ICT course:

Mobile Wireless Communications

Lecturers:
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Course Schedule

- Lectures:

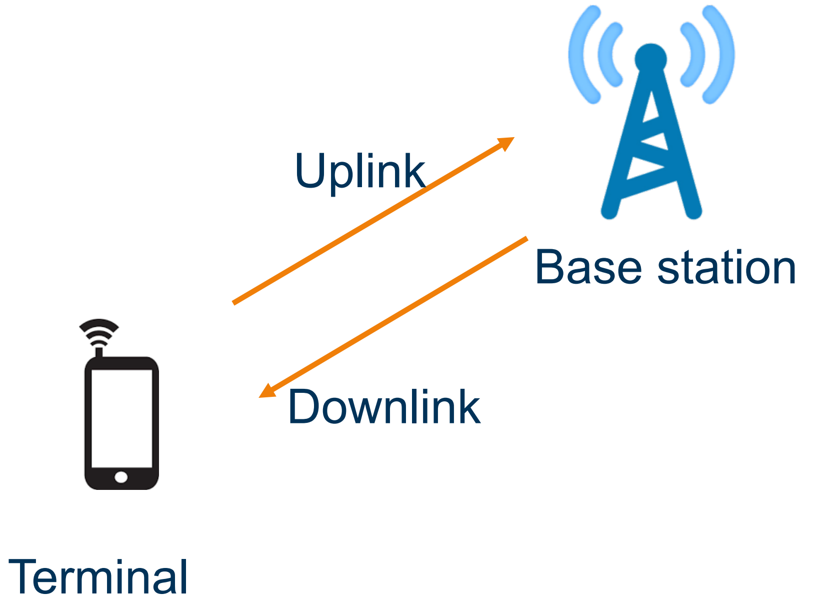
1. Introduction
2. Characteristics of mobile radio environment:
   - Propagation
   - Fading and mitigations
3. Cellular concept
4. Channel assignment (optional)
5. Modulation techniques
6. Multiple Access techniques
7. Coding for error detection and correction
8. Applications – Mobile network Generations:
   - GSM
   - 3G/LTE-4G
   - 5G and future of mobile networks (discussion)

- Exercises
- References:

[1]. Mischa Schwartz: Mobile Wireless Communication, CAMBRIDGE UNIVERSITY PRESS, 1st Edition (2005)
[2]. Wireless Communications: Principles and Practice (2nd Edition) by Theodore S. Rappaport

Lecture 2: Radio environment (wireless channels)

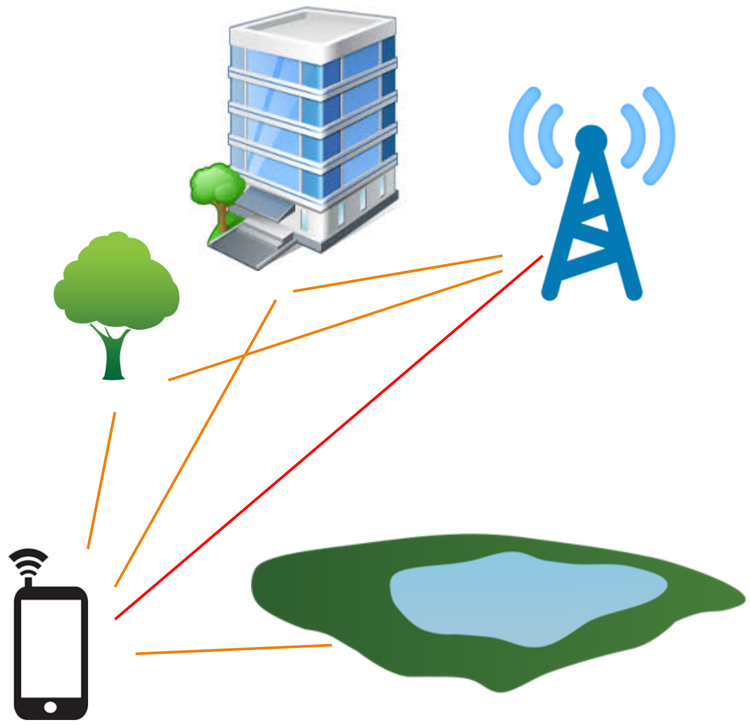
- ❑Propagation phenomena
- ❑Propagation models
- ❑ Random Channel Characterization
- ❑Fading:
  - What is fading? Fading rate?
  - Causes
  - Impacts of fading to transmission
  - Mitigations to fading



Propagation Phenomena

- Electromagnetic signals vary randomly at receivers because of:
  - Obstacles → reflection, diffraction, scattering
  - Terminal moves → signal amplitudes fluctuate randomly

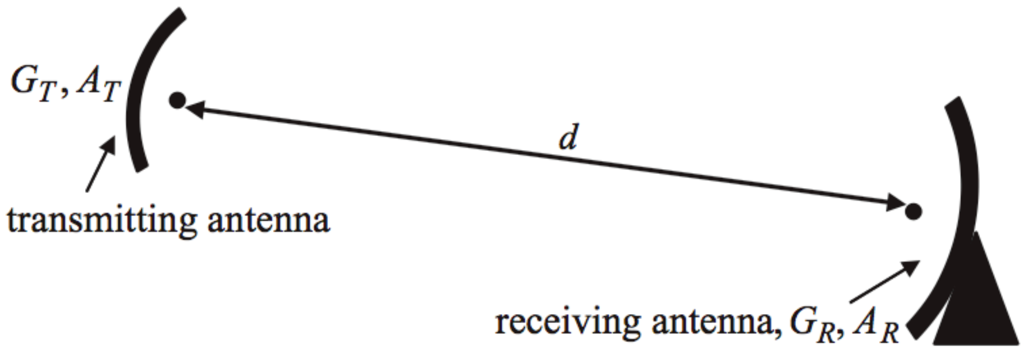
  → **Fading**
- Propagation model captures the variation of power along distances in wireless communication



Propagation models

Propagation Models

- Three common effects in wireless communication:
  - Average power varying
  - Long-term variation of average power (Shadow fading)
  - Power variation in wavelength scale (Short-term multipath fading)
- Free space propagation:



$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2$$

- Wireless case:

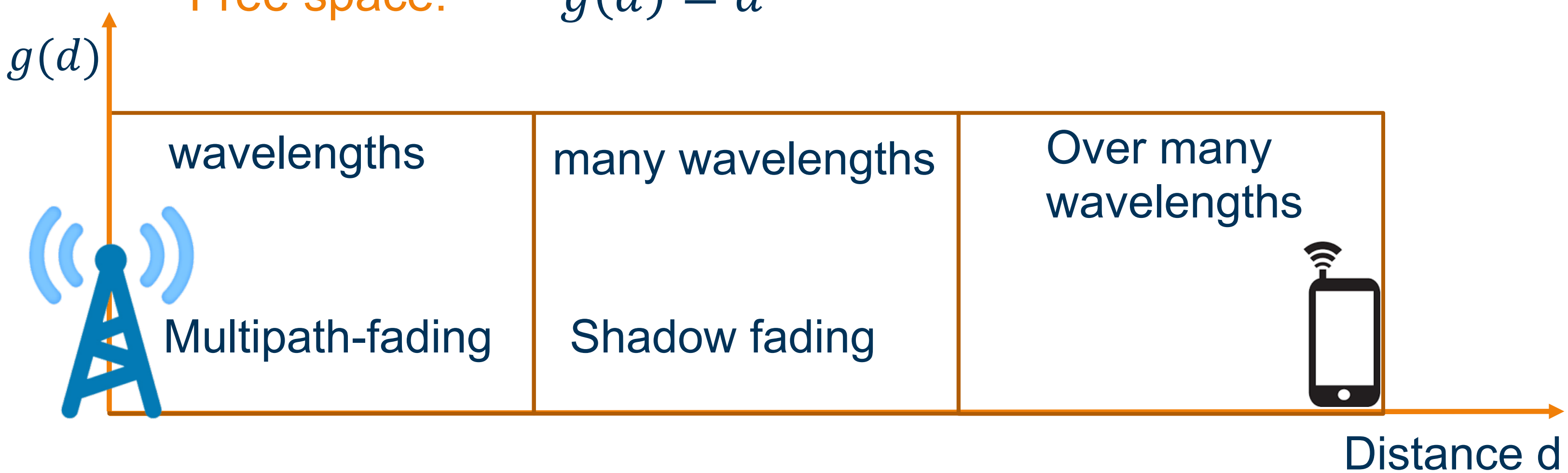
$$P_R = \propto^2 10^{x/10} g(d) P_T G_T G_R$$

