Mobile Networking

Mohammad Hossein Manshaei

manshaei@gmail.com

1393

Processing and Transmitter and Receiver, Wireless Channel, Throughput, Path loss, …

FUNDAMENTALS OF WIRELESS TRANSMISSION

Contents

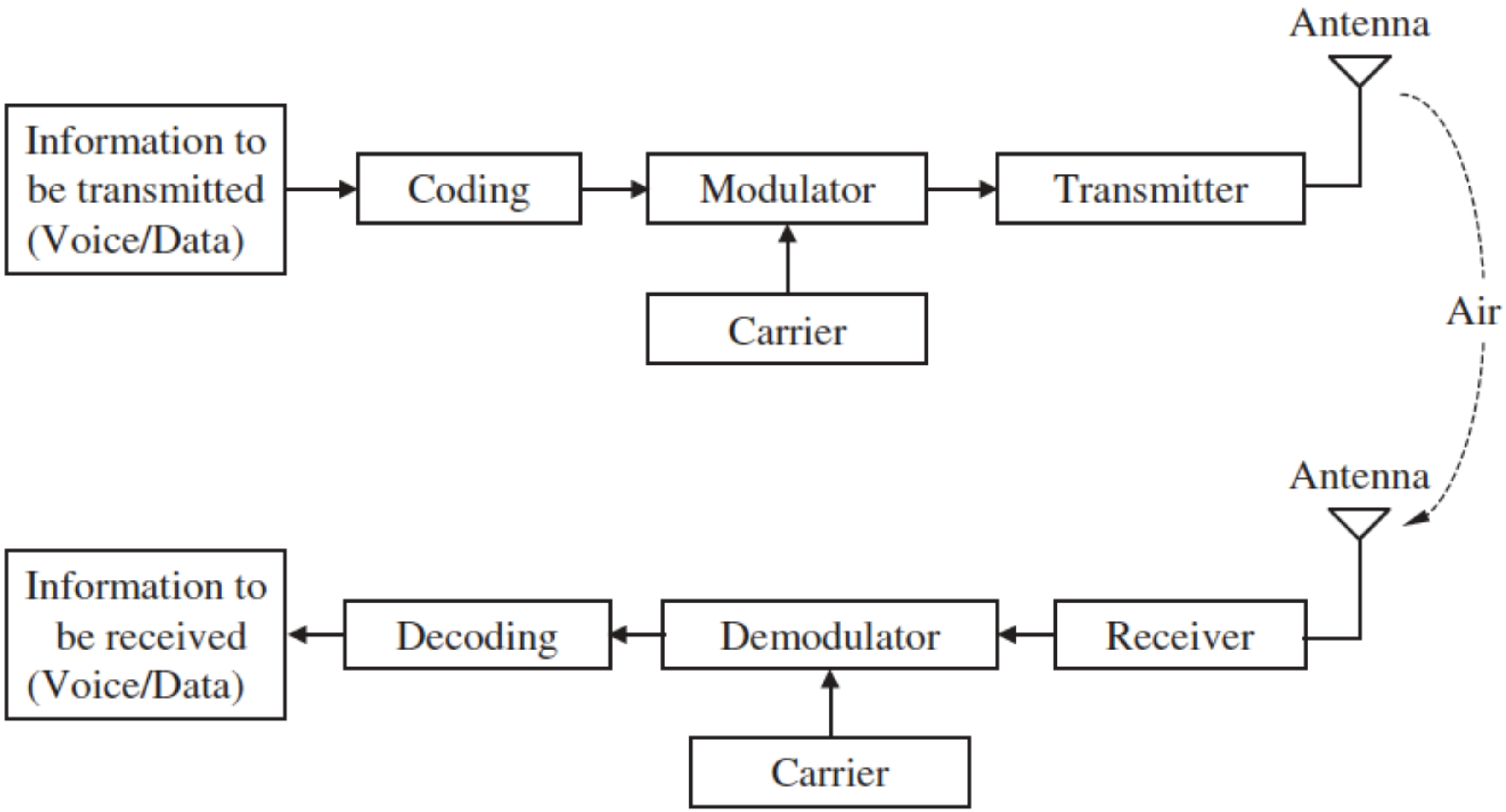
From Application to Physical Layer

PROCESSING AT THE TRANSMITTER

Our Basic Model

- Alice and Bob communicate using a voice-over-IP application
- Their computers are connected by a wireless link
- There are three main phases for the signal:
  - Processing at the Transmitter
  - Propagation through wireless channel
  - Processing at the receiver

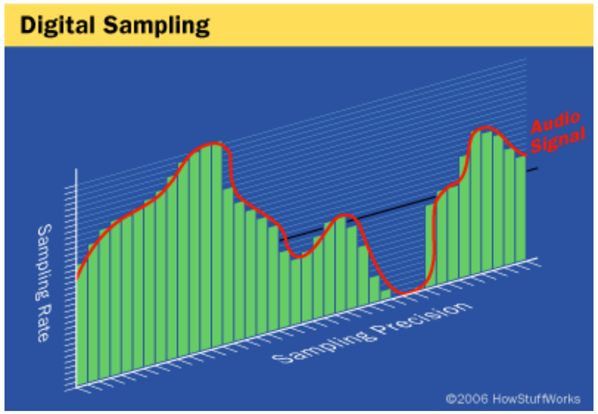
Wireless Communication Link: A Simplified Model



Processing at the Transmitter

1. Digital Representation of Information

- Analog audio signal ➔ Analog electrical signal
- Signal sampling ➔ Binary bits ➔ Symbols

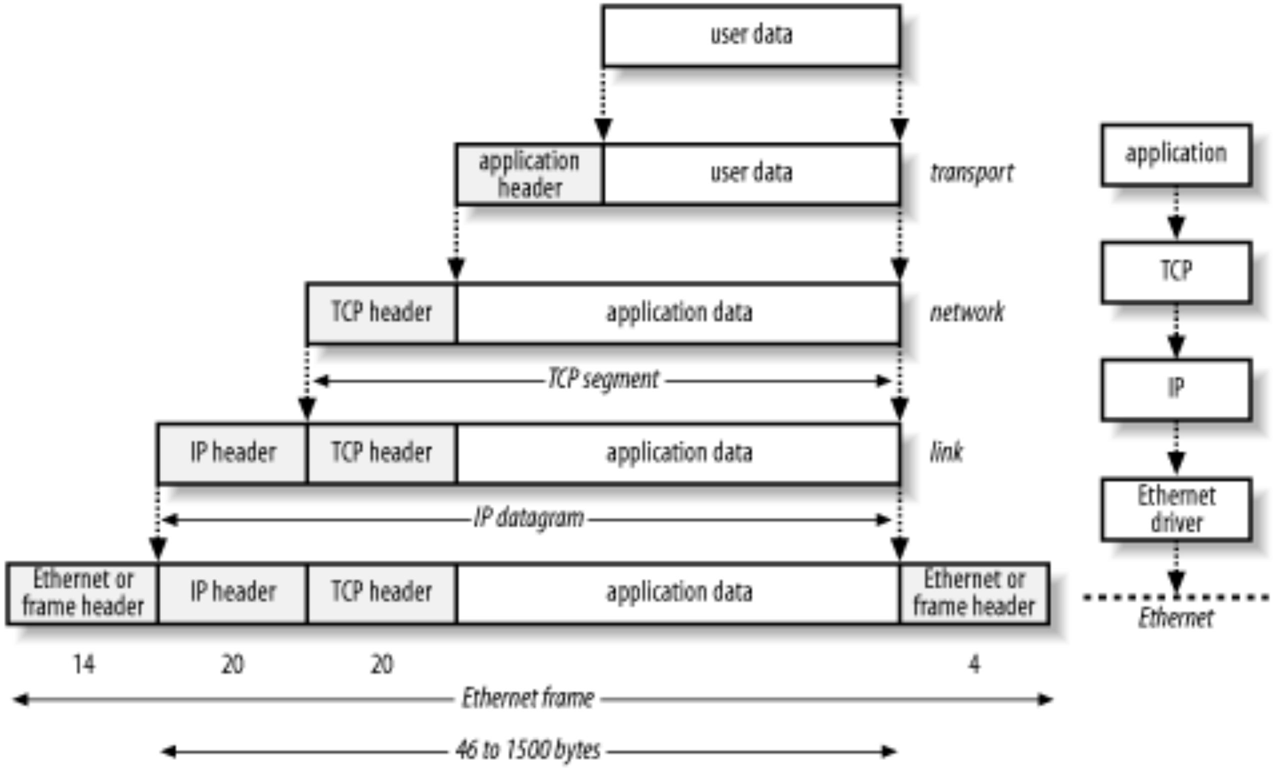


Processing at the Transmitter

2. **Packetization**
   - The bits obtained after source coding are divided into chunks of consecutive bits
   - E.g., each 20 ms of speech to one chunk ➔ 50 packets each second

