Wireless Communication Fundamentals

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Dr. Chengzhi Li

Suggested Reading

- Chapter 2 “Wireless Communications” by T. S. Rappaport, 2001 (version 2)

- “Rayleigh Fading Channels in Mobile Digital Communication Systems Part I: Characterization”, IEEE Communications Magazine, 1997

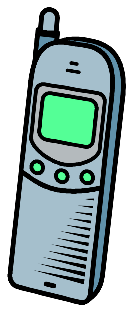
Mobile Devices

Pager
- receive only
- tiny displays
- simple text messages

PDA
- simpler graphical displays
- character recognition
- simplified WWW

Laptop
- fully functional
- standard applications

Sensors, embedded controllers



Mobile phones
- voice, data
- simple graphical displays

Palmtop
- tiny keyboard
- simple versions of standard applications

Frequencies for Mobile Communication

RADIO	IR	VISIBLE	UV	X-RAYS	GAMMA RAYS

0 300GHz

VLF	LF	MF	HF	VHF	UHF	SHF	EHF

3k 30k 300k 3M 30M 300M 3G 30G 300GHz

VLF: Very Low Frequency
LF : Low Frequency
MF : Medium Frequency
HF : High Frequency
VHF: Very High Frequency
UHF: Ultra High Frequency
SHF: Super High Frequency
EHF: Extremely High Frequency

Some US Frequency Allocations

Submarine Communications: 30 kHz

Navigation (Loran C): 100 kHz

AM Radio: 540 – 1,600 kHz (medium wave)

Tactical Comms/Radio Amateur: 3 – 30 MHz (short wave)

Cordless Phones: 46 - 49 MHz (FM) or 902-928 MHz &
2.4 - 2.4835 GHz (Spread Spectrum)

FM Radio: 88 – 108 MHz

TV: 54 – 216 MHz (VHF) & 420 – 890 MHz (UHF) [not contiguous]

Cellular: 824 - 894 MHz (UHF) [not contiguous]

PCS: 1.85- 1.99 GHz (UHF) [not contiguous]

Satellite Comms: SHF

Wireless LAN's: ISM bands

ISM = Industry, Science & Medicine - transmit power of 1 watt or less.

ISM Bands:

902 --- 928 MHz
2.4 --- 2.4835 GHz
5.725 --- 5.850 GHz

Time-Domain View of Signals

- A generic sine wave $s(t) = A \cdot \sin(2\pi f t + \phi)$

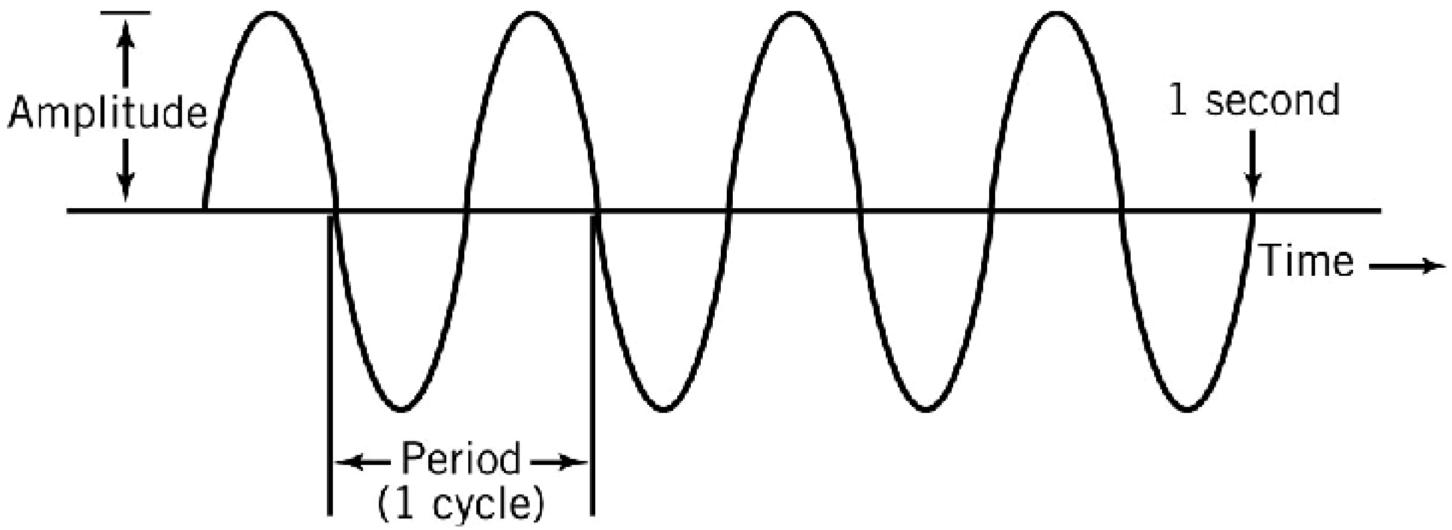
  – Amplitude A: Peak value of a signal at any time.

