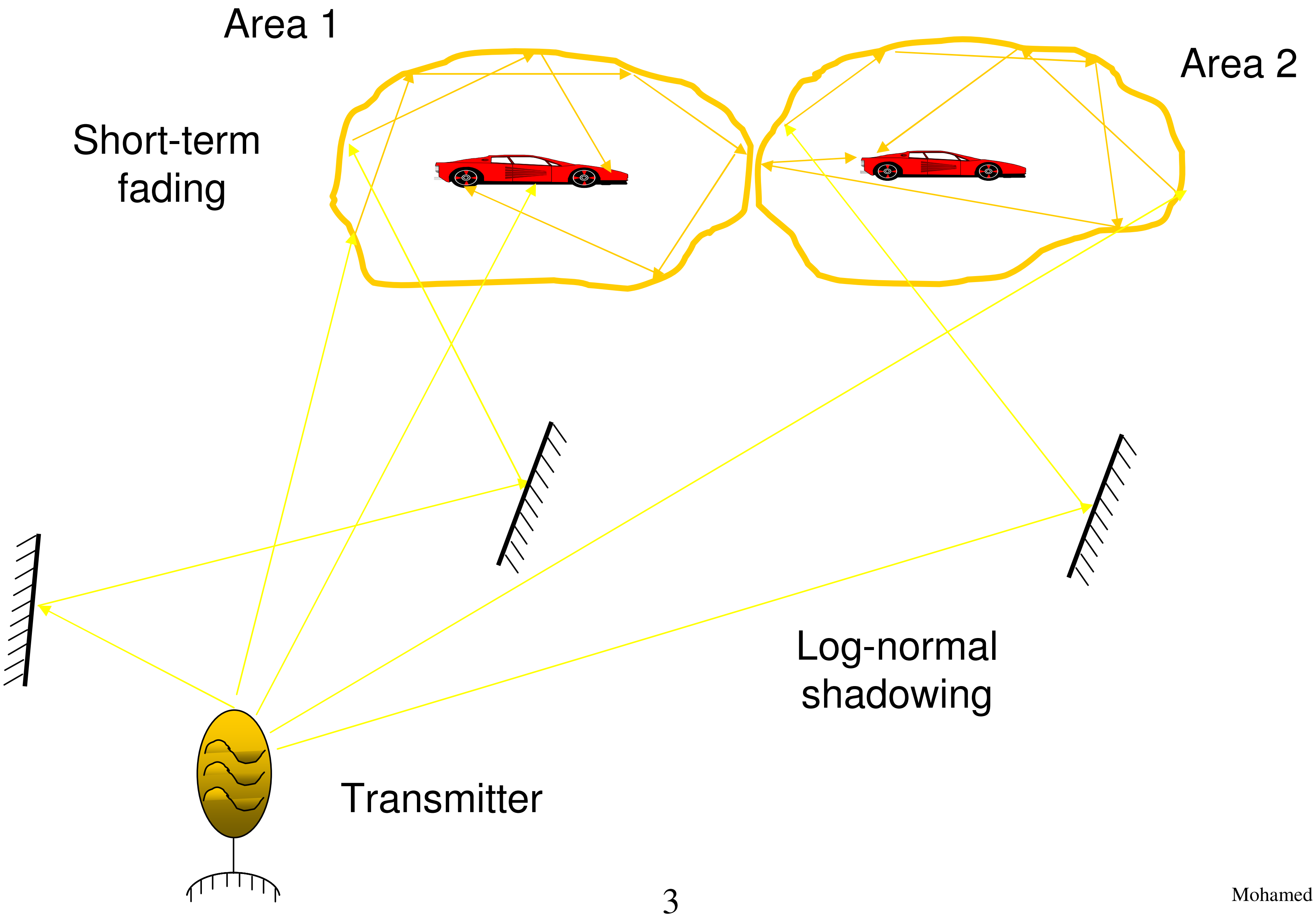
Syllabus

- Tentatively

Week 1	Overview, Probabilities, Random variables, Random process
Week 2	Wireless channels, Statistical Channel modelling, Path loss models
Week 3	**Cellular concept and system design fundamentals**
Week 4	Modulation techniques, single and multi-carrier
Week 5	Diversity techniques
Week 6	Equalization techniques
Week 7	Mid Term exam
Week 8	802.11 and Mac evaluation
Week 9	Energy models in 802.11
Week 10	Wimax and Mac layer
Week 11	Presentations
Week 12	Presentations
Week 13	Presentations
Week 14	Presentations
Week 15	Final Exam