Shadow fading and multipath-fading effects

Inverse variation of power with distance

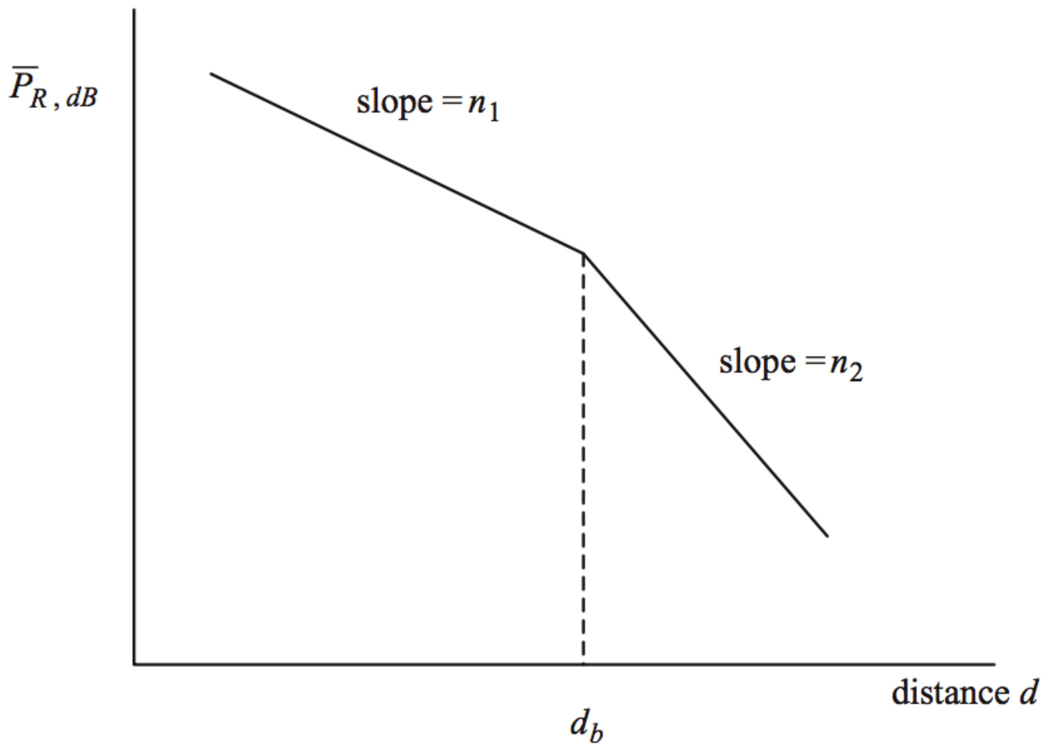
Average power measured at receiver at distance d $\bar{P}_R$

- Example of g(d):
  - two-ray model: $g(d) = kd^{-4}$
  - Free space: $g(d) = d^{-2}$



Propagation models: Average receive power

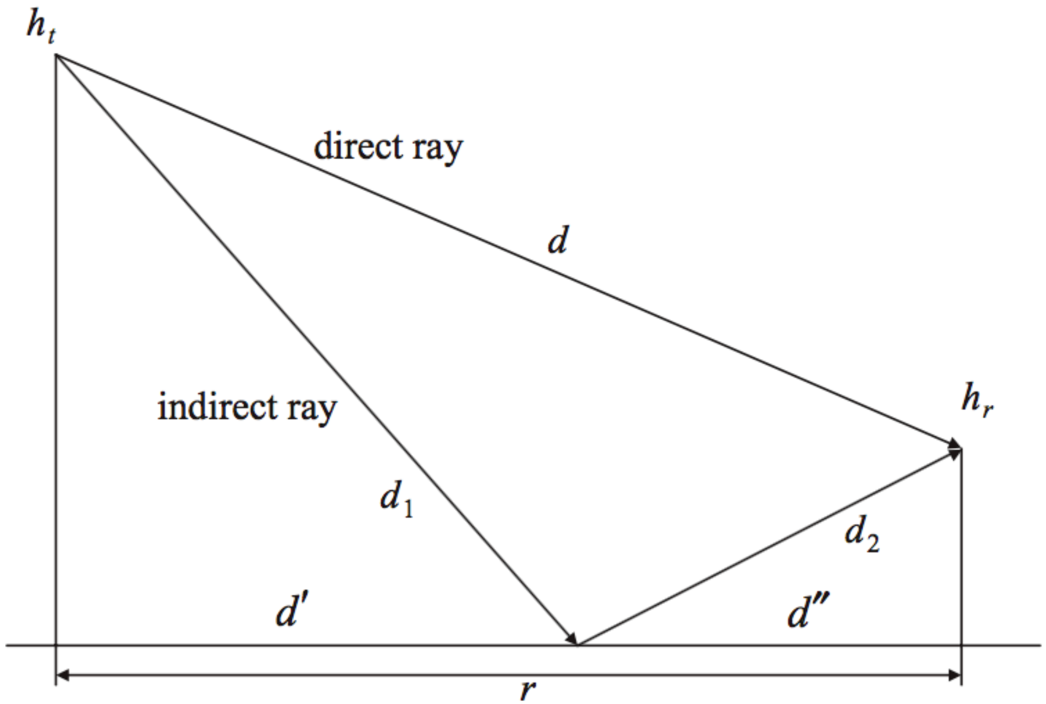
- Average receive power: $\bar{P}_R$
  - Path loss:
    - Two-slope received signal model: for microcells



$$\bar{P}_R = g(d) P_T G_T G_R$$

$$g(d) = d^{-n_1}\left(1 + \frac{d}{d_b}\right)^{-n_2}$$

- Path loss: two-ray model:



$$\bar{P}_R = g(d) P_T G_T G_R$$

$$g(d) = \frac{(h_t h_r)^2}{d^4}$$

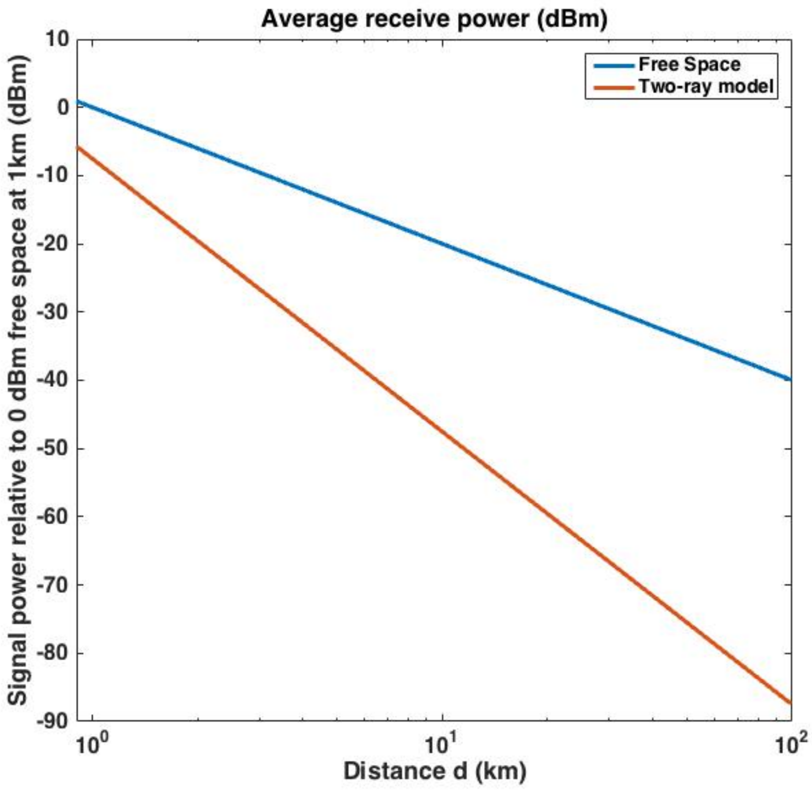


Figure of average power vs distance with different ht

Propagation models: Shadow (Log-normal) fading

- Shadow-fading (large scale variation): $10^{x/10}$
  - Slowly varying: on the order of meters
  - Over relatively long distance: many wavelengths
  - Average receive power:

$$\bar{P}_{R,dB} = 10\log_{10}\bar{P}_R = 10\log_{10}P_T + 10\log_{10}g(d) + 10\log_{10}G_T G_R$$