  – Frequency f: Inverse of the period (f = 1/T) represents number of cycles per second (measured in Hertz (Hz)) i.e., this is the rate at which the signal repeats.

  – Phase ϕ: Relative position within a signal period.

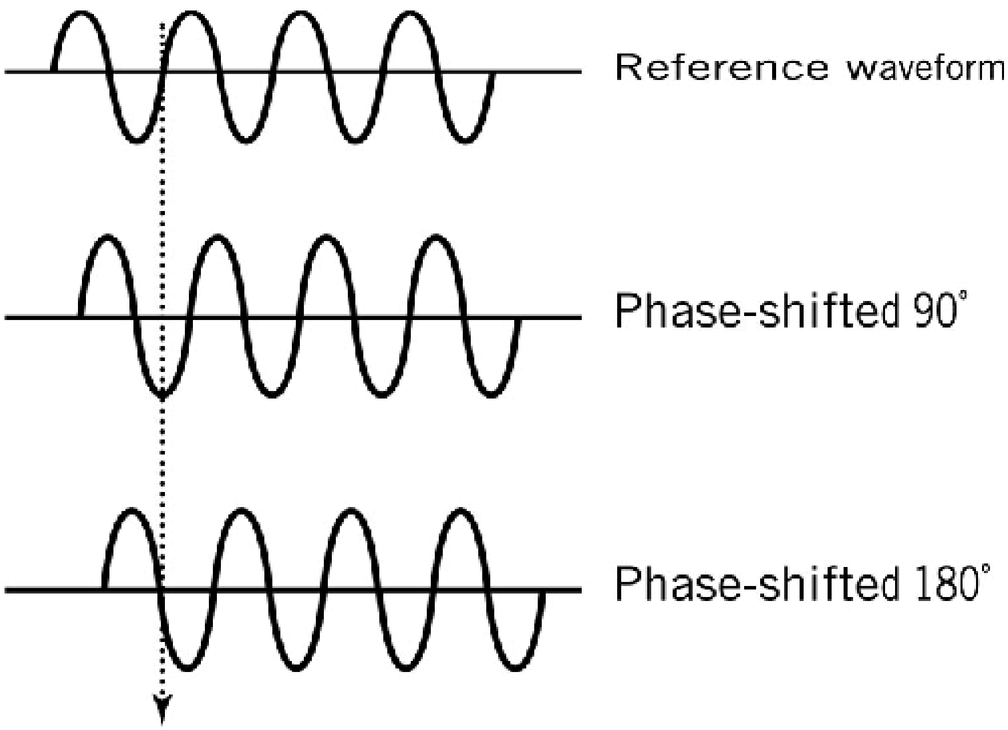
Frequency and Amplitude

- Measure of frequency
- 1 Hertz = 1 cycle/sec
  - Unit of bandwidth for analog device
  - Frequency of sine wave in diagram: 4Hz