Large and Small Scale Propagation Models



Area 1

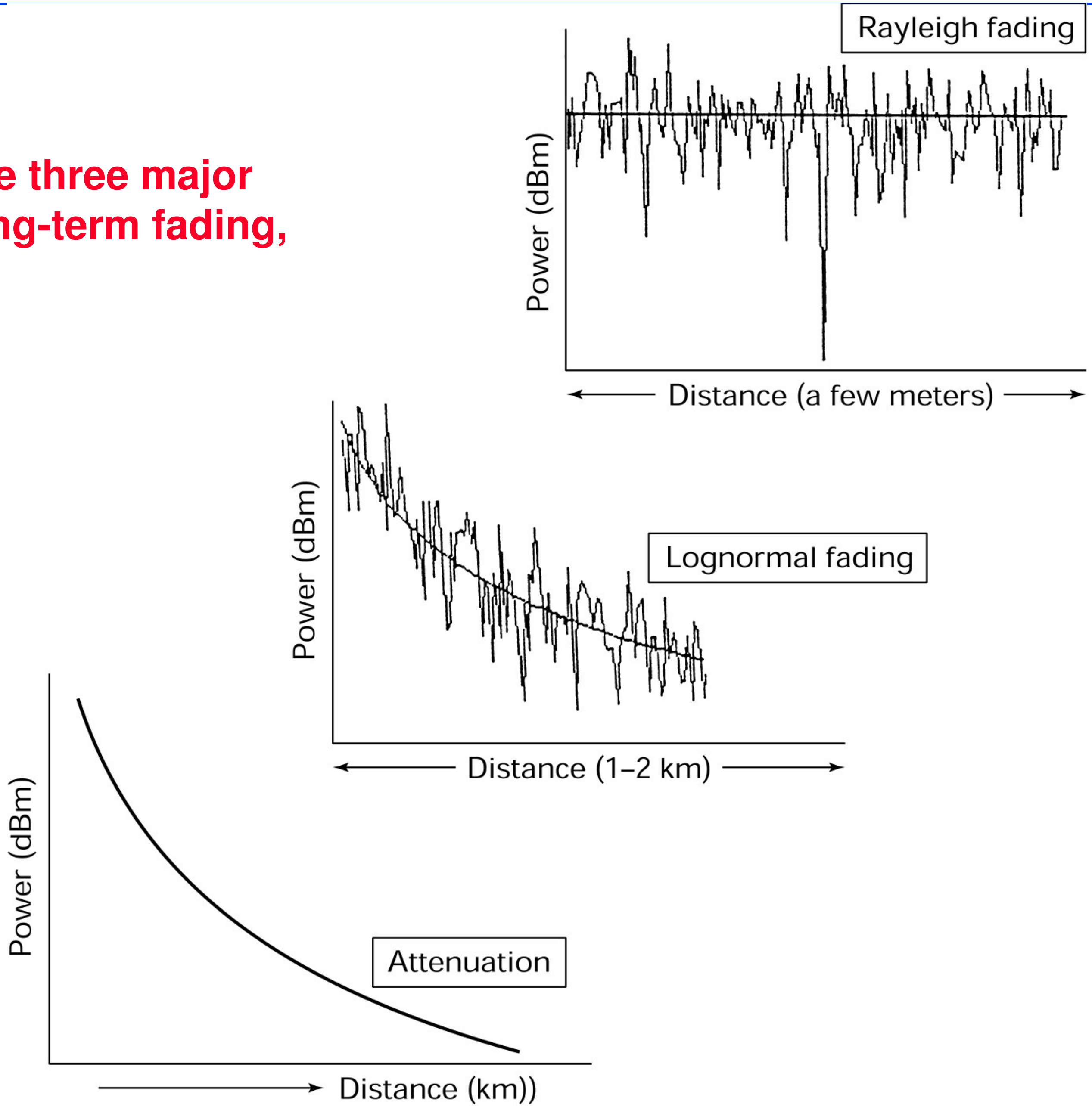
Area 2

Short-term
fading

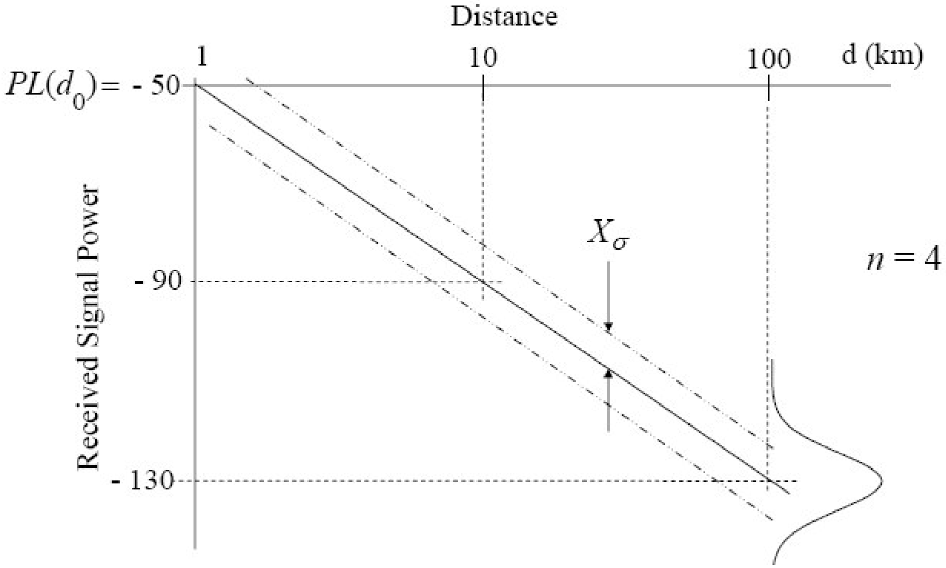
Log-normal
shadowing

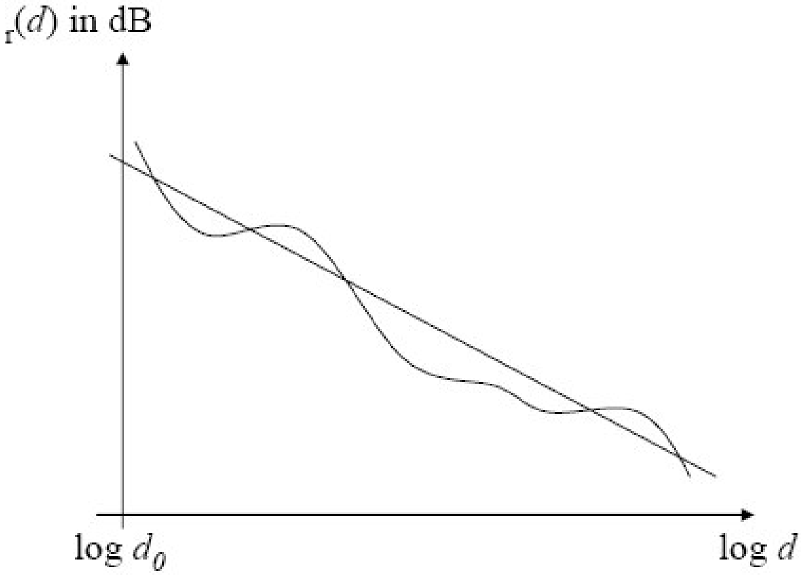
Transmitter

Power loss showing the three major effects: attenuation, long-term fading, and short-term fading.