Processing at the Transmitter

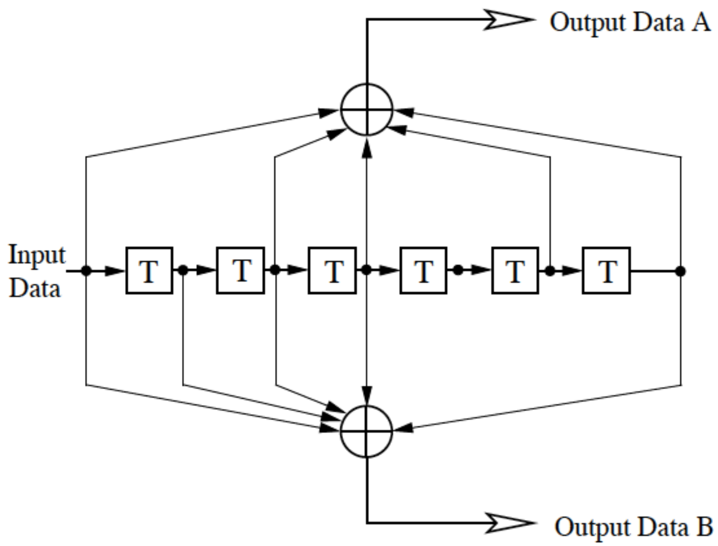
3. **Encapsulation**
   – Add application layer header (e.g., voip header), make transport layer segment (e.g., UDP), make datagram (i.e., adding IP header), and make frame



Processing at the Transmitter

4. Error Control Codes

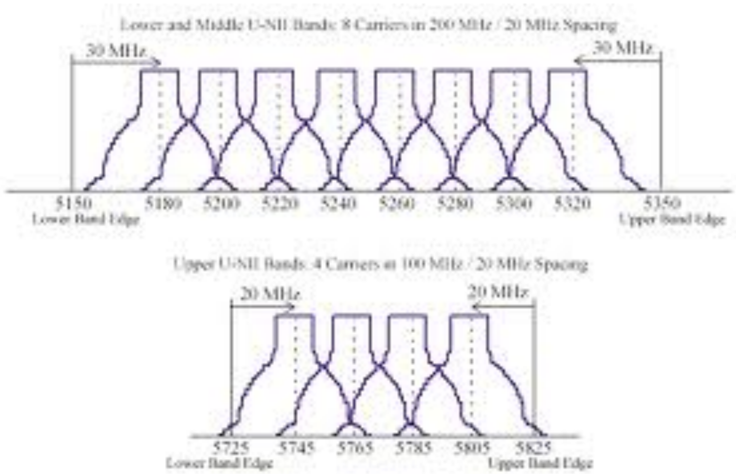
– Add redundancy in the transmitted signal (e.g., Checksum in TCP, Checksum for IP header, CRC in MAC header, and convolutional code in 802.11a PHY layer)

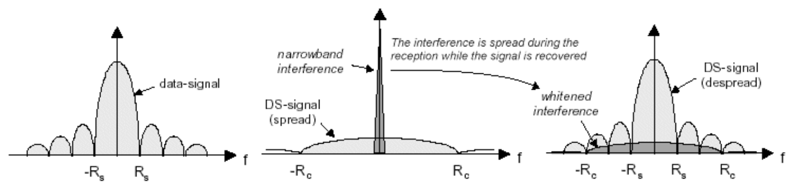


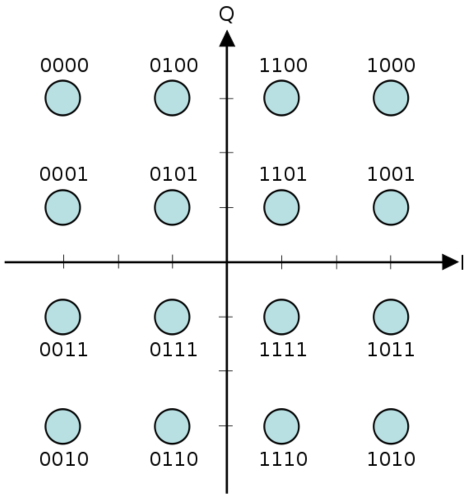
Processing at the Transmitter

5. Modulation

– The process by which the packet to be transmitted is encoded on a “carrier”.







Contents

- Processing at the Transmitter
- The Wireless Channel
- Processing at the Receiver
- Noise
- Mobile Radio Propagation
- Throughput Limit for a Wireless Link

How to model?

THE WIRELESS CHANNEL

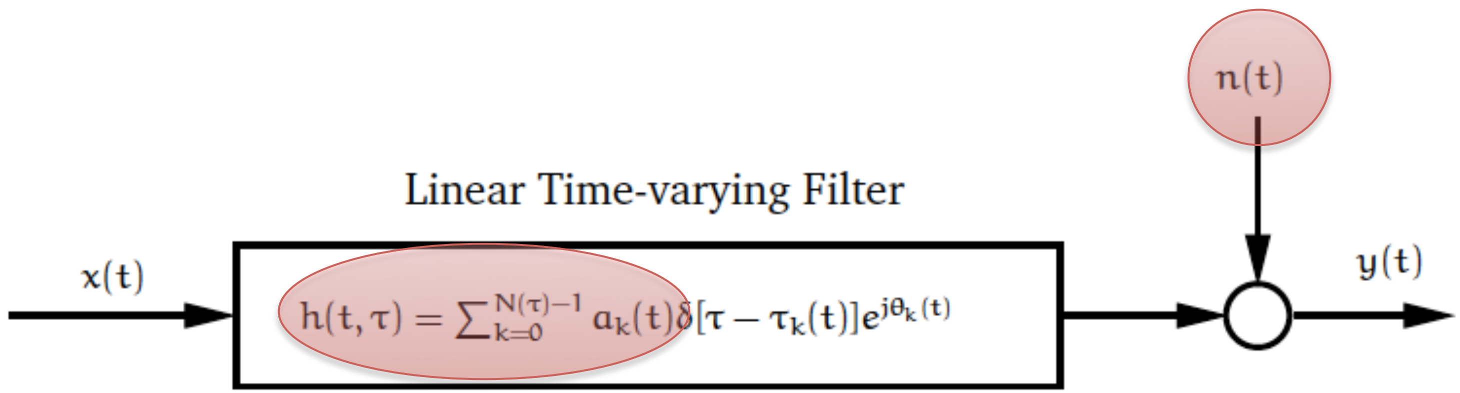
Wireless Channel

- The received signal is different from the transmitted signal:
  1. **Channel Characteristics** (e.g., signal attenuation, signal reflection, scattering, …)
  2. **Noise** (e.g., thermal noise by communication hardware)
  3. **Interference** (e.g., simultaneous transmissions)

Wireless Channel: A Simple Model

$$r(t) = \sum_i a_i\, x(t - \tau_i) \;+\; n(t) \;+\; i(t)$$

- Path i having a delay τ_i and attenuation factor a_i
- $i(t)$ is the composite of the interfering signal at receiver at the time t
- $n(t)$ denotes the noise at time t



Contents

- Processing at the Transmitter
- The Wireless Channel
- Processing at the Receiver
- Noise
- Mobile Radio Propagation
- Throughput Limit for a Wireless Link

Processing at the Receiver

- *Demodulation* is performed, to attempt to recover the transmitted symbols
- *Error Detection/Correction* using error control codes used in the channel coding stage
- Error checks at *MAC, IP and Transport Layer*
- The *application* layer will translate the received samples of Alice's voice into an audible signal

Contents

- Processing at the Transmitter
- The Wireless Channel
- Processing at the Receiver
- Noise
- Mobile Radio Propagation
- Throughput Limit for a Wireless Link

Brief Review!