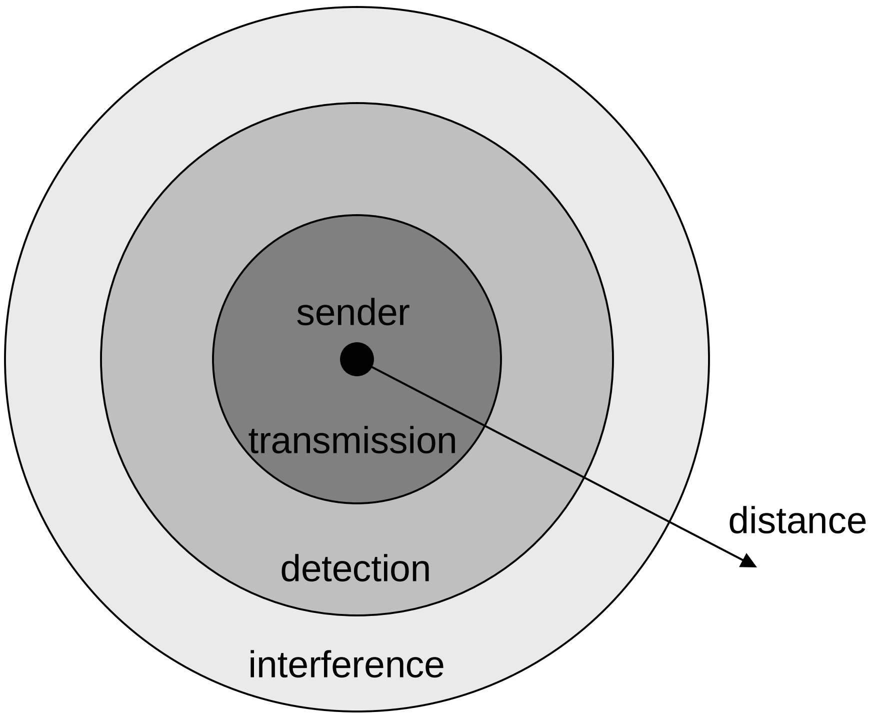
Phase

- Difference, measured in degrees, from a reference sine wave



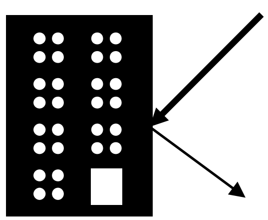
Signal Propagation Ranges

- Transmission range
  - communication possible
  - low error rate
- Detection range
  - detection of the signal possible
  - no communication possible
- Interference range
  - signal may not be detected
  - signal adds to the background noise



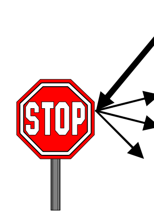
Propagation Mechanisms

- **Reflection:** propagation wave reflected by object larger than wavelength
- **Diffraction:** wave obstructed by surface with sharp, irregular edges
- **Scattering:** wave hits loose objects smaller than wavelength; signal scattered in bunch of outgoing weaker signals