Log normal Shadowing





Log normal Shadowing model

Order of magnitude of the up & down:
Several wave length

$$\frac{P_r(d)}{P_r(d_0)} = \left(\frac{d_0}{d}\right)^{\beta} \cdot \varepsilon \qquad (\varepsilon \text{ is random variable})$$

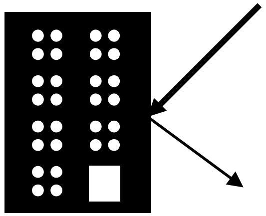
$$10\log\left(\frac{P_r(d)}{P_r(d_0)}\right) = 10\beta\log\left(\frac{d_0}{d}\right) + 10\log(\varepsilon)$$

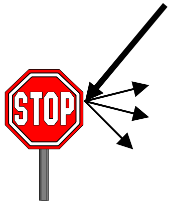
$10\log(\varepsilon)$: random~$N(0,\sigma)$ in dB $\Rightarrow$ log normal shadowing

macro cellular system: $\sigma \approx 8$

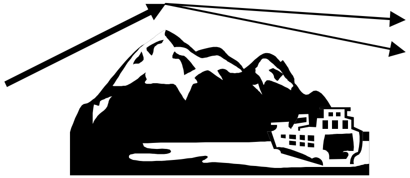
Rf generally propagate according to 4 mechanisms

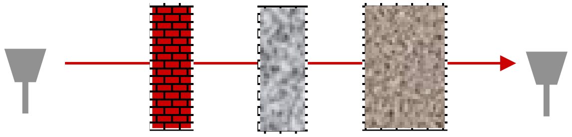
- **Reflection at large obstacles:** plane waves are incident on a surface with dimensions that are very large relative compared to the wavelength.
- **Scattering at small obstacles:** occurs when the plane waves are incident upon an object whose dimensions are on the order of a wavelength or less, and causes energy to be redirected in many directions.
- **Diffraction at edges:** occurs according to Huygen's principle when there is an obstruction between the transmitter and receiver antennas, and secondary waves are generated behind the obstructing body. As the frequency gets higher, the *rf* wave will diffract less and start to behave like light.
- **Penetration:** In addition to diffraction, penetration of objects will allow *rf* reception when there is an obstruction(s) between the transmitter and receiver.


reflection



scattering


diffraction


penetration

CIR of a wideband fading channel

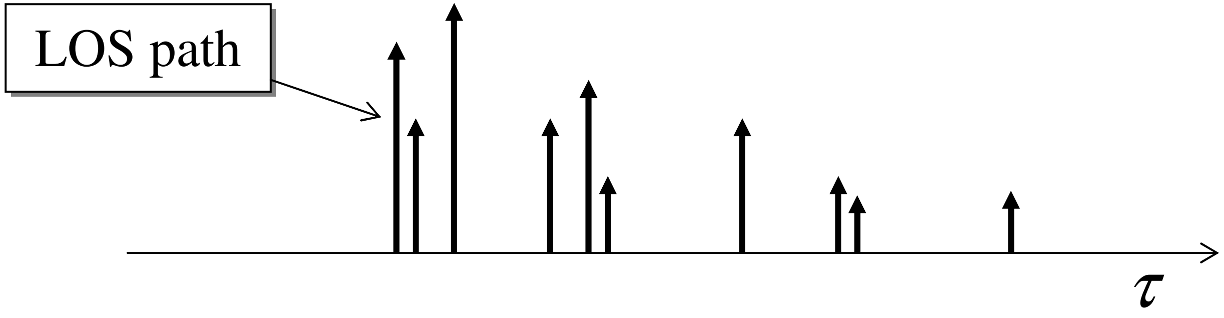
The CIR consists of L resolvable propagation paths

$$h(\tau,t)=\sum_{i=0}^{L-1}\underbrace{a_i}_{\text{path attenuation}}(t)\,e^{j\overbrace{\phi_i}(t)}\,\delta(\tau-\underbrace{\tau_i}_{\text{path delay}})$$