NOISE

Categories of Noise

- Thermal Noise
- Intermodulation noise
- Crosstalk
- Impulse Noise

Noise Terminology

- **Intermodulation noise:** occurs if signals with different frequencies share the same medium
  - Interference caused by a signal produced at a frequency that is the sum or difference of original frequencies
- **Crosstalk:** unwanted coupling between signal paths
- **Impulse noise:** irregular pulses or noise spikes
  - Short duration and of relatively high amplitude
  - Caused by external electromagnetic disturbances, or faults and flaws in the communications system

Thermal Noise

- Also called white noise
- Due to agitation of electrons
- Present in all electronic devices and transmission media
- Cannot be eliminated
- Function of temperature
- Particularly significant for satellite communication

Thermal Noise

- Amount of thermal noise to be found in a bandwidth of 1Hz in any device or conductor is:

$$N_0 = \mathrm{k}T\left(\mathrm{W/Hz}\right)$$

  - N_0 = noise power density in watts per 1 Hz of bandwidth
  - k = Boltzmann's constant = 1.3803×10^{-23} J/K
  - T = temperature, in kelvins (absolute temperature)

Additive White Gaussian Noise Process (AWGN)

- *Additive:* Noise adds to the signal
- *Process:* The noise n(t) at each time t is a random variable
- *Gaussian:* n(t) has a Gaussian distribution with zero mean.
  - It is customary to denote the variance of this Gaussian distribution as $N_0/2$

$$p(\mathcal{N} = n) = \frac{1}{\sqrt{\pi N_0}} e^{-\frac{n^2}{N_0}}$$

Additive White Gaussian Noise Process (AWGN)

- *White:* The power spectral density for the noise is "flat" or constant for all frequencies.

- If the bandwidth for the signal of interest is W, then the noise introduced over that bandwidth will have power: $N = N_0 W$ (Watts)

- E.g., W is 10 MHz and N_0 is 8×10^{-21} W/Hz
➔ Noise power equal to 8×10^{-14} Watts or −131dBW or −101dBm

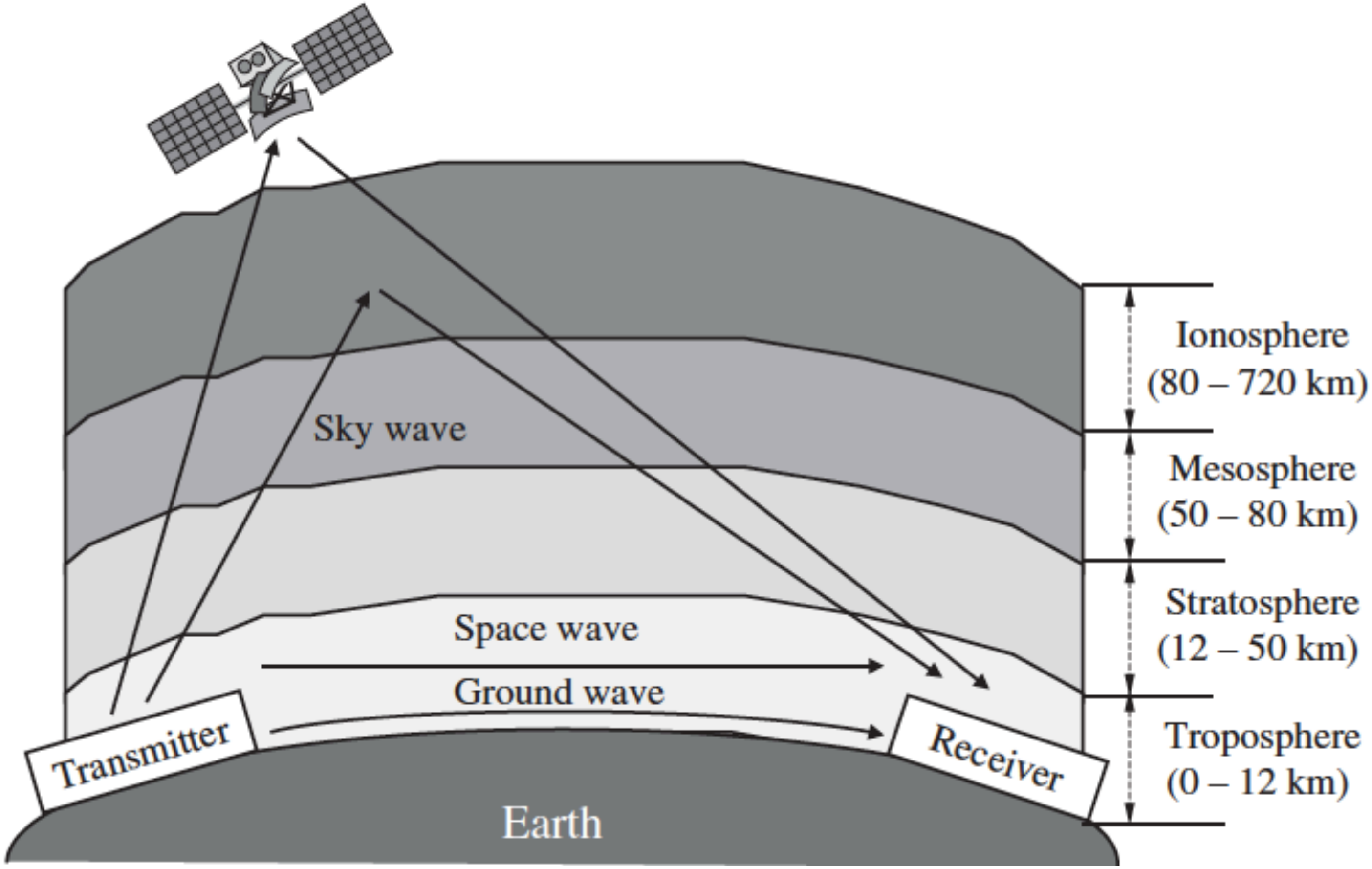
Contents

- Processing at the Transmitter
- The Wireless Channel
- Processing at the Receiver
- Noise
- Mobile Radio Propagation
- Throughput Limit for a Wireless Link

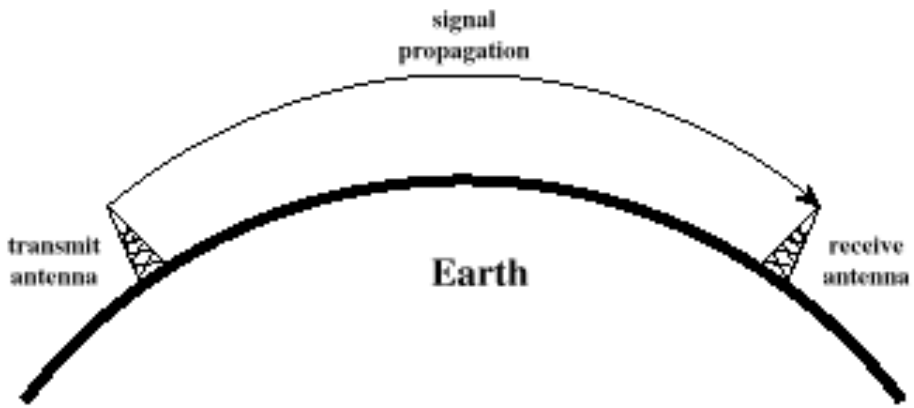
Propagations, Path Loss, Fading, Doppler, …

MOBILE RADIO PROPAGATION

Type of Radio Waves



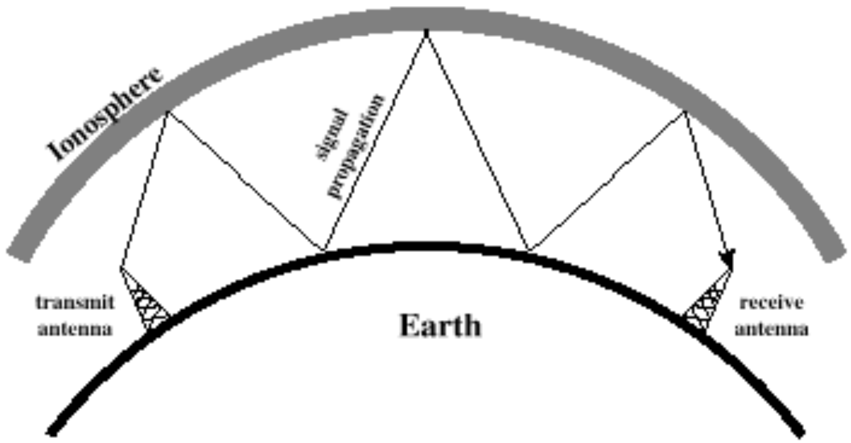
Ground Wave Propagation



Ground Wave Propagation

- Follows contour of the earth
  - The electromagnetic wave induces a current in the earth's surface → the waveform tilts downwards
- Can Propagate considerable distances
- Frequencies up to 2 MHz
- Example
  - AM radio