  - Receive power:

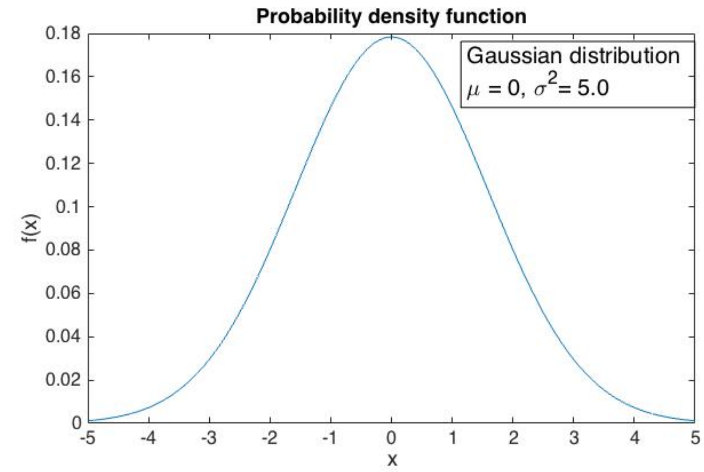
Local-mean power p_{dB}

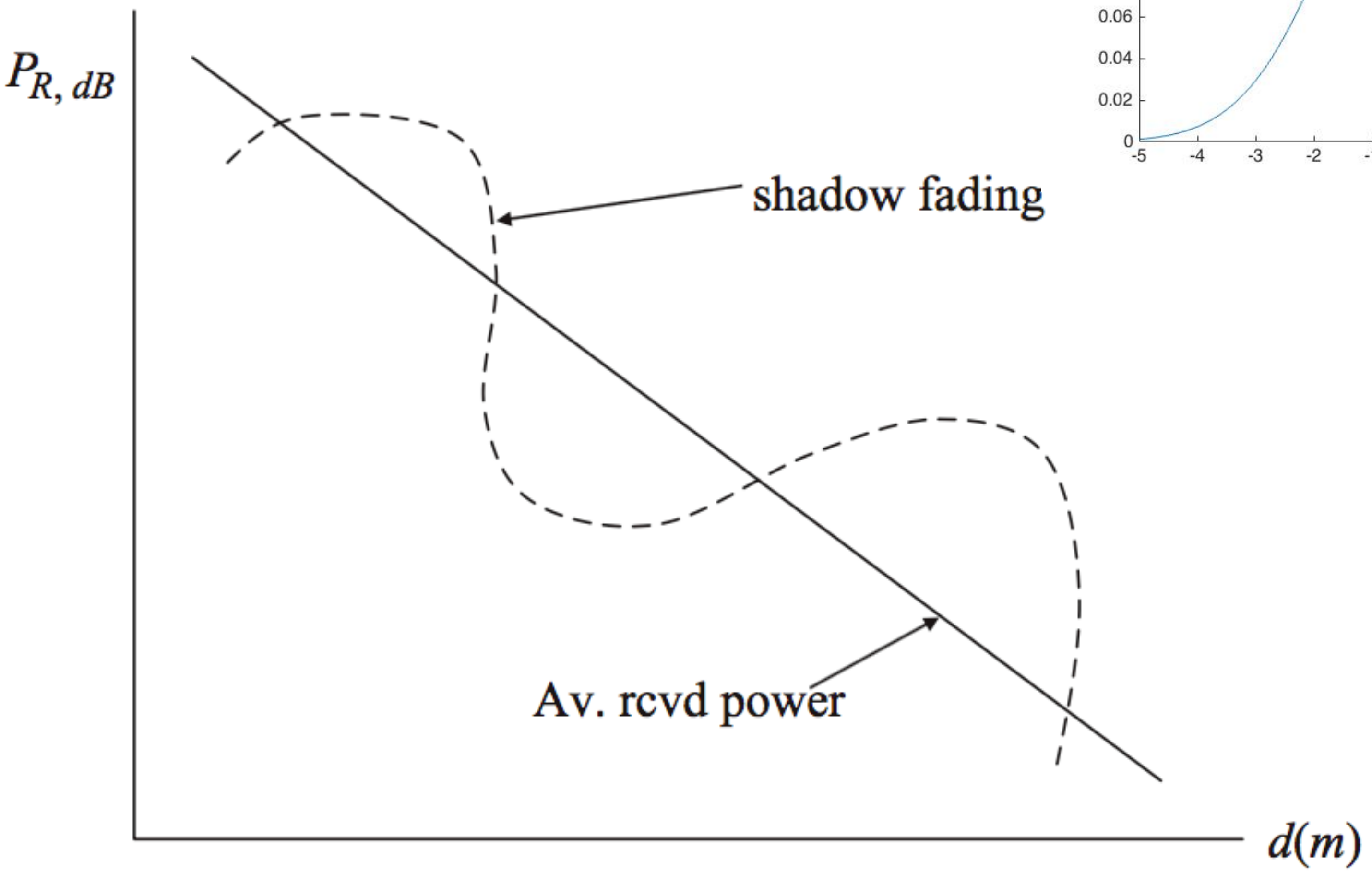
$$P_{R,dB} = 10\log_{10}P_R = 10\log_{10}\propto^2 + x + \bar{P}_{R,dB}$$

  - Shadow-fading random variable x (dB) is a zero-mean Gaussian rv with variance σ^2

$$f(x) = \frac{e^{-x^2/\sigma^2}}{\sqrt{2\pi\sigma^2}} \qquad f(p_{dB}) = \frac{e^{-(p_{dB}-\bar{P}_{R,dB})^2/\sigma^2}}{\sqrt{2\pi\sigma^2}}$$

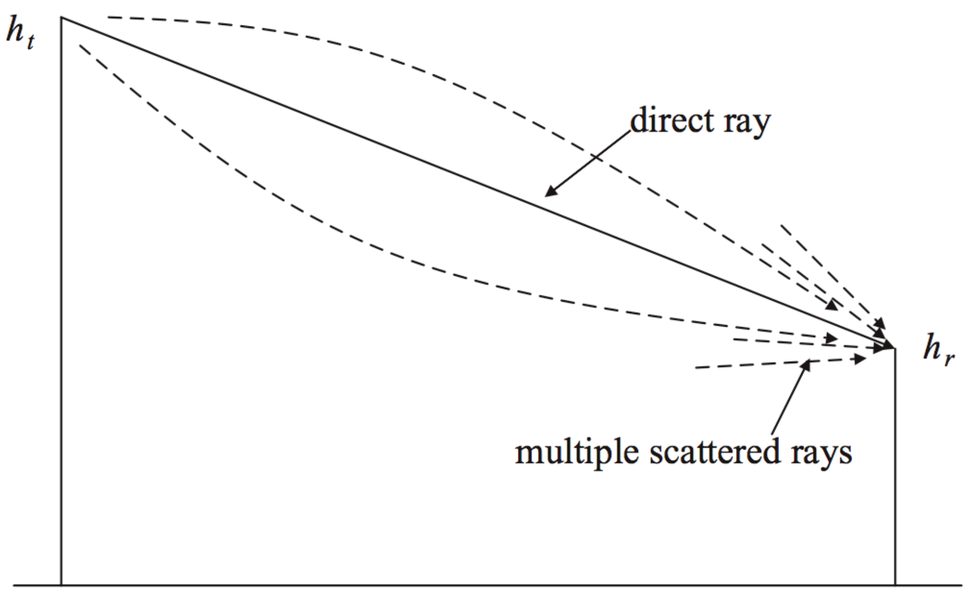
Propagation Models





Propagation models: Rayleigh and Ricean Models

- Rayleigh model:



  - Over distance of wavelengths
  - The direct ray is made up of superposition of scattered L rays

$$S_R(t) = \sum_{k=1}^{L} a_k \cos[\omega_c(t - t_0 - \tau_k) + \theta_k]$$

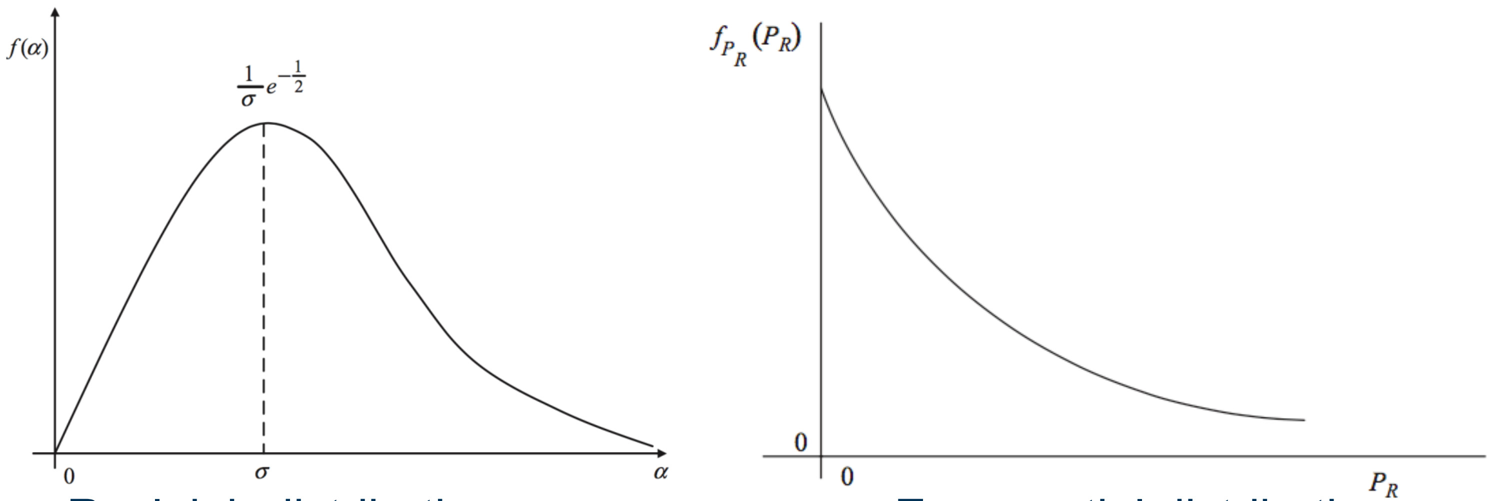
$$t_0 = d/c$$

Random amplitude — Delay variation — Phase variation

Propagation Models - Rayleigh model

$$S_R(t) = a.\cos[\omega_c(t - t_0) + \theta]$$

- a is Rayleigh distributed (proved)
- $\propto = \sqrt{\frac{c}{2p}}a$ is Rayleigh distributed (proved): $pdf(\propto) = \frac{\propto}{{\sigma_r}^2} e^{-\propto^2 / 2{\sigma_r}^2}$, $\propto \geq 0$



Rayleigh distribution

Exponential distribution

- Receive power $P_R = \frac{ca^2}{2p} = \propto^2 p$ then:

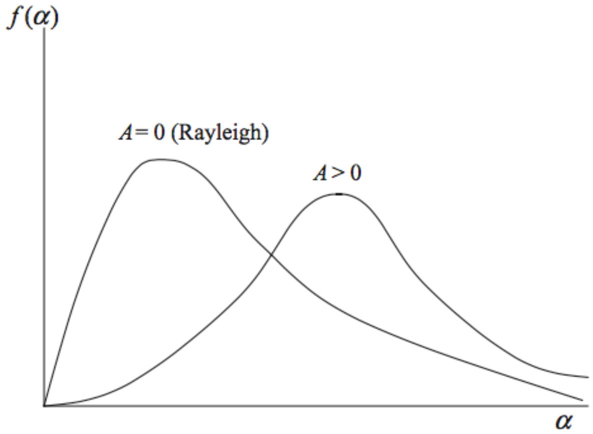
$$pdf(P_R) = pdf(\propto).\frac{d\propto}{dP_R} = \frac{1}{p} e^{-P_R/p}$$

- Ricean model:
  - Distance between two antennas is not too large (e.g., microcellular case)
  - At the receiver: one direct ray and scattered L rays

$$S_R(t) = Acos\omega_c(t - t_0) + \sum_{k=1}^{L} a_k \cos[\omega_c(t - t_0 - \tau_k) + \theta_k]$$

$$S_R(t) = \mathrm{a}^* \cos[\omega_c(t - t_0) + \theta]$$

  - a^* is Ricean distributed (proved)



  - Receive power varying about local-mean power

$$f_{P_R}(P_R) = \frac{(1+K)e^{-K}}{p} e^{-\frac{1+K}{p}P_R} I_0\left(\sqrt{\frac{4K(1+K)}{p}P_R}\right)$$

Exercise 1.1:

Empirical power drop-off values

City	n_1	n_2	$d_b(m)$
London	1.7-2.1	2-7	200-300
Melbourne	1.5-2.5	3-5	150
Orlando	1.3	3.5	90

- plot $P_{R,dB} - P_{T,dB}$ for Orlando as a function of distance *d*, in meters, with $0 < d < 200$ m. Assume transmitter and receiver antenna gains are both 1; average power effect is experienced, two-slope model is used.

Exercise 1.2:

The average power received at mobiles 100 m from a base station is 1 mW. Log- normal, shadow, fading is experienced at that distance. The log-normal standard deviation σ is 6dB.

(a) What is the probability that the received power at a mobile at that distance from the base station will exceed 1 mW? Be less than 1 mW?

(b) An acceptable received signal is 10 mW or higher. What is the probability that a mobile will have an acceptable signal?

- Repeat for σ = 10 dB.
- Repeat both cases for an acceptable received signal of 6 mW.

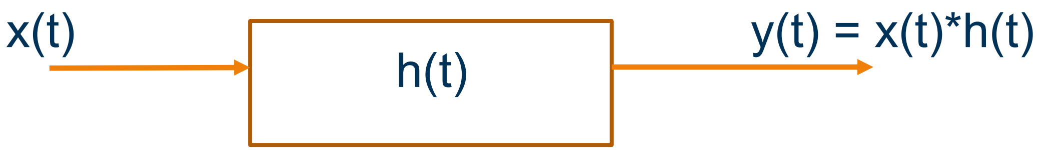
Note: The integral of a Gaussian error function

Random channel characterization

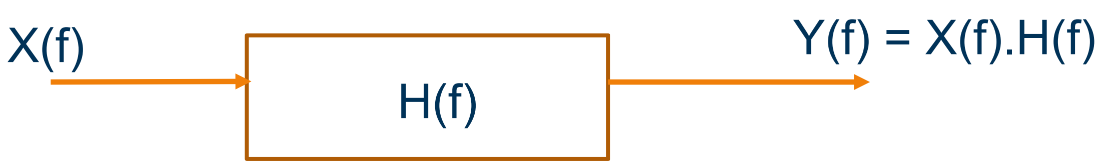
Random channel characterization

- System response -Transfer function of a linear system
  - Impulse response

  - In time domain:



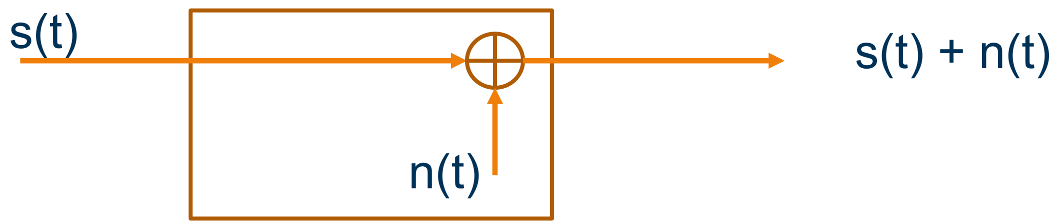
  - In frequency domain:



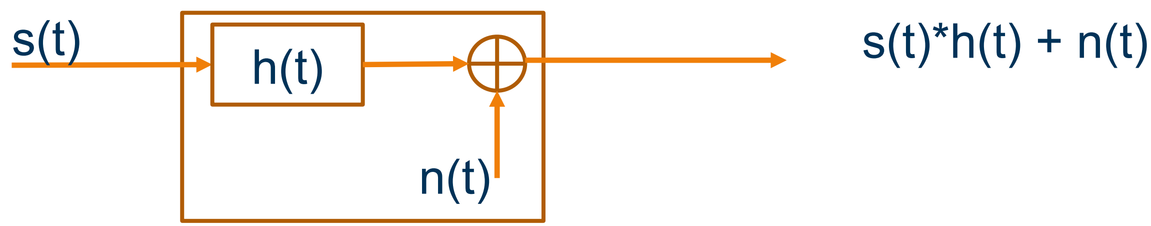
- Ideal channel: H(f)=1

- Common channels

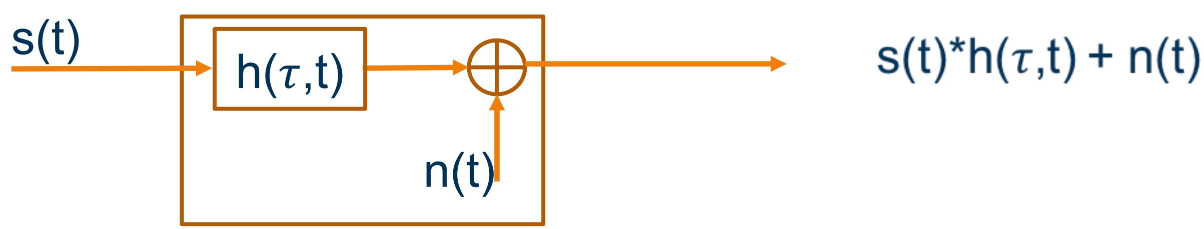
Additive Noise channel



Linear Filter channel (time-invariant)



Linear time-variant filter channel

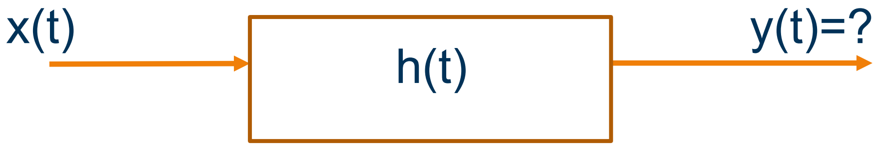


Exercise 2.1:

- Determine output signal of below system:

$$x(t) = e^{t}[u(t-1) - u(t-3)]$$

$$h(t) = \delta(t-1)$$



- Determine its transfer function

Note: u(t) is a rectangular function

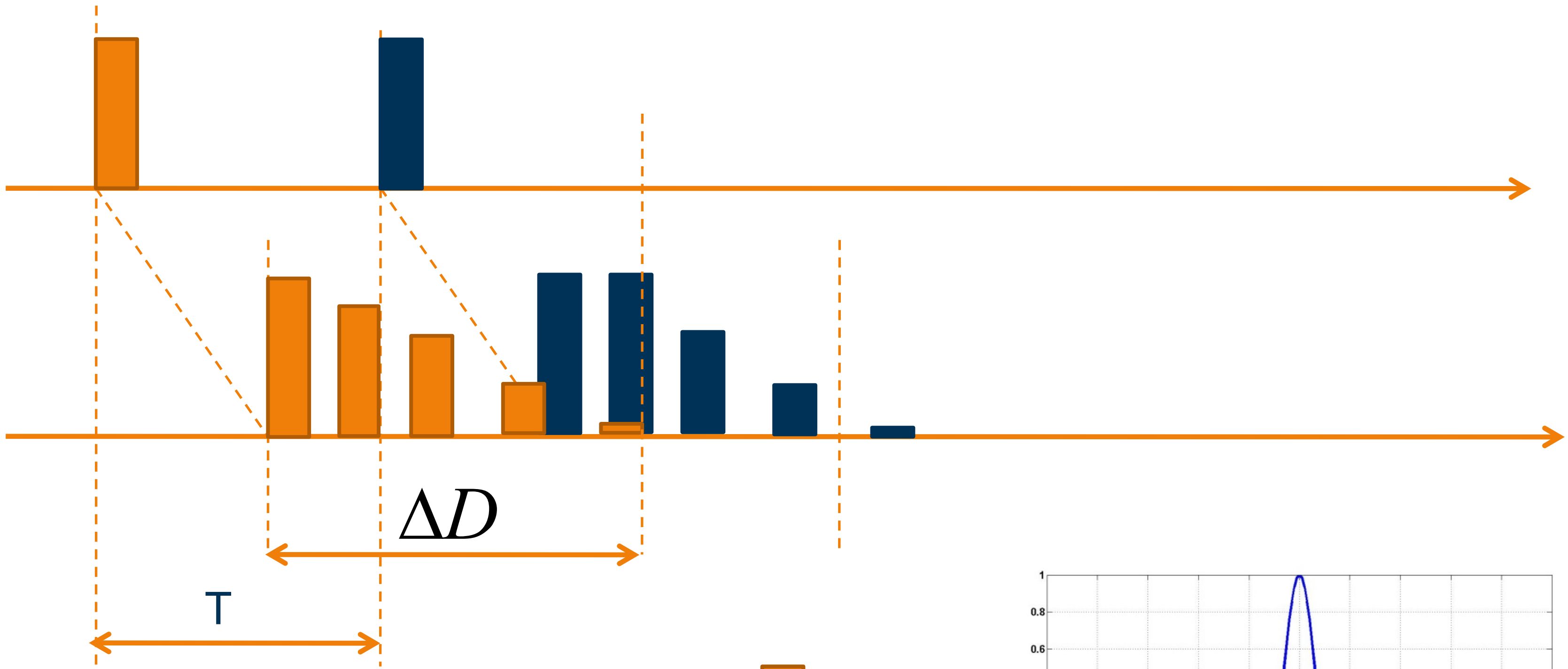
Fading

Fading

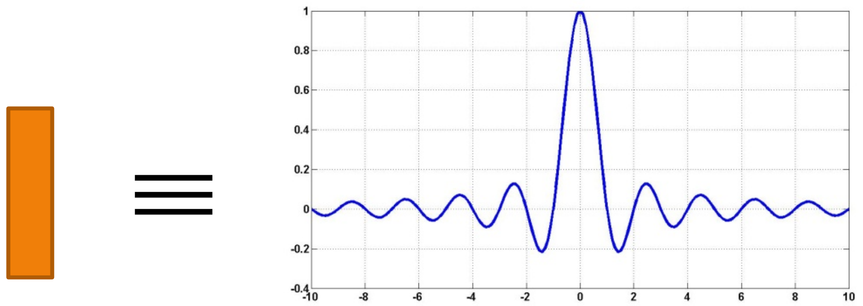
- What is fading?
  - The variation of a transmitted signal at the receiver
- Causes of fading
  - Delay spread and Inter-symbol Interference (ISI)
  - Doppler effect
- Impacts of fading on transmitted signal:
  - Coherence bandwidth and coherence time
  - Frequency dispersion: Frequency-selective fading
  - Time dispersion: Time-selective fading
- Mitigations to fading

Fading:
Causes of fading

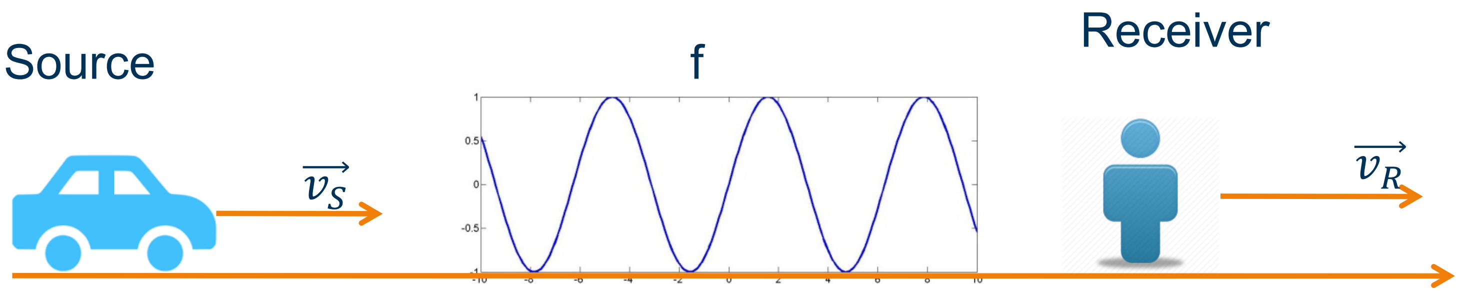
- Causes of fading
  - Delay spread and ISI:



ΔD: Delay spreading
T: symbol interval



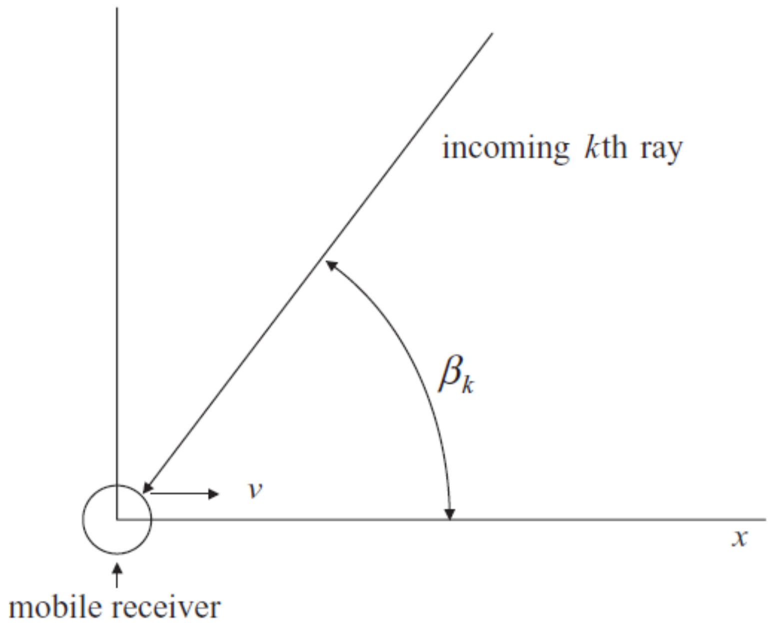
- Doppler effect:
  - General case:



$$f_R = f + \frac{v_R - v_S}{c} f$$

$$\Delta f = \frac{\Delta v}{c} f = \frac{\Delta v}{\lambda}$$

- Considering terminal mobility



$$f_{Rc} = f_c + f_k$$

$$f_k = \frac{v}{\lambda}\cos\beta_k$$

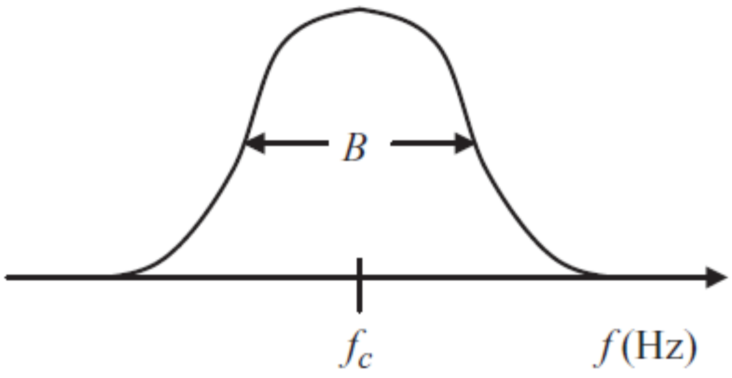
$$w_k = 2\pi f_k$$

- Received signal:

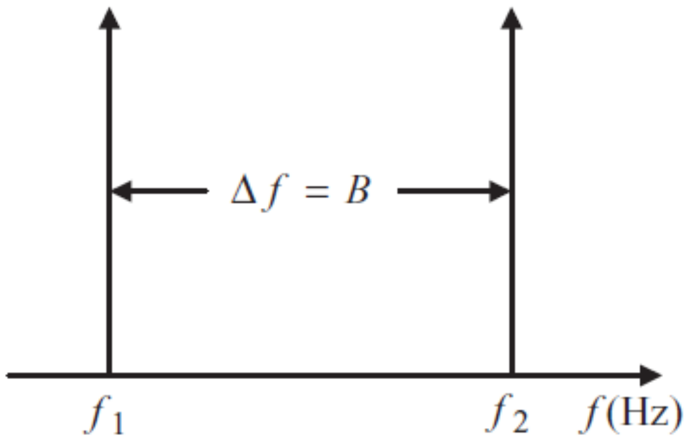
$$S_R(t) = \sum_{k=1}^{L} a_k \cos[w_c(t - t_0) + \phi_k + w_k t]$$

Fading:
Impacts of fading on transmitted signal

- Impacts of fading on transmitted signal
  - How propagation path impacts on the reception of a signal?



(a) Modulated carrier spectrum



(b) Two-carrier model

Signal bandwidth

- Two carriers represent two frequency components in the spectrum of a real information-bearing signal.
- Frequency separation = bandwidth of the real signal
- The real signal is **distorted** by the channel if two received signals are **not correlated**
- I.e., frequency components fade in different ways

- Received signals

$$S_1(t) = \sum_{k=1}^{L} a_k \cos[\omega_1(t - t_1 - \tau_k) + \omega_k t + \theta_k\ ]$$

$$S_2(t) = \sum_{l=1}^{M} a_l \cos[\omega_2(t - t_2 - \tau_l) + \omega_l t + \theta_l\ ]$$

t_1, t_2: large-scale delays of two received signals

$\tau_k, \tau_l,\ \theta_k, \theta_l$: delays and additional angles of each scattered ray

$$\omega_k = \frac{2\pi(cos\beta_k\ )v}{\lambda}, \omega_l = \frac{2\pi(cos\beta_l)v}{\lambda}$$

$$\Delta t = t_2 - t_1;\ \Delta f = f_2 - f_1$$

$f_m = \frac{v}{\lambda}$: The maximum Doppler frequency

- The coherence depends on bandwidth of the signal and the relative variation in time of the signal to the channel:
  - Correlation function : quantizes the coherence of two random variables (rvs) (How similar?)

$p_a = 0$ uncorrelated

$p_a = 1$ Completely correlated

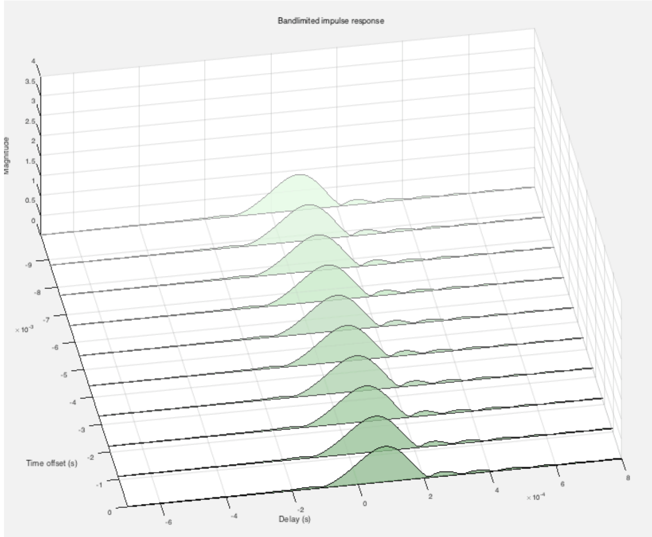
  - Using Rayleigh model and exponential incremental delay, correlation function is a function of large-scale time delay and frequency separation:

$$p_a(\Delta\tau, \Delta f)$$

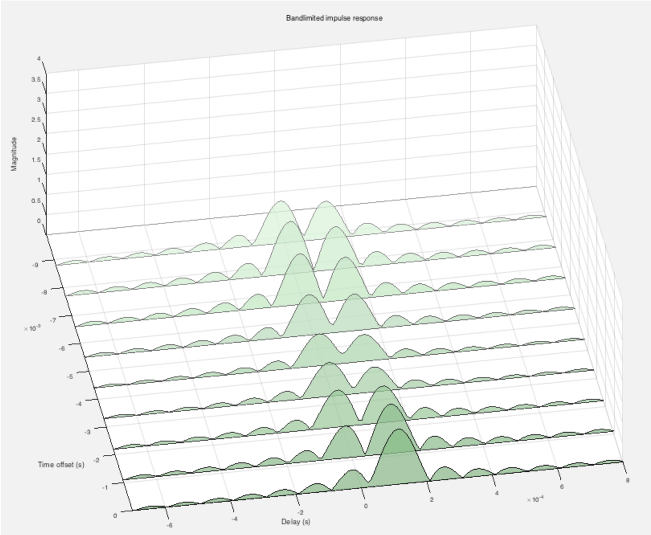
- Coherence bandwidth: is the frequency separation on which $p_a = 0.5$
  - If τ has exponential distribution with average value τ_{av} and $\Delta t = 0$
    - **Coherence bandwidth = $\frac{1}{2}\pi\tau_{av}$**
    - τ_{av} *is average delay spread*