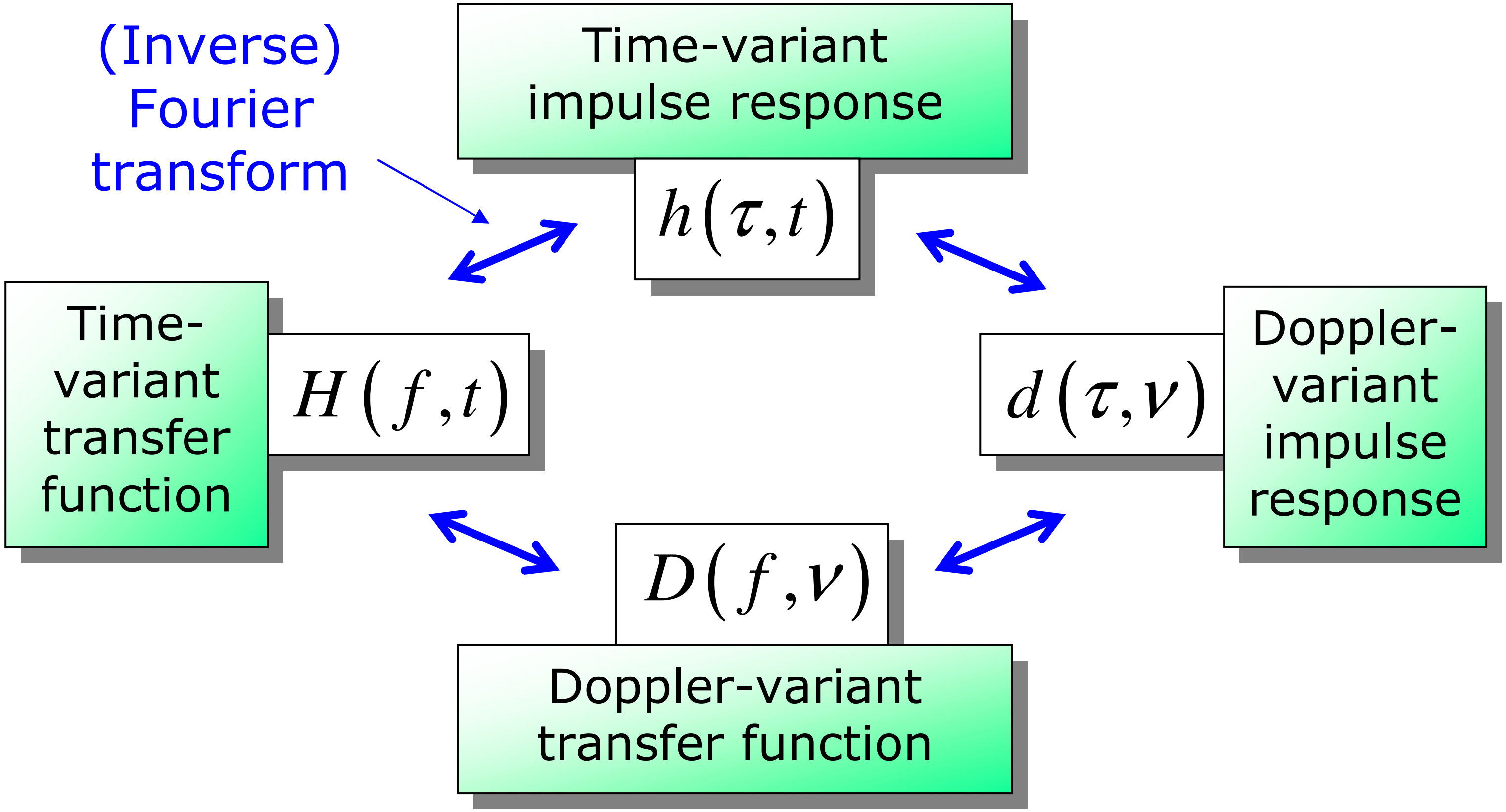
path attenuation

path phase

path delay



Deterministic channel functions



(Inverse) Fourier transform

Time-variant impulse response

$h(\tau,t)$

Time-variant transfer function

$H(f,t)$

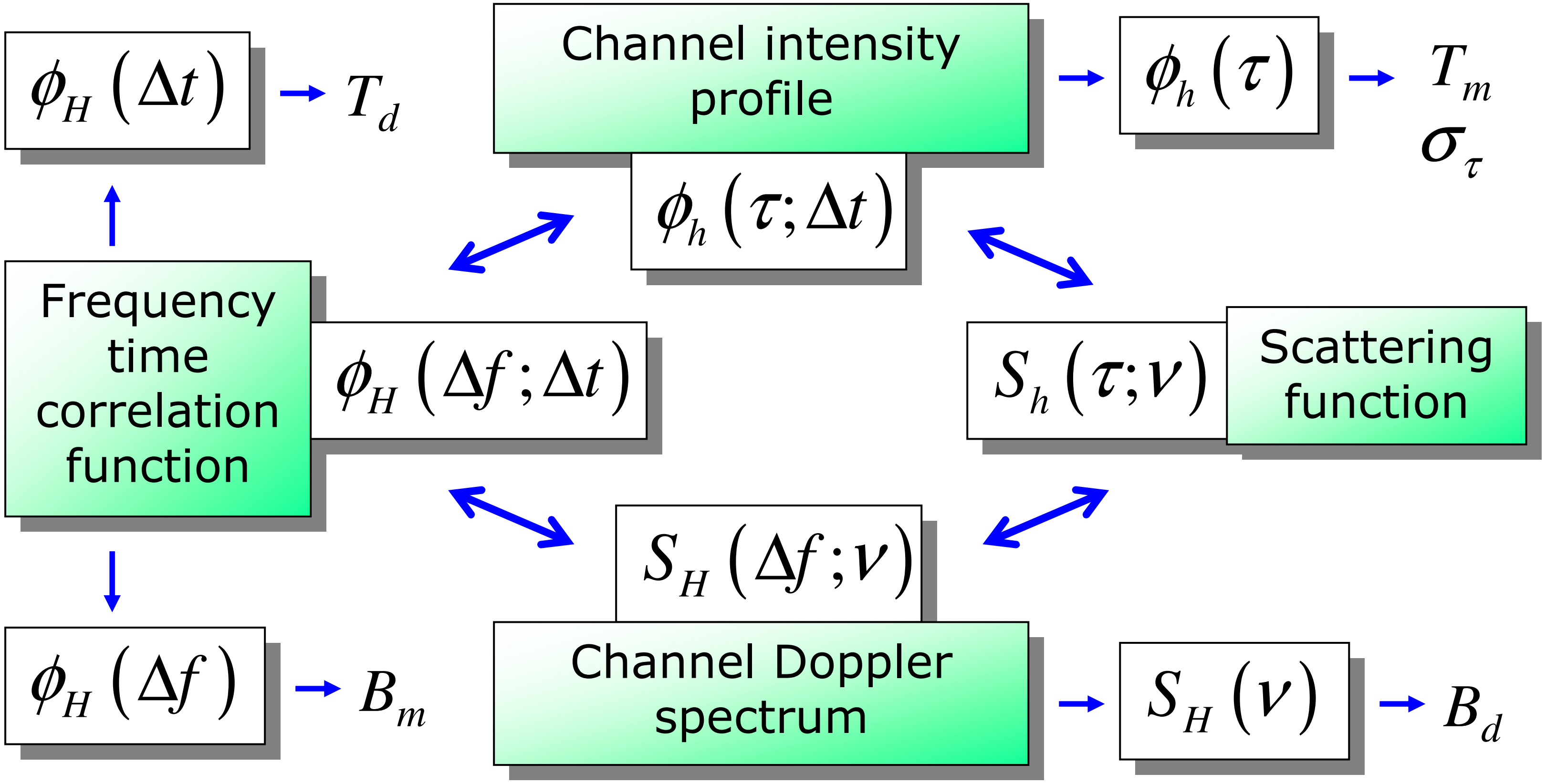
Doppler-variant impulse response

$d(\tau,\nu)$

Doppler-variant transfer function

$D(f,\nu)$

Stochastical (WSSUS) channel functions



$\phi_H(\Delta t) \rightarrow T_d$

Channel intensity profile

$\phi_h(\tau) \rightarrow T_m$

σ_τ

$\phi_h(\tau;\Delta t)$

Frequency time correlation function

$\phi_H(\Delta f;\Delta t)$

$S_h(\tau;\nu)$

Scattering function

$S_H(\Delta f;\nu)$

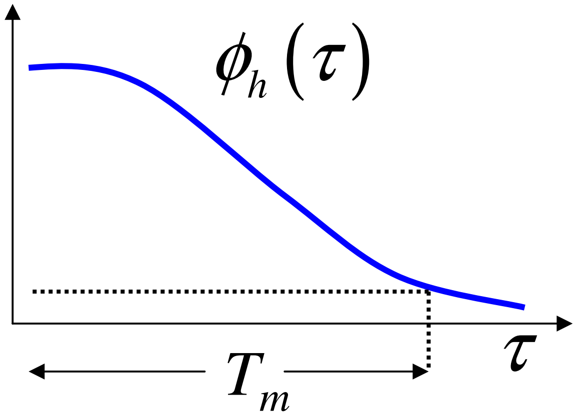
Channel Doppler spectrum

$\phi_H(\Delta f) \rightarrow B_m$

$S_H(\nu) \rightarrow B_d$

Stochastical (WSSUS) channel variables

Maximum delay spread: T_m

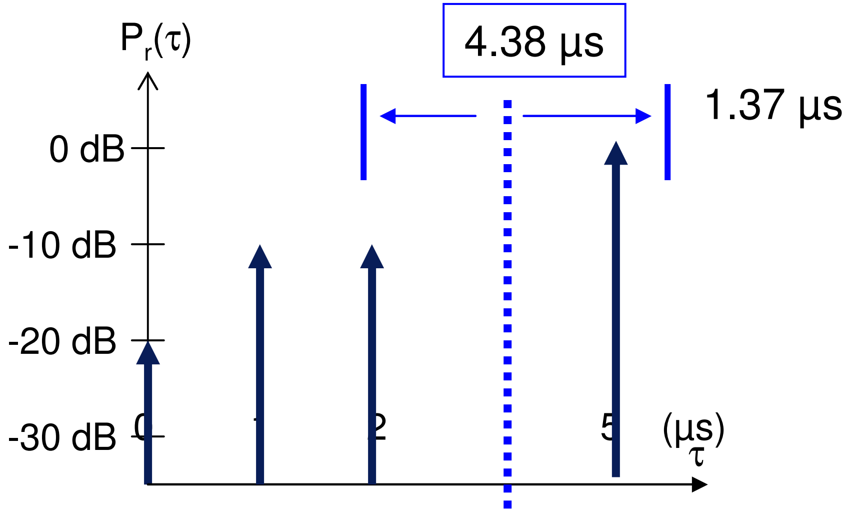


Maximum delay spread may be defined in several ways.