Sky Wave Propagation



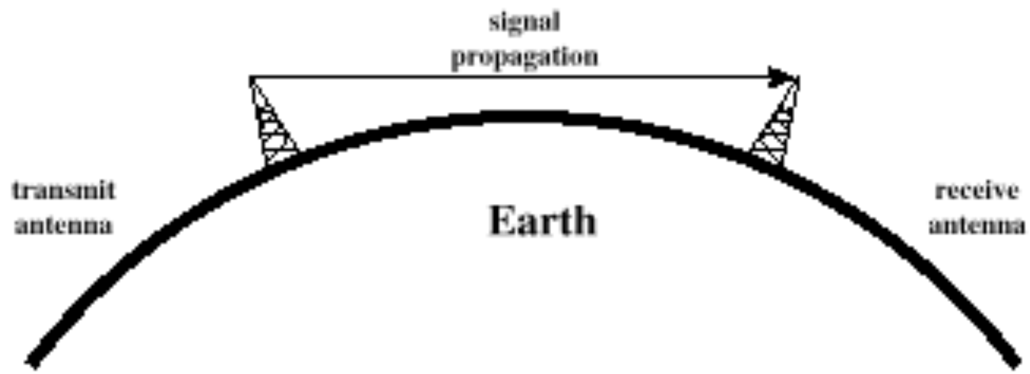
Sky Wave Propagation

- Signal reflected from ionized layer of atmosphere back down to earth
- Signal can travel a number of hops, back and forth between ionosphere and earth's surface
- Examples
  - Amateur radio

Radio Frequency Bands

Classification Band	Initials	Frequency Range	Propagation Mode
Extremely low	ELF	<300 Hz ~3 kHz	Ground wave
Infra low	ILF	300 Hz ~3 kHz	Ground wave
Very low	VLF	3 kHz ~30 kHz	Ground wave
Low	LF	30 kHz ~300 kHz	Ground wave
Medium	MF	300 kHz ~3 MHz	Ground/sky wave
High	HF	3 MHz ~30 MHz	Sky wave
Very high	VHF	30 MHz ~300 MHz	Space wave
Ultra high	UHF	300 MHz ~3 GHz	Space wave
Super high	SHF	3 GHz ~30 GHz	Space wave
Extremely high	EHF	30 GHz ~300 GHz	Space wave
Tremendously high	THF	300GHz ~3000 GHz	Space wave

Line-of-Sight Propagation



Line-of-Sight Propagation

- Required above 30 MHz
- Transmitting and receiving antennas must be within line of sight
  - **Satellite communication** – signal above 30 MHz not reflected by ionosphere
  - **Ground communication** – antennas within *effective* line of site due to refraction

Radio Line-of-Sight

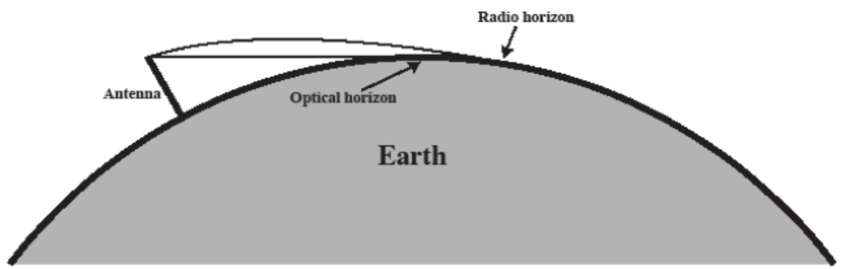
- Optical line of sight

$$d = 3.57\sqrt{h}$$

- Effective, or radio, line of sight

$$d = 3.57\sqrt{\mathrm{K}h}$$

  - *d* = distance between antenna and horizon (km)
  - *h* = antenna height (m)
  - K = adjustment factor to account for refraction, rule of thumb K = 4/3



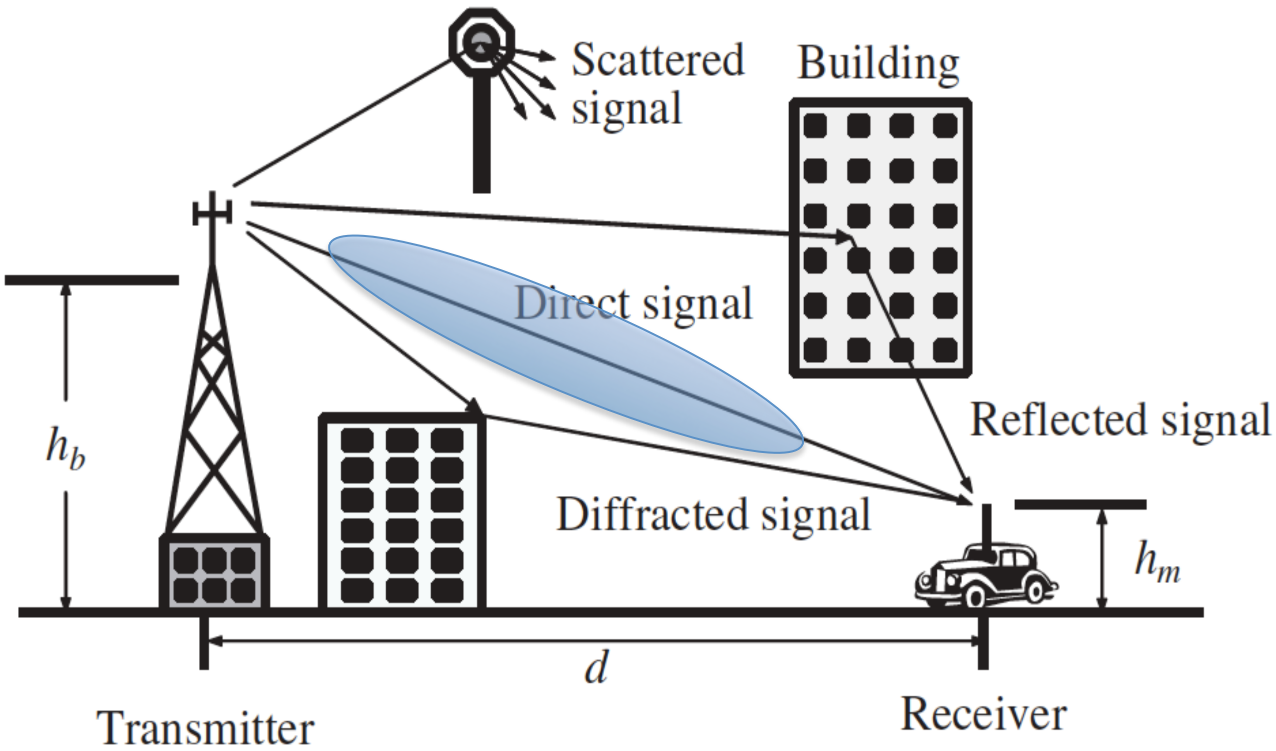
Radio Line-of-Sight

- **Maximum distance** between two antennas for **LOS** propagation:

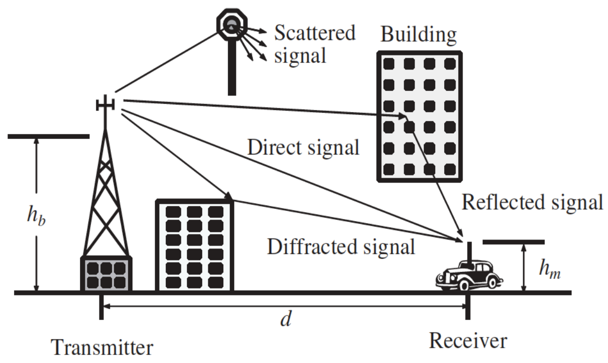
$$3.57\left(\sqrt{\mathrm{K}h_1} + \sqrt{\mathrm{K}h_2}\right)$$