- Coherence time:
  - Channel is a time-variant system due to Doppler effect.
  - Coherence time is the time over which the channel impulse response is considered to be unvarying $\leftrightarrow p_a = 0.5$
  - If τ has exponential distribution with average value τ_{av}
  - Considering the delay spread of one signal: $\Delta f = 0$
    - **Coherence time = $0.18/f_m$**

Fading-Impacts of fading on transmitted signal



$f_m = 1$

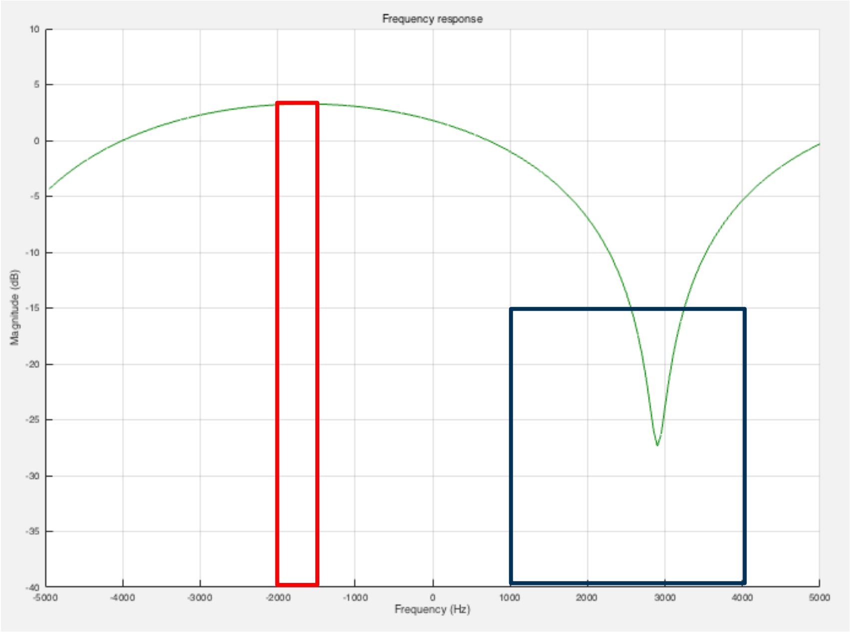


$f_m = 100$

Impulse response of a time-variant channel

- Frequency-selective fading:
  - Different frequency components experience uncorrelated fading
  - Occurs when:

    Signal Bandwidth > Coherence Bandwidth



- Flat fading: when signal bandwidth is narrow
  - Frequency components experience correlated fading

- Time-selective fading:
  - The channel is time-variant due to Doppler effect

  →At different time, the fading varies

  →One transmitted signal experiences different fading conditions

  - Occurs when:

    Signal symbol interval > Coherence time

- In conclusion:

  Fading channel can distort or cancel the transmitted signal.

  → The received signal differs from the original.

  → Receiving errors and/or nothing

Exercise 3.1

- Consider several a delay spread of
  - 0.5 msec
  - 1 msec
  - 6 msec

Determine whether individual multipath rays are resolvable for the two transmission bandwidths:

- 1.25 MHz used in IS-95 and cdma2000
- 5 MHz used in WCDMA

Note: Relation between bandwidth and symbol interval

$B.T = 1$ (Fourier analysis)

Exercise 3.2

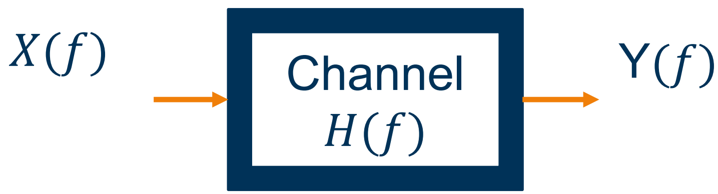
- Indicate the condition for flat fading for each of the following data rates:
  - 8 kbps
  - 40 kbps
  - 100 kbps
  - 6 Mbps
- Indicate which, if any, radio environments would result in flat fading for each of these data rates.

Fading:
Mitigation to fading

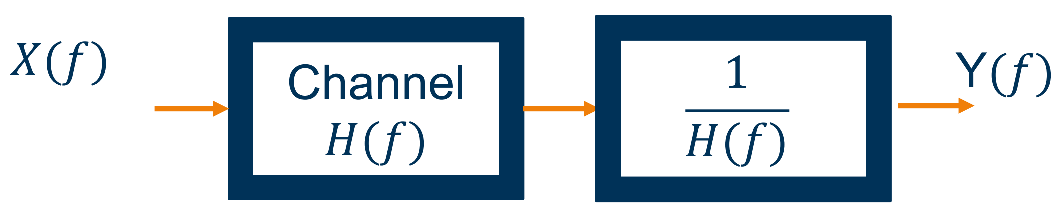
- Mitigation to fading
  - Channel equalization
  - Diversity reception
  - RAKE time-diversity scheme
  - Others:
    - Interleaving
    - OFDM
    - Coding techniques

Mitigation to fading: Equalization technique

- Equalization technique:
  - Carried out at baseband after demodulating received signal
  - Idea:



- No distortion if: $Y(f) = X(f)$
- However, $Y(f) = X(f).H(f)\ and\ H(f) \neq 1$
- Solution:

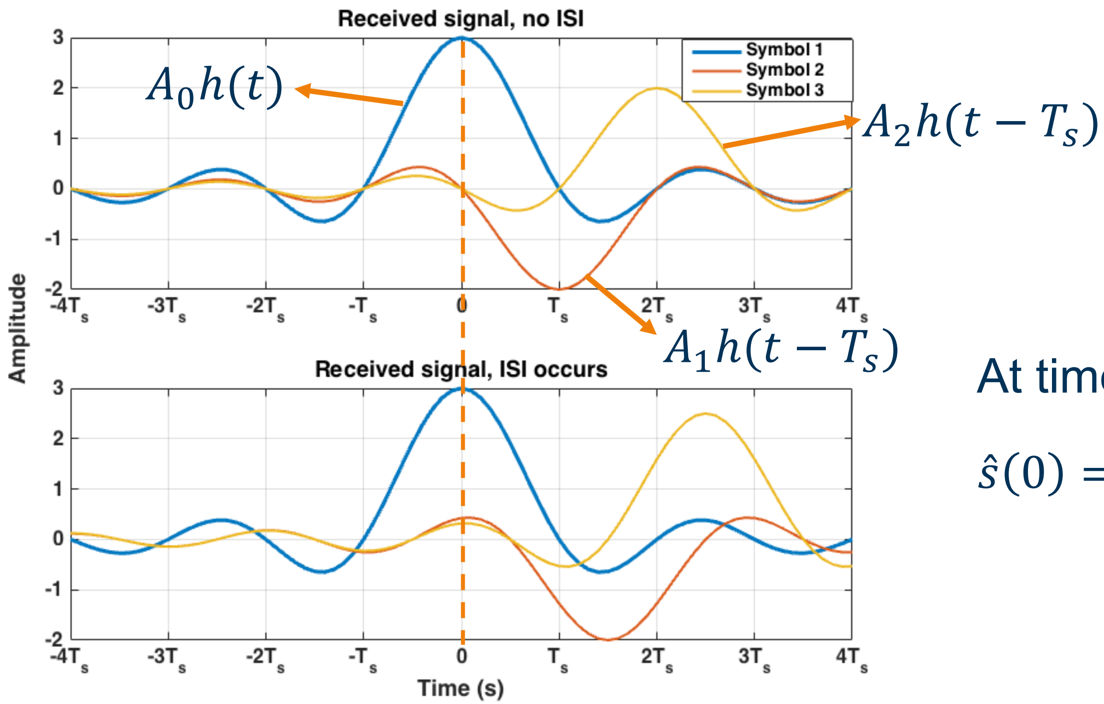


- Operation:
  - Transmitted signal: Pulse Amplitude Modulation (PAM)

$$s(t) = \sum_{k=-\infty}^{\infty} A_k \delta(t - kT_s)$$

  - Received signal after channel: $\hat{s}(t) = s(t) * h(t)$

$$\hat{s}(t) = \sum_{k=-\infty}^{\infty} A_k h(t - kT_s)$$



At time t=0:

$$\hat{s}(0) = A_0 h(0) + \sum_{\substack{k=-\infty \\ k \neq 0}}^{\infty} A_k h(-kT_s)$$