For this reason, the RMS delay spread is often used instead:

$$\sigma_\tau = \sqrt{\frac{\int \tau^2 \phi_h(\tau)\,d\tau}{\int \phi_h(\tau)\,d\tau} - \left[\frac{\int \tau\,\phi_h(\tau)\,d\tau}{\int \phi_h(\tau)\,d\tau}\right]^2}$$

Example (Power delay profile)



$$\bar{\tau} = \frac{(1)(5)+(0.1)(1)+(0.1)(2)+(0.01)(0)}{[0.01+0.1+0.1+1]} = 4.38\,\mu s$$

Avg delay

$$\bar{\tau^2} = \frac{(1)(5)^2+(0.1)(1)^2+(0.1)(2)^2+(0.01)(0)^2}{[0.01+0.1+0.1+1]} = 21.07\,\mu s^2$$

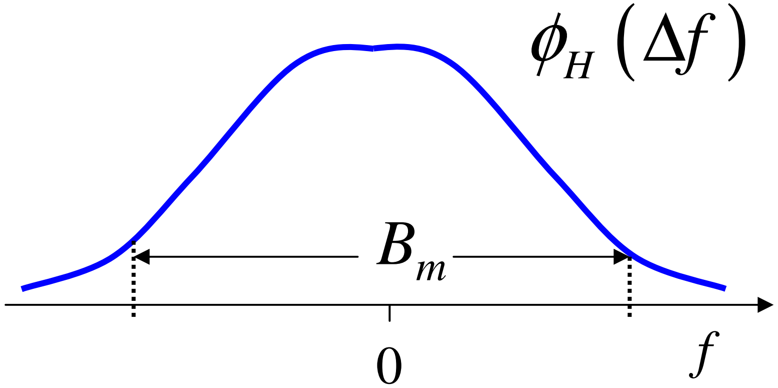
$$\sigma_\tau = \sqrt{21.07-(4.38)^2} = 1.37\,\mu s$$

→ Delay spread

Stochastical (WSSUS) channel variables

Coherence bandwidth of channel:

$$B_m \approx 1/T_m$$



Implication of coherence bandwidth:

If two sinusoids (frequencies) are spaced much less apart than B_m , their fading performance is similar.

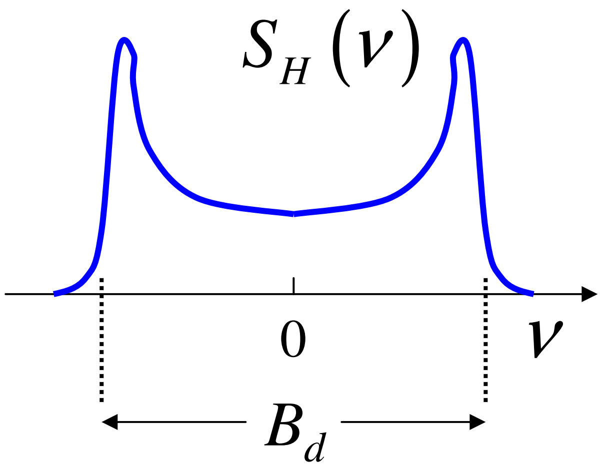
If the frequency separation is much larger than B_m , their fading performance is different.