reflection

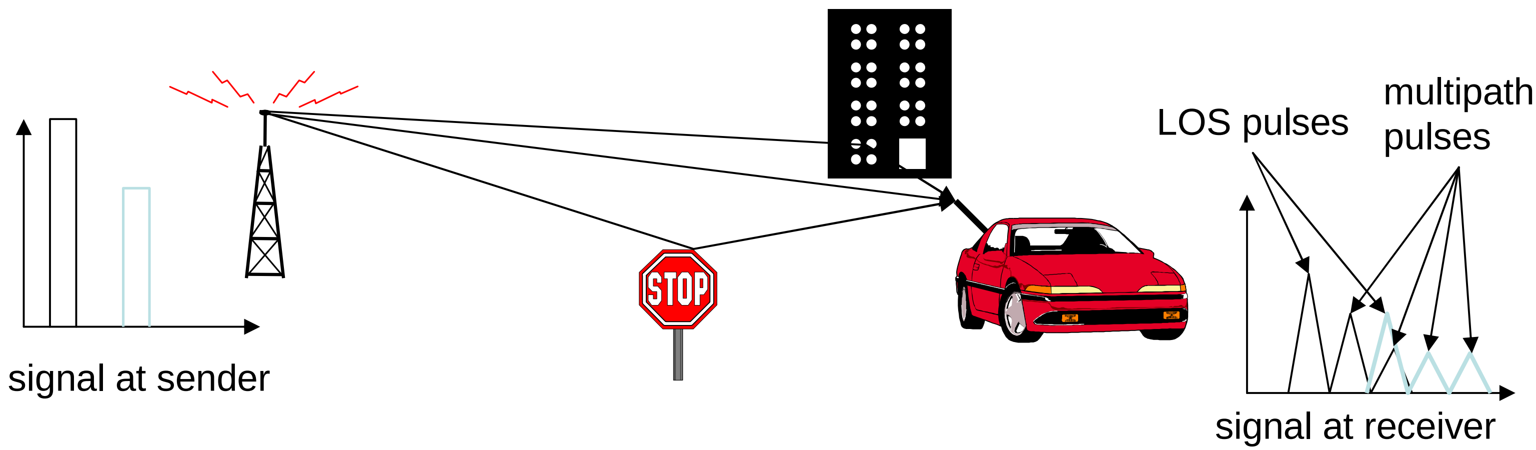
diffraction



scattering

Multipath Propagation

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



- Time dispersion: signal is dispersed over time

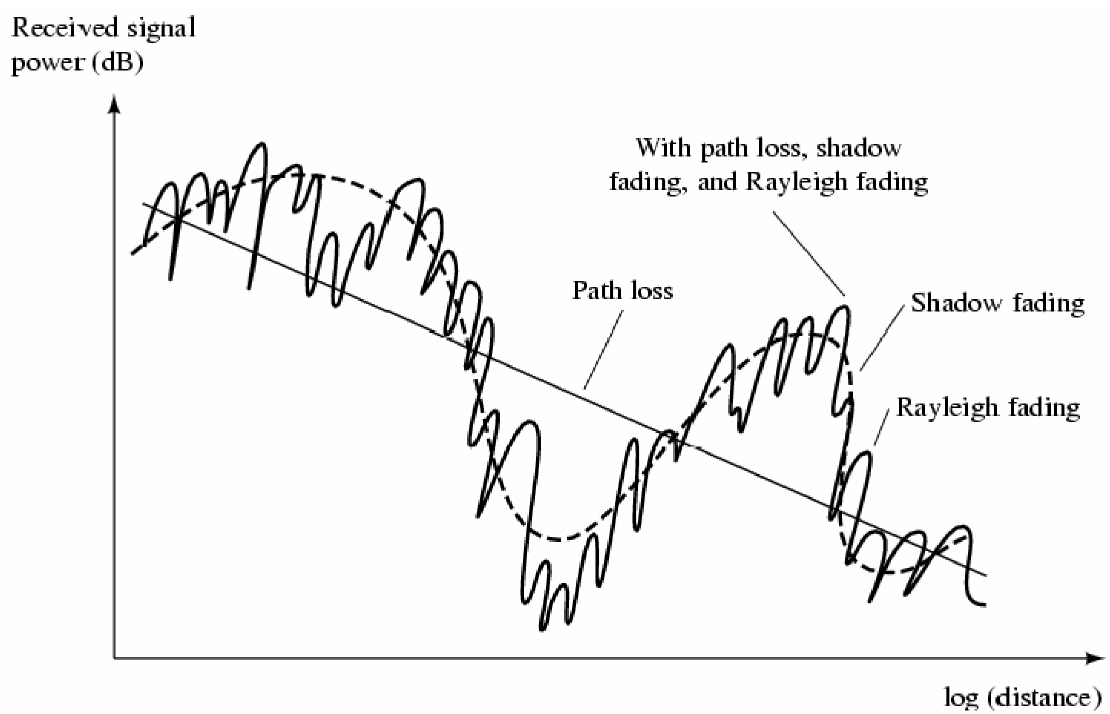
  è interference with "neighbor" symbols, Inter Symbol Interference (ISI)

è the transmission rate R is limited by the delay spread

Propagation Models

- Large scale propagation model
  - Predict the mean signal strength over the distance between transmitter and receiver (path loss)

- Small scale propagatio model
  - Characterize the fluctuations of signal strength over very short travel distances or very short time period (multipath fading)



Large Scale Propagation Models

- Propagation in free space:
  - Friis free space equation:

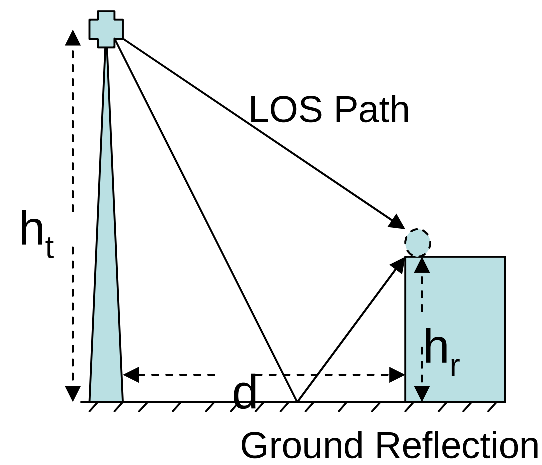
$$P_r = P_t \left(\frac{\lambda}{4\pi d} \right)^2 g_t g_r$$

P_t = transmit power
g_t, g_r = transmit/receive antenna gains
d = distance between the antennas

- Propagation along the earth's surface:
  - 2-ray model

$$P_r = P_t \left(\frac{h_t h_r}{d^2} \right)^2 g_t g_r$$

h_t, h_r = transmit/receive antenna height



Path Loss

- Path Loss (PL)
  - PL = P_t/P_r
  - PL_{dB} = 10*log(PL) = 10*log(P_t /P_r)
- Path Loss Model