  - h_1 = height of antenna one
  - h_2 = height of antenna two

LOS Propagation Mechanisms



Propagation Mechanisms

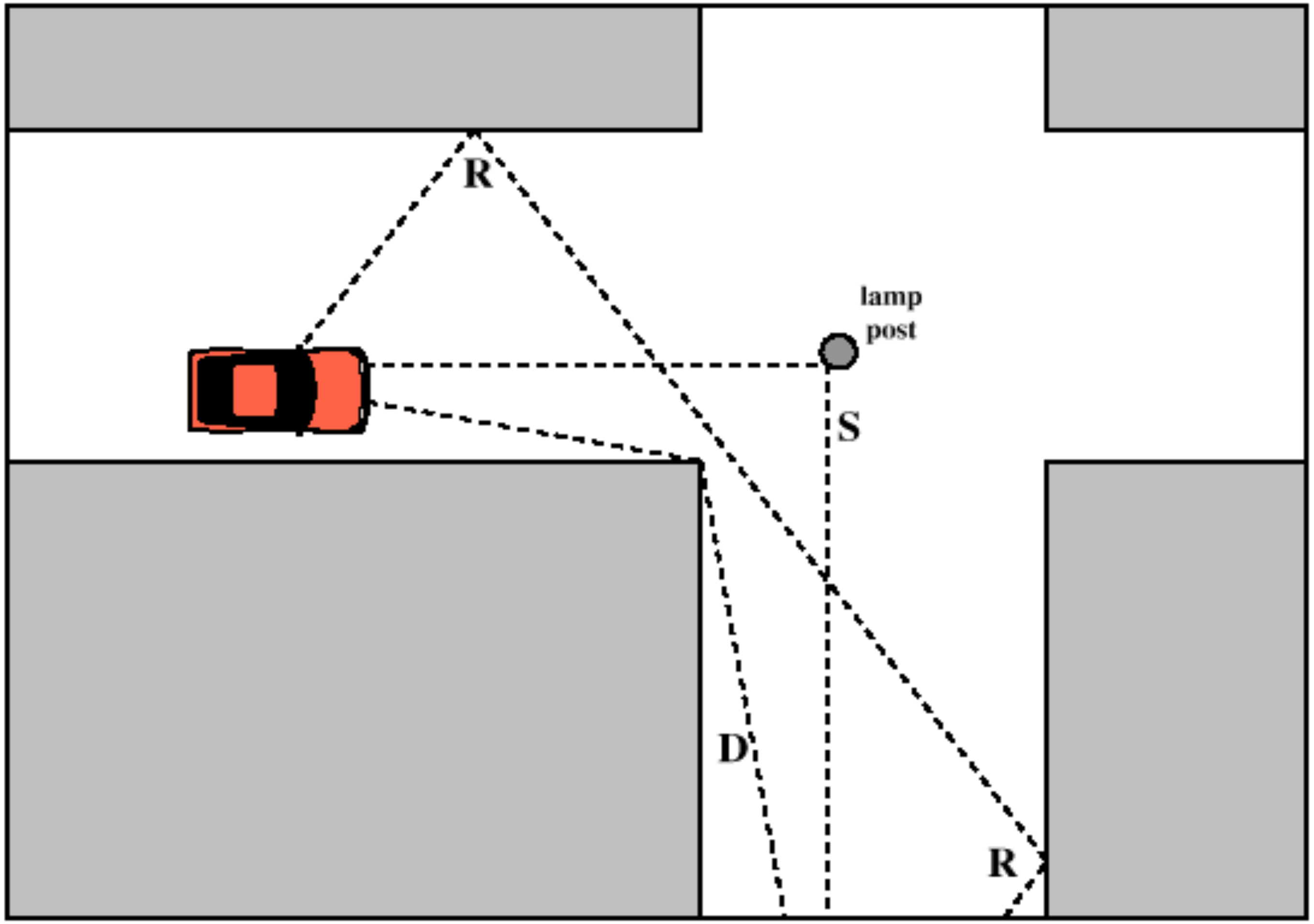


Reflection: Impinges on an object that is larger as compared to its wavelength (for example, the surface of the earth, tall buildings, large walls).

Diffraction: Obstructed by a surface with sharp irregular edges

Scattering: Scattered into several weaker outgoing signals

Reflection, Diffraction, and Scattering



Free Space Propagation

- Received power at distance d, with the effective area covered by the transmitter (A_e), and G_t the transmission antenna gain:

$$P_r = \frac{A_e G_t P_t}{4\pi d^2}$$

- Relation between A_e (effective area covered) and receiving antenna gain (λ is the wavelength of the electromagnetic wave):

$$G_r = \frac{4\pi A_e}{\lambda^2}$$

Free Space Propagation

- The free space path loss L_f is then (i.e., amount of power lost in the space):

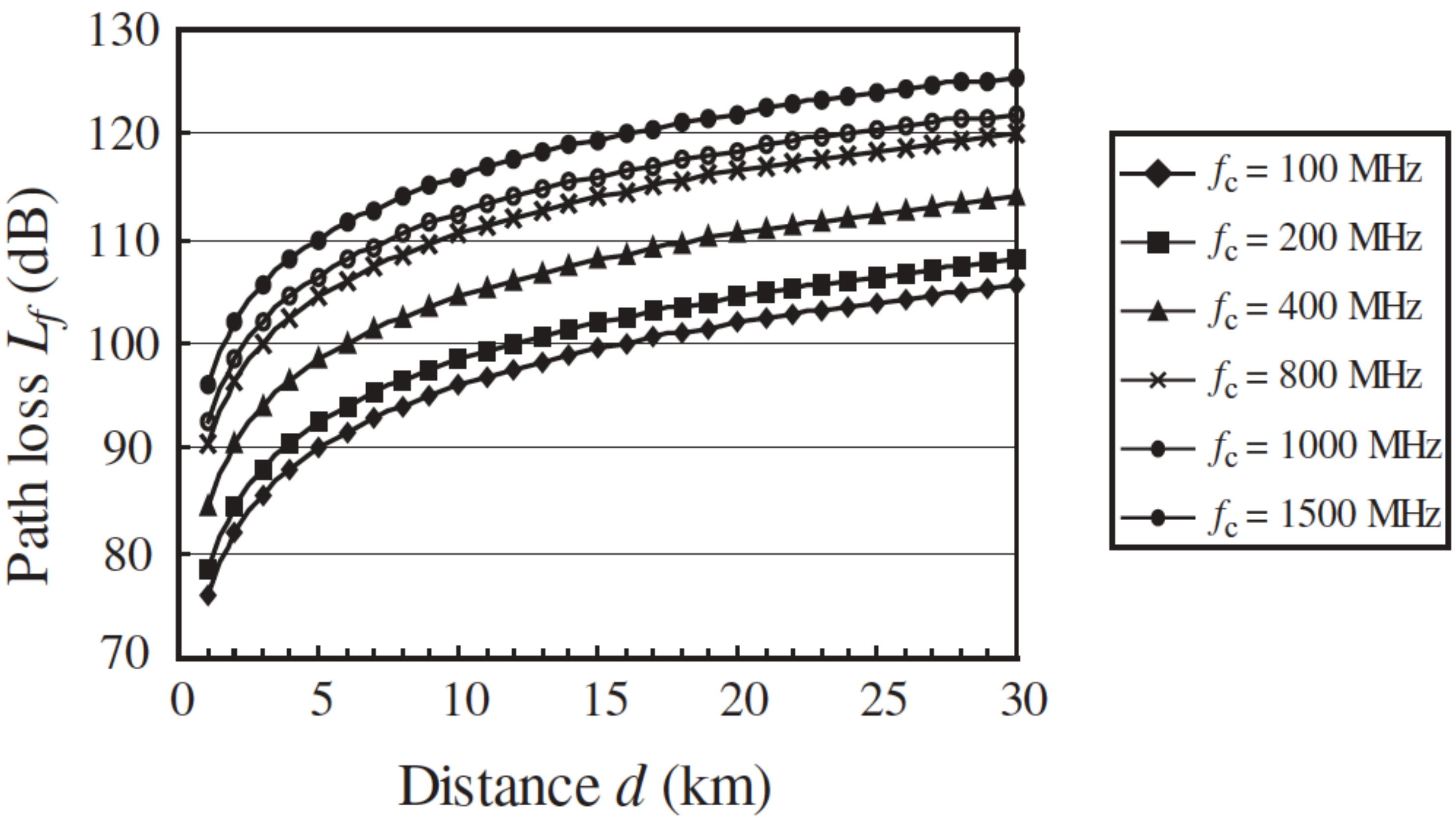
$$L_f = \frac{P_t}{P_r}$$

$$= \frac{1}{G_r G_t} \left(\frac{4\pi d}{\lambda} \right)^2$$

- If $G_r = G_t = 1$ ➔ $$= \left(\frac{4\pi f_c d}{c} \right)^2$$

$$L_f\,(\text{dB}) = 32.45 + 20 \log_{10} f_c\ (\text{MHz}) + 20 \log_{10} d\ (\text{km})$$