Stochastical (WSSUS) channel variables

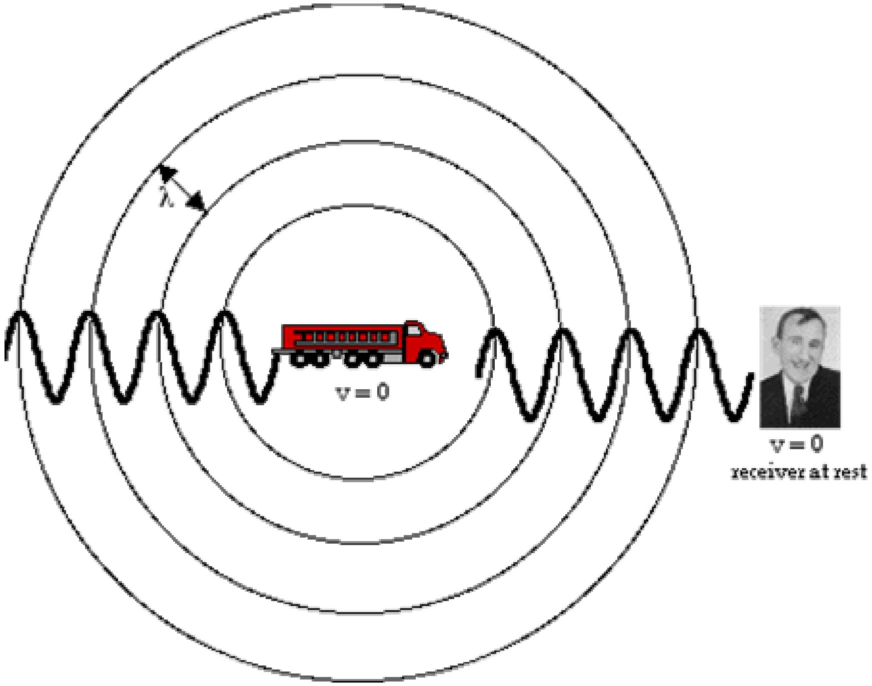
Maximum Doppler spread: B_d

The Doppler spectrum is often U-shaped (like in the figure on the right). The reason for this behaviour is the relationship

$$\nu = \frac{V}{\lambda} \cos \alpha = f_d \cos \alpha$$

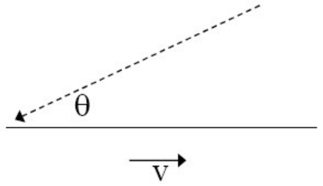


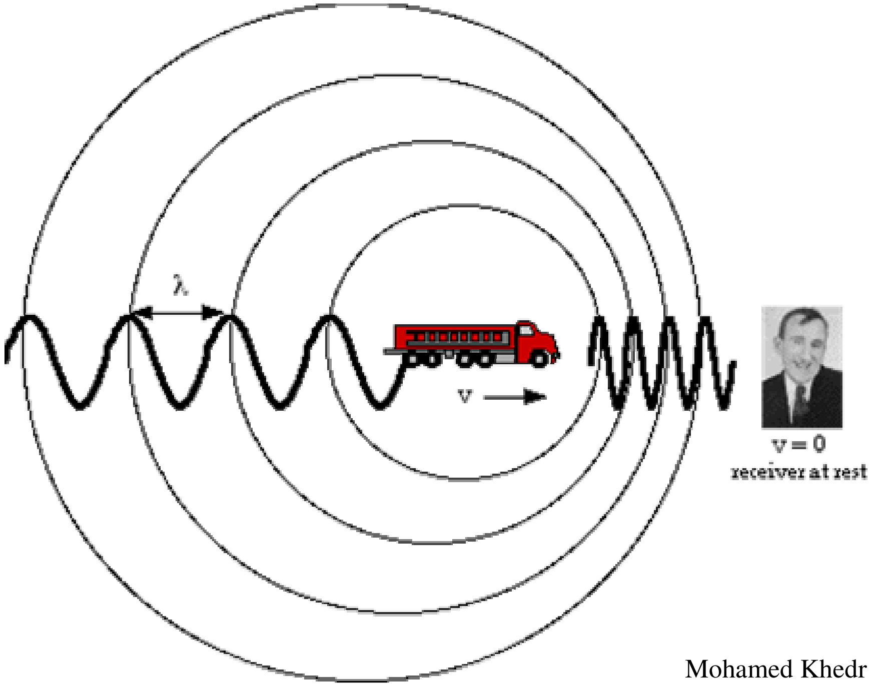
Physical interpretation of Doppler shift