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

$$\overline{PL}(d)_{dB} = \overline{PL}(d_0)_{dB} + 10n\log\left(\frac{d}{d_0}\right)$$

- Log-normal Shadowing Model

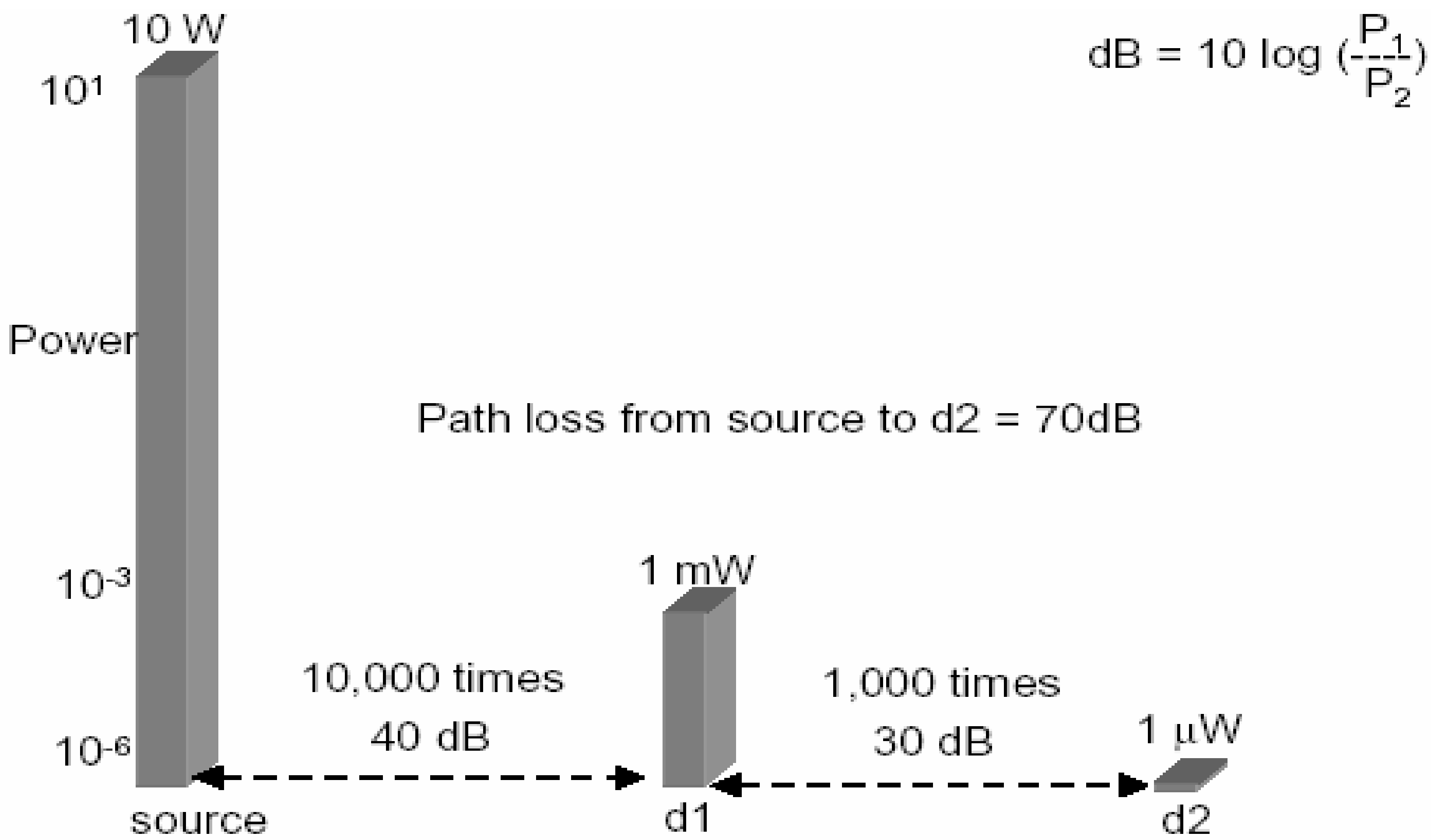
$$PL(d)_{dB} = \overline{PL}(d_0)_{dB} + 10n\log\left(\frac{d}{d_0}\right) + X_s$$