Free Space Propagation



Land Propagation

- The signal reaches the destination using many different paths, because of diffraction and reflection from various objects along the path of propagation
- Received signal power: $P_r = \dfrac{G_t G_r P_t}{L}$
- L is the propagation loss in channel:

$$L = L_P L_S L_F$$

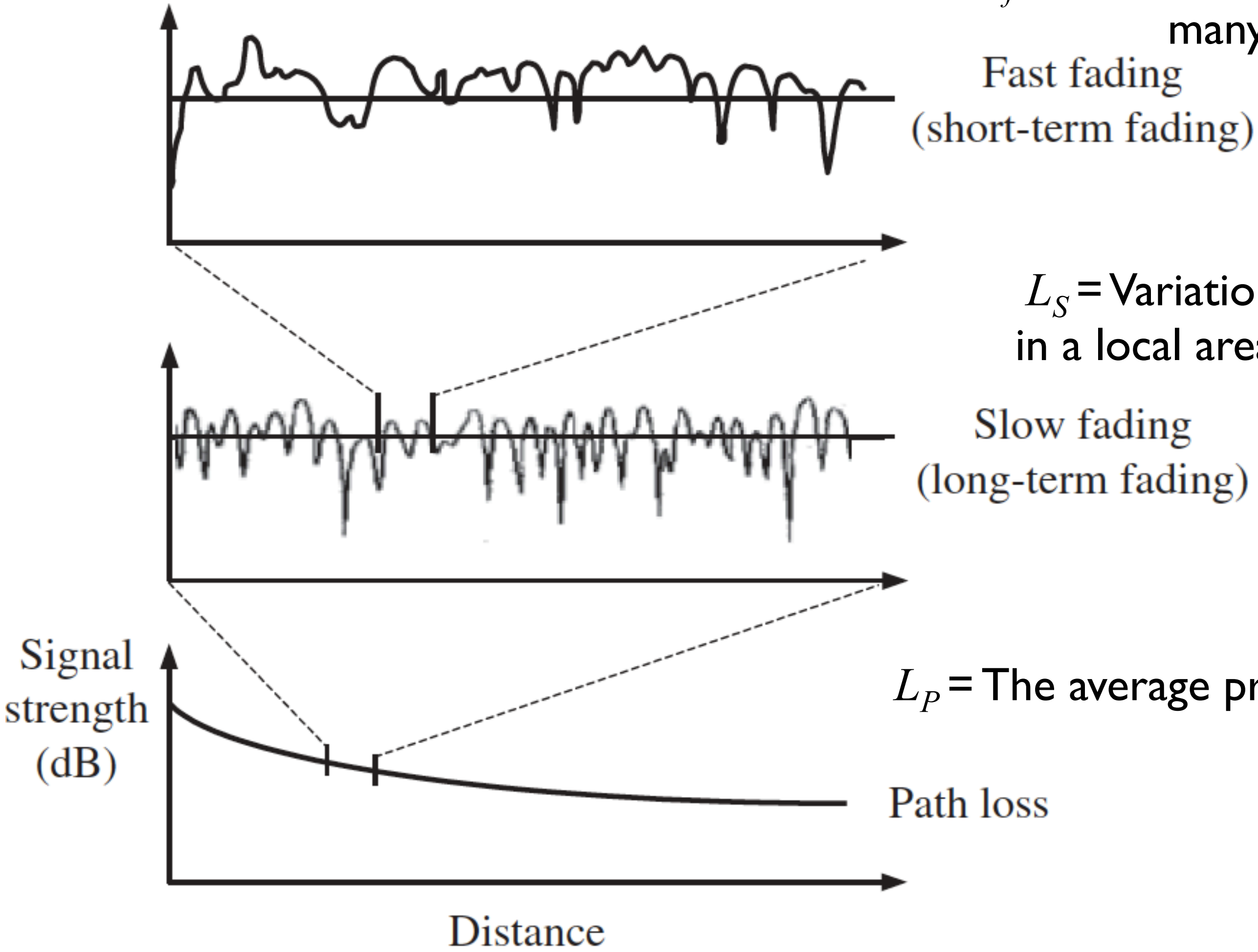
Land Propagation

$$L = L_P \, L_S L_F$$

L_f = The motion of the MS that consists of many diffracted waves

L_S = Variation of the propagation loss in a local area (several tens of meters)

L_P = The average propagation loss over a wide area



Path Loss

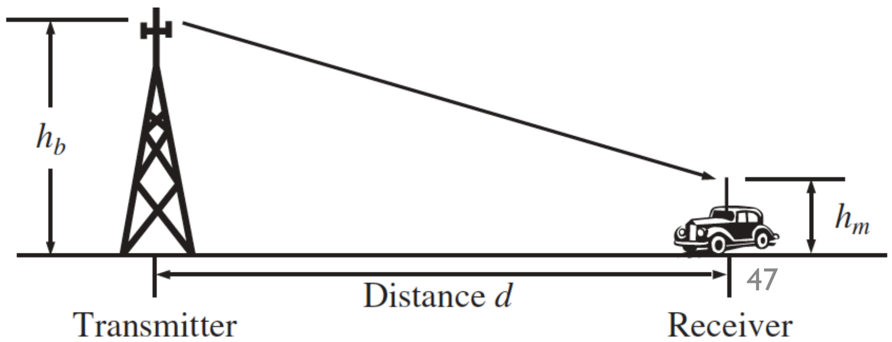
- Simple definition: $$L_P = Ad^{\alpha}$$
- "A" and "α" are propagation constant
- "α" is about 3~4 in typical urban area

Path Loss Example: Urban Area

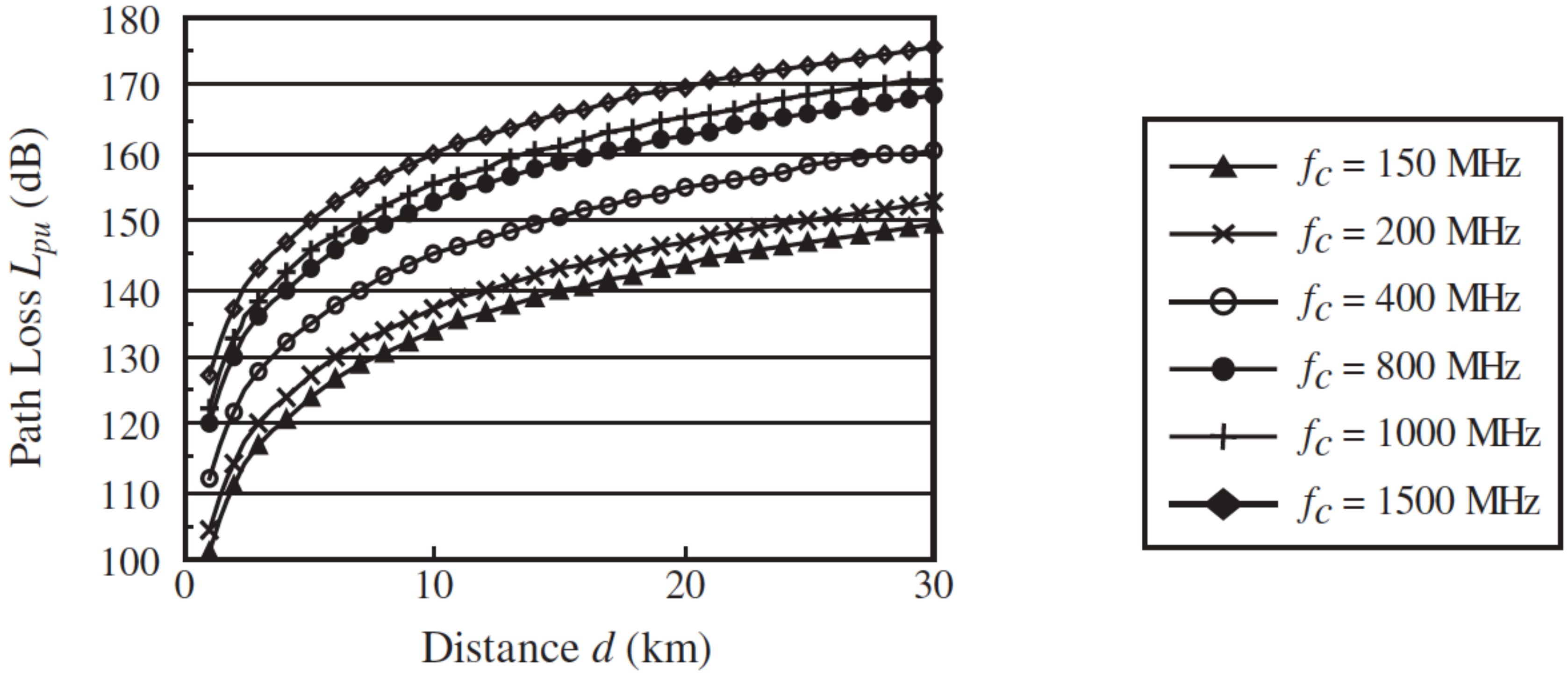
$$L_{PU}(\text{dB}) = 69.55 + 26.16 \log_{10} f_c(\text{MHz}) - 13.82 \log_{10} h_b(\text{m}) - \alpha\,[h_m(\text{m})] + \left[44.9 - 6.55 \log_{10} h_b(\text{m})\right] \log_{10} d\ (\text{km})$$