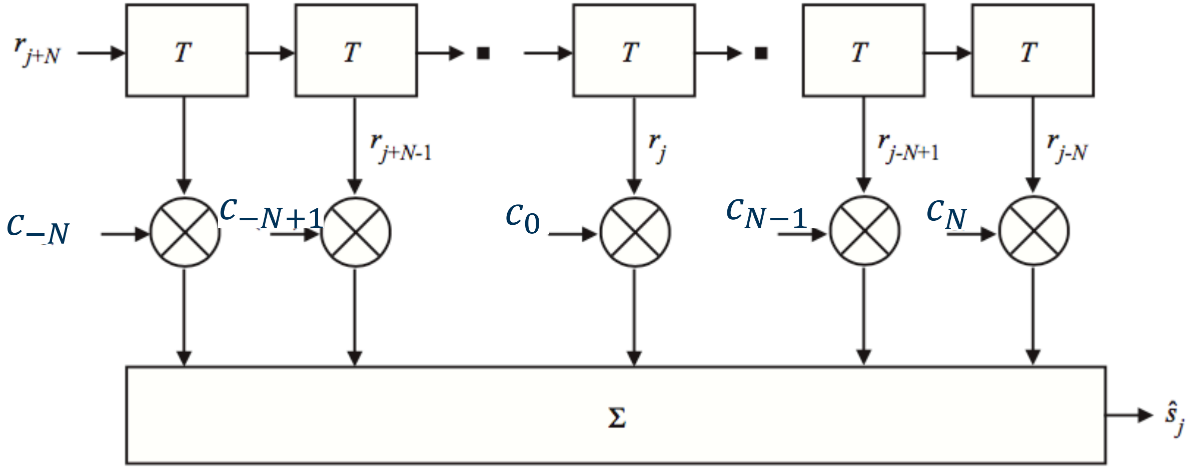
ISI

- Canceling the ISI: $\mathrm{c} = (\mathrm{c}_{-\mathrm{N}}, \mathrm{c}_{-\mathrm{N}+1}, \dots, \mathrm{c}_0, \mathrm{c}_1, \mathrm{c}_2, \dots, \mathrm{c}_\mathrm{N})$

$$A_0 h(0).c_0 = r_j.c_0 = 1$$

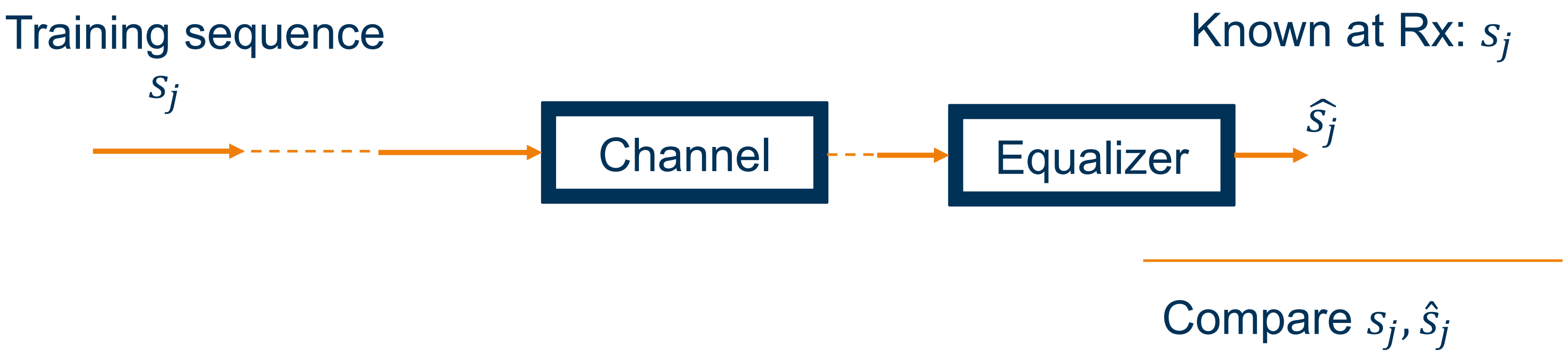
$$\sum_{\substack{k=-N \\ k\neq 0}}^{N} A_k h(-kT_s).c_k = \sum_{\substack{k=-N \\ k\neq 0}}^{N} r_{j-k}.c_k = 0$$

- At each symbol interval j:



Transversal filter Equalizer

- How to identify c?
  - Training sequence K bits long: known at both Tx and Rx
  - Compare transmitted and estimated sequence of bits:



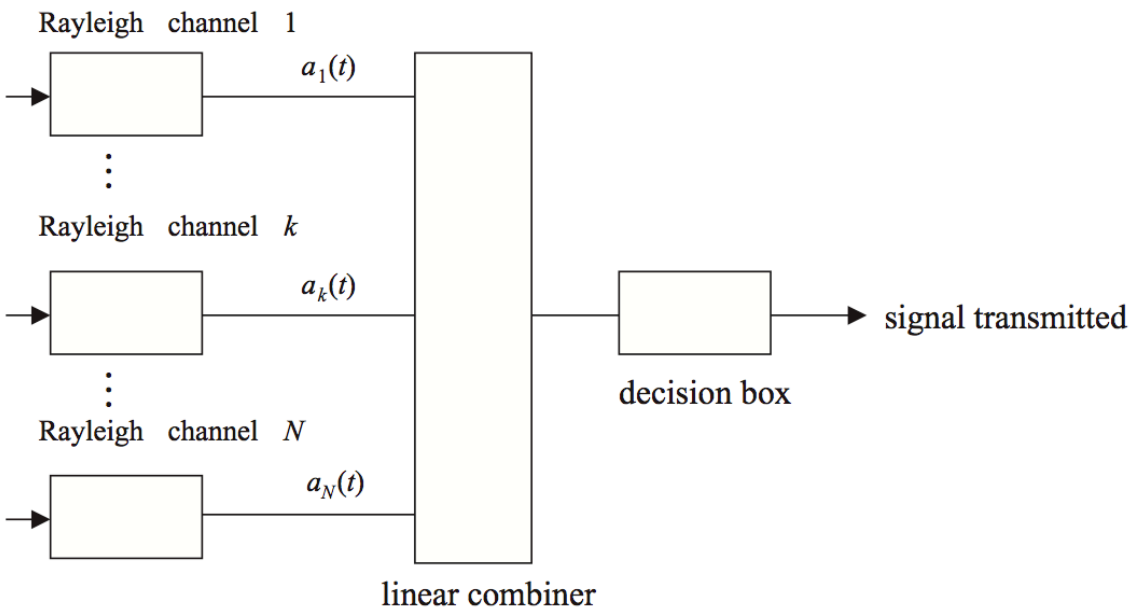
- How to compare?

Min. Mean-Squared Objective
Find c_k, $-N \leq k \leq N$, such that $\sum_{j=1}^{K}(s_j - \hat{s}_j)^2$ is minimum

Mitigation to fading: Diversity reception

- Diversity reception:
  - Space diversity
  - Frequency diversity
  - **Time diversity: RAKE-receiver**
  - Angle diversity
  - Polarization diversity

- General form of diversity reception



- Frequency diversity:
  - OFDM
  - Spread Spectrum

- RAKE receiver:
  - Improving performance of wideband wireless systems
  - combining separately arriving rays of a signal transmitted over a fading channel