Path loss exponents	
Free space	2
Urban area	2.7 to 3.5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6

n :path loss exponent
d_0 :close-in reference distance
X_σ :zero mean Gausian random variable

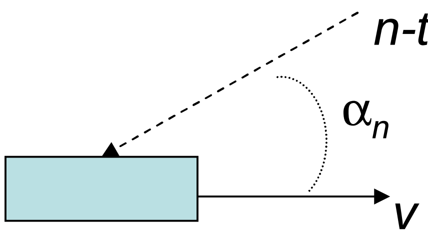
$1/(2\pi\sigma)^{0.5} \exp[\ \{-x^2/2\sigma^2\}]$

Example for Path Loss



Doppler Effect

- Caused by
  - the speed of mobile
  - speed of surrounding objects
    - If the surrounding objects move at a greater speed than the mobile, this effect dominates, otherwise it can be ignored
- Doppler shift
  - Mobile moving towards the transmitter with speed *v*: a maximum positive Doppler shift
  - The *n-th* path, moving within an angle α_n, has a Doppler shift of



$$f_d^{max} = \frac{v}{l}$$

$$f_d = \frac{v}{l}\cos(a_n)$$

  - If mobile moves away from transmitter, the frequency of received signal will be fr = fc - fd
  - If mobile moves towards transmitter, the frequency of received signal will be fr = fc + fd

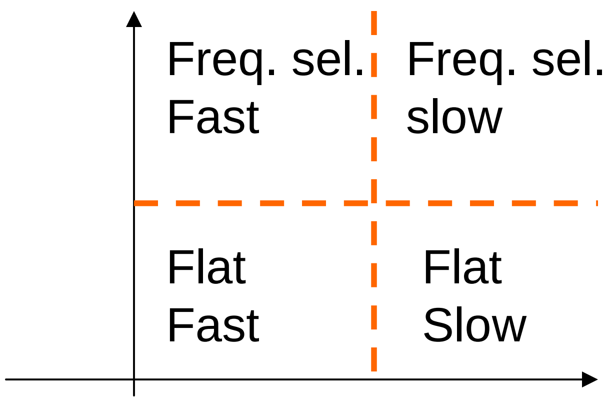
Classification of Small Scale Fading

Small Scale Fading (Based on multipath delay spread)

Flat Fading	Frequency Selective Fading
Delay Spread < Symbol period	Delay Spread > Symbol period

Small Scale Fading (Based on Doppler spread)

Fast Fading	Slow Fading
1/Doppler Shift < Symbol period	1/Doppler Shift > Symbol period



Two Commonly Used Small Scale Channel Fading Models

- **Rayleigh** Fading Model (Multi paths without LOS signal path**)**

$$p(r) = \begin{cases} \frac{r}{s^2} \exp(-\frac{r^2}{2s^2}) & \text{for r} \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

- **Rician** Fading Model (Multi paths contains one LOS signal path)

$$p(r) = \begin{cases} \frac{r}{s^2} \exp(-\frac{r^2 + a^2}{2s^2}) \mathrm{I}_0(\frac{a\,\mathrm{r}}{s^2}) & \text{for r} \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

r: envelope amplitude of received signal

$2\sigma^2$: $E(r^2)$ mean power of multipath signal

a: peak amplitude of the dominant signal

I_0 : Zero ordered modified Bessel Function

Digital Modulation

- Modern wireless systems use digital modulation
- Three types of digital modulation
  - Amplitude shift keying (ASK)
  - Frequency shift keying (FSK)
  - Phase shift keying (PSK)

Modulation Examples

- M-ary Phase Shift Keying (MPSK)
  - Phase modulation

$$S_i(t) = A\cos(2\pi f t + q_i),\ 0 \le t \le T,\ i = 1,2,\cdots,M$$

  - $\log_2 M$ bits encoded into one symbol

  - Examples
    - BPSK: $q_1 = 0,\ q_2 = p$
    - QPSK: $q_1 = 0,\ q_2 = p/2,\ q_3 = p,\ q_4 = 3p/2$

- M-ary Quadrature Amplitude Modulation (M-QAM)
  - Combining phase modulation and amplitude modulation

$$S_i(t) = A_i\cos(2\pi f t + q_i),\ 0 \le t \le T,\ i = 1,2,\cdots,M$$

Examples for M-QAM

bases functions

$$\left.\begin{aligned} j_1 &= \sin(2pft) \\ j_2 &= \cos(2pft) \end{aligned}\right\}$$