- Medium and Small Cities: An Example

$$\alpha\,[h_m(\text{m})] = \begin{cases} 8.29\,[\log_{10} 1.54 h_m(\text{m})]^2 - 1.1, & f_c < 300\ \text{MHz} \\ 3.2\,[\log_{10} 11.75 h_m(\text{m})]^2 - 4.97, & f_c > 300\ \text{MHz} \end{cases}$$



Path Loss Example: Urban Area Medium and Small Cities

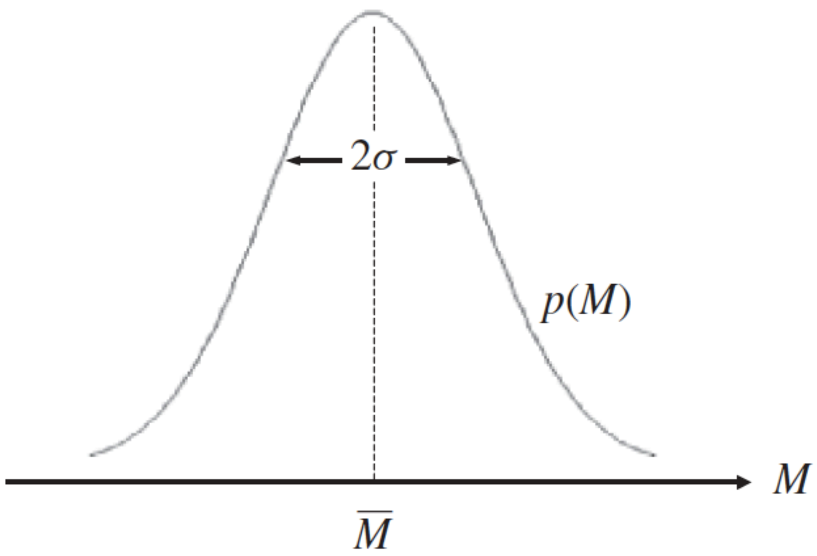


Slow Fading
(Log-normal fading or Shadowing)

- **Long term spatial** and temporal variations over **distances large enough** to produce gross variation in the overall path between the transmitter and receiver

Slow Fading
(Log-normal fading or Shadowing)

- Experiments have indicated that slow fading obeys the log-normal distribution (M is true received signal level)



$$p(M) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{(M-\overline{M})^2}{2\sigma^2}}$$

Fast Fading

- **Scattering** of the signal by object **near** transmitter

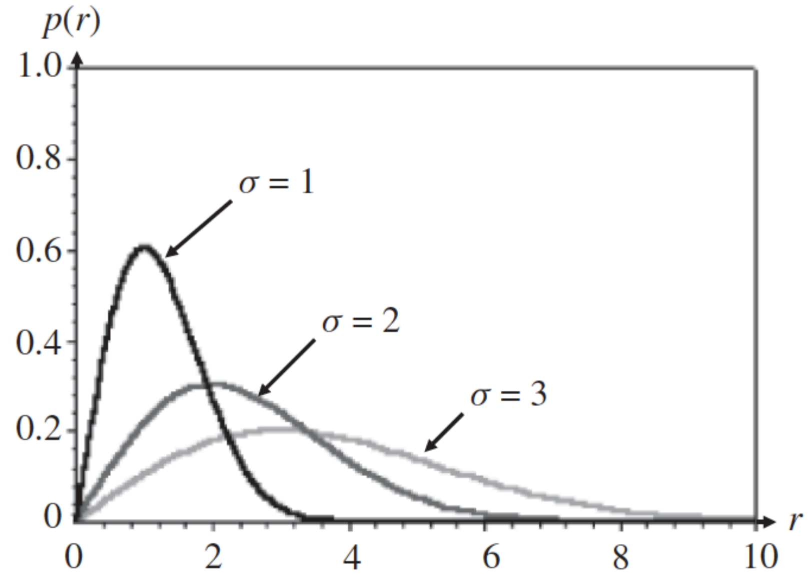
Or

- The **rapid fluctuations** in the spatial and temporal characteristics caused by local multipath are known as fast fading

Fast Fading: Receiver Far from the Transmitter

- **Rayleigh Distribution (No Direct Radio Wave):** Probability distribution of signal amplitude of every path is a Gaussian distribution, and their phase distribution has a uniform distribution within (0, 2π) radians.

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, \qquad r > 0$$

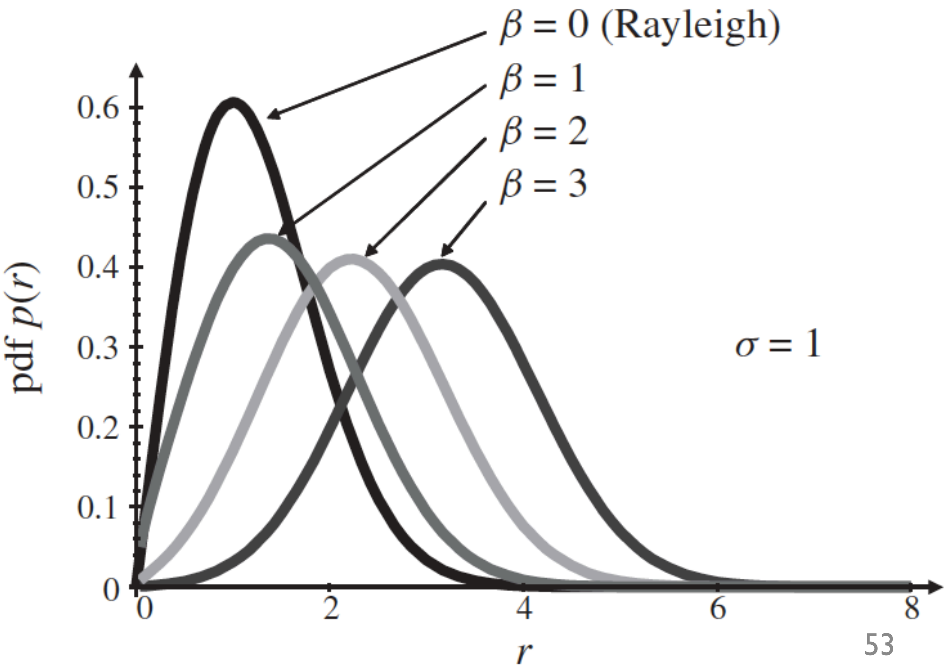


Fast Fading: Receiver Close to the Transmitter

- **Rician Distribution (With Direct Wave):**

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{(r^2+\beta^2)}{2\sigma^2}} \; I_0\left(\frac{\beta r}{\sigma^2}\right)$$

$$I_0(x) = \frac{1}{2\pi} \int_0^{2\pi} e^{x\cos\theta} d\theta \approx \frac{e^x}{\sqrt{2\pi x}}.$$