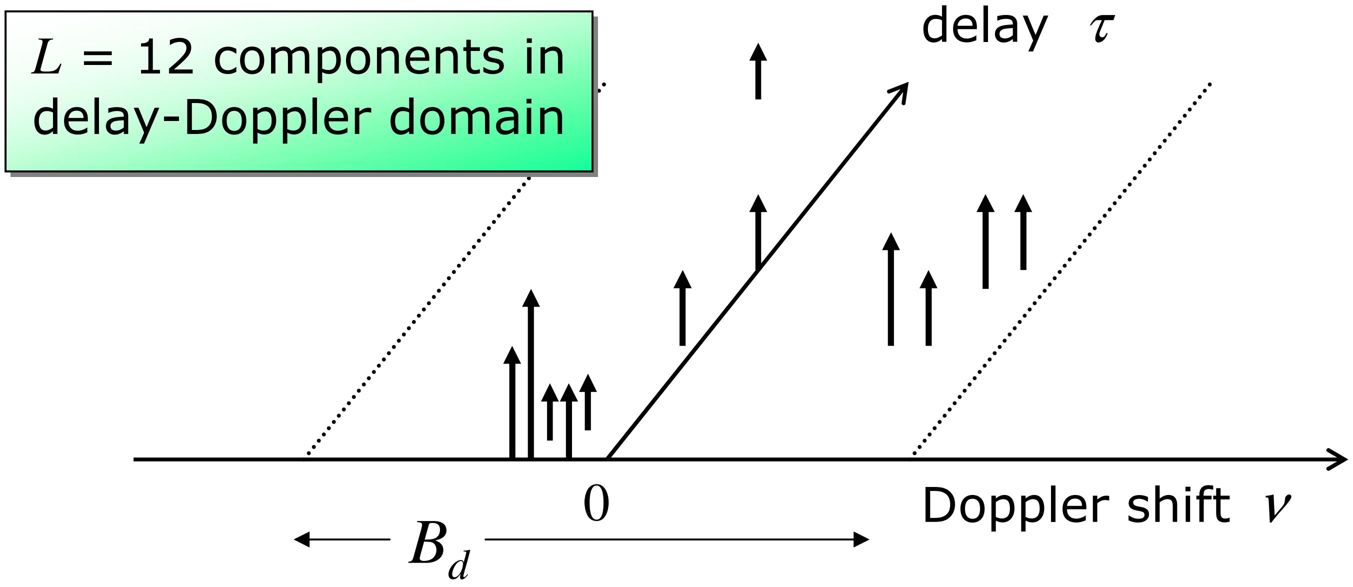
Doppler Shift

- Transmit at f_c
- Velocity v, c: speed of light, θ: arrival angle
- Receive at $f_c + v/c\ f_c \cos(\theta)$





Delay - Doppler spread of channel

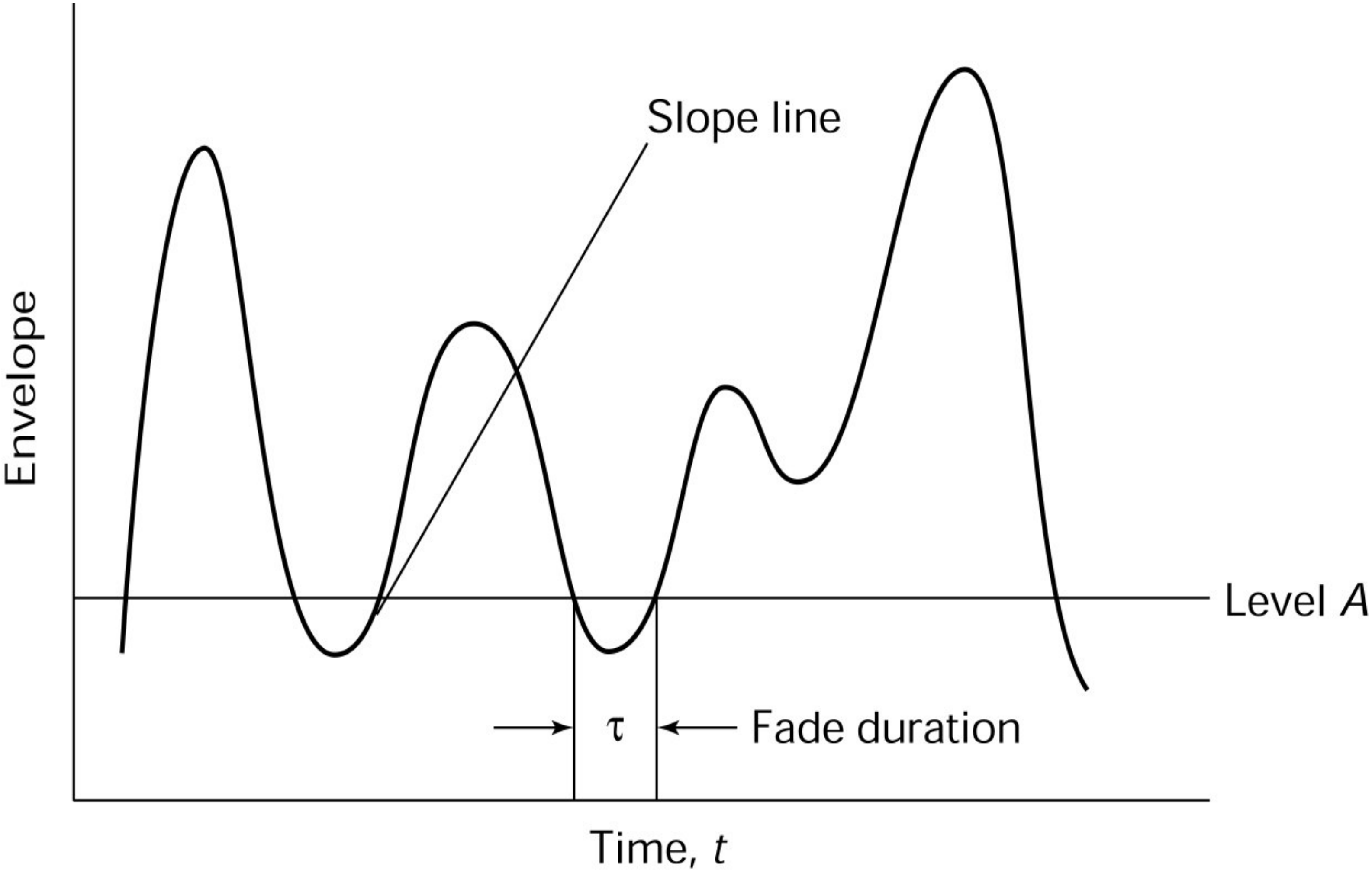

L = 12 components in delay-Doppler domain

$$h(\tau,t)=\sum_{i=0}^{L-1} a_i(t)\,e^{j(2\pi\nu_i t+\phi_i)}\,\delta(\tau-\tau_i)$$

Mitigate Doppler shift

- If the baseband signal bandwidth is much greater than the maximum Doppler shift, then the effects of Doppler spread are negligible at the receiver.
  - To minimize the effect of Doppler, we should use as wide a baseband signal as feasible [e.g. spread spectrum]

The concept of level crossing.



Channel Autocorrelation Functions

- Time-spreading: Multipath characteristics of channel
  - Multi-path delay spread, T_m
    - Characterizes time dispersiveness of the channel,
    - Obtained from power delay-profile, $\Phi_c(\tau)$
    - Indicates delay during which the power of the received signal is above a certain value.
  - Coherence bandwidth, B_c approx. $1/T_m$
    - Indicates frequencies over which the channel can be considered flat
    - Two sinusoids separated by more than B_c: affected differently by the channel
    - Indicates frequency selectivity during transmission.

Channel Autocorrelation Functions

- Time variations of channel: Frequency-spreading

  - Doppler Spread, B_d
    - Characterizes frequency dispersiveness of the channel, or the spreading of transmitted frequency due to different Doppler shifts
    - Obtained from Doppler spectrum, $S_c(\lambda)$
    - Indicates range of frequencies over which the received Doppler spectrum is above a certain value

  - Coherence time, T_c approx. $1/B_d$
    - Time over which the channel is time-invariant
    - A large coherence time: Channel changes slowly

Statistical Models

- ❑ Design and performance analysis based on statistical ensemble of channels rather than specific physical channel.

$$h_\ell[m] \approx \sum_i a_i e^{-j2\pi f_c \tau_i}$$

- ❑ Rayleigh flat fading model: many small scattered paths

$$h[m] \sim \mathcal{N}(0, \frac{1}{2}) + j\mathcal{N}(0, \frac{1}{2}) \sim \mathcal{CN}(0, 1)$$

Complex circular symmetric Gaussian .

Squared magnitude is exponentially distributed.

- ❑ Rician model: 1 line-of-sight plus scattered paths

$$h[m] \sim \sqrt{\kappa} + \mathcal{CN}(0, 1)$$

Fading distributions (Rayleigh)

In a flat fading channel, the (time-variant) CIR reduces to a (time-variant) complex channel coefficient:

$$c(t) = a(t)e^{j\phi(t)} = x(t) + j\,y(t) = \sum_i a_i(t)\,e^{j\phi_i(t)}$$

When the quadrature components of the channel coefficient are independently and Gaussian distributed, we get:

$$p(a) = \frac{a}{\sigma^2}e^{-a^2/2\sigma^2} \qquad p(\phi) = \frac{1}{2\pi}$$

Rayleigh distribution

Uniform distribution

Fading distributions (Rice)

In case there is a strong (e.g., LOS) multipath component in addition to the complex Gaussian component, we obtain:

$$c(t)=a_0+a(t)e^{j\phi(t)}=a_0+\sum_i a_i(t)e^{j\phi_i(t)}$$

From the joint (magnitude and phase) pdf we can derive:

$$p(a)=\frac{a}{\sigma^2}e^{-\left(a^2+a_0{}^2\right)/2\sigma^2}I_0\left(\frac{aa_0}{\sigma^2}\right)$$

Rice distribution

Modified Bessel function of first kind and order zero

Raleigh Flat Fading: Statistical Model

- **Frequency of fades - *Level Crossing Rate***

  - rate at which envelope crosses a specified level in positive direction

$$N_R = \sqrt{2\pi} f_m \rho e^{-\rho^2} = \sqrt{2\pi} \frac{v}{\lambda} \rho e^{-\rho^2}$$

where $\rho = \frac{R}{R_{RMS}}$ is the specified amplitude level relative to RMS

and f_m is the maximum Doppler frequency.

- **Average fade duration**

  - approximation: $\bar{\tau} = \frac{e^{\rho^2} - 1}{\rho f_m \sqrt{2\pi}} = \frac{1 - e^{-\rho^2}}{N_R}$

  - 0.957 ms @ 900 MHz, 50 km/h, -20 dB
  - 23.94 ms @ 900 MHz, 2 km/h, -20 dB
  - 6.308 ms @ 900 MHz, 24 km/h, -10 dB

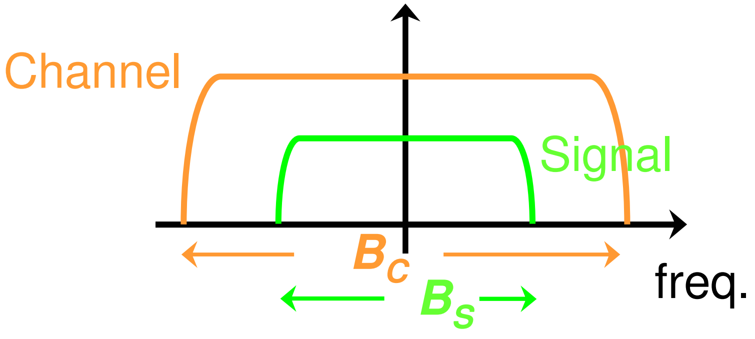
- **Statistics depend primarily on speed of the mobile!**

Channel Classification

- Based on Time-Spreading

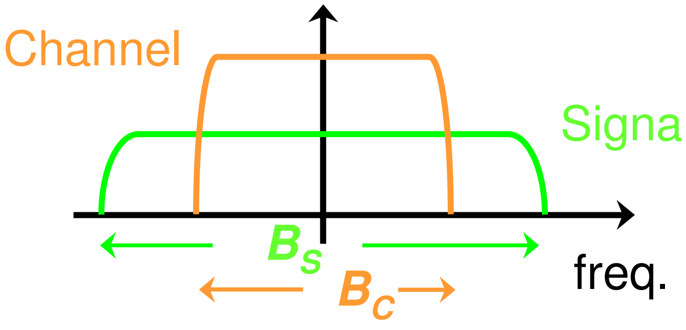
Flat Fading

1. $B_S < B_C \Leftrightarrow T_m < T_s$
2. Rayleigh, Ricean distrib.
3. Spectral char. of transmitted signal preserved



Frequency Selective

1. $B_S > B_C \Leftrightarrow T_m > T_s$
2. Intersymbol Interference
3. Spectral chara. of transmitted signal not preserved
4. Multipath components resolved



Channel Classification

- Based on Time-Variations

Fast Fading

1. High Doppler Spread
2. $1/B_d \cong T_C < T_s$

Slow Fading

1. Low Doppler Spread
2. $1/B_d \cong T_C > T_s$