Nakagami Model: A Generalized Model

$$p(r) = \frac{2r^{2m-1}}{\Gamma(m)} \left(\frac{m}{\Omega}\right)^m e^{-\frac{mr^2}{\Omega}} \qquad \text{for } r \geq 0.$$

- m is fading factor:
  - $m=1$ ➔ Rayleigh Distribution
  - $m \to \infty$ ➔ No fading
- Rician distribution can be approximated by Nakagami

$$m = \frac{(K+1)^2}{2K+1}$$

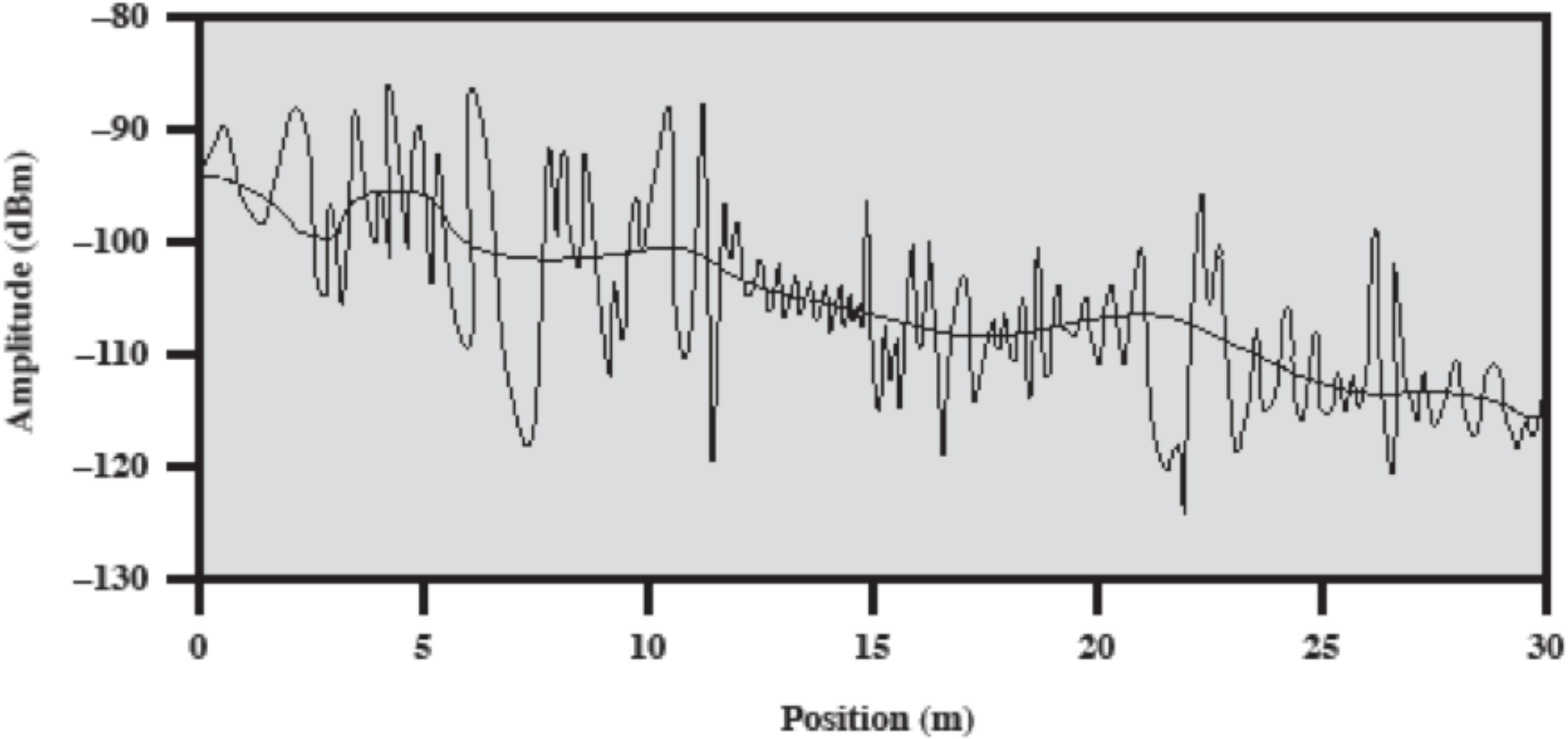
Where K is the rician factor: $K \left(= \frac{\beta}{2\sigma}\right)$

Flat and Selective Fading

- **Flat fading**: All frequency components of the received signal fluctuate in the same proportions simultaneously

- **Selective fading:** Affects unequally the different spectral components of a radio signal

Slow and Fast Fading in an Urban Mobile Environment



Fading Channel Model

No LOS	A LOS	Signal is degraded by thermal noise only
Multiple indirect paths	Multiple indirect paths	$K=\infty$
Outdoor	Indoor	
$K=0$	K	

$$K = \frac{\text{Power in the dominant path}}{\text{Power in the scattered paths}}$$

Signal-to-Noise Ratio

- Ratio of the power in a signal to the power contained in the noise that's present at a particular point in the transmission
- Typically measured at a receiver
- Signal-to-noise ratio (SNR, or S/N)

$$(SNR)_{\mathrm{dB}} = 10\log_{10}\frac{\text{signal power}}{\text{noise power}}$$

- A high SNR means a high-quality signal, low number of required intermediate repeaters
- SNR sets upper bound on achievable data rate

Expression E_b/N_0

- Ratio of signal energy per bit to noise power density per Hertz

$$\frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S}{\mathrm{k}TR}$$

where *S* is the signal power, *R* the bitrate, *k* Boltzmann's constant and *T* the temperature

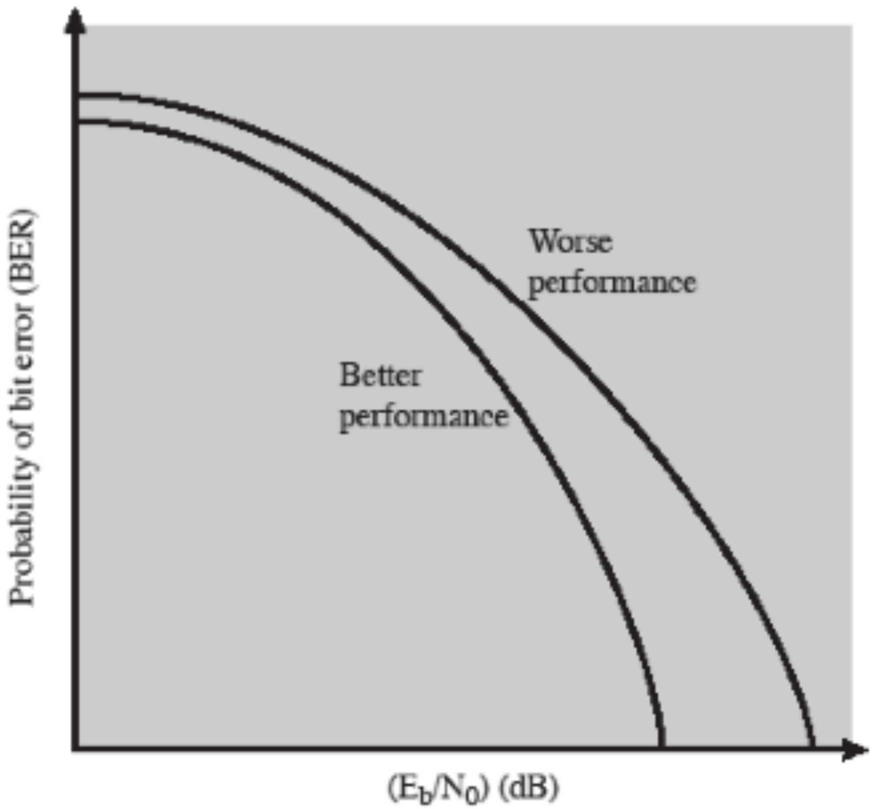
- The bit error rate for digital data is a function of E_b/N_0
  - Given a value for E_b/N_0 to achieve a desired error rate, parameters of this formula can be selected
  - As bit rate *R* increases, transmitted signal power must increase to maintain required E_b/N_0

SNR vs E_b/N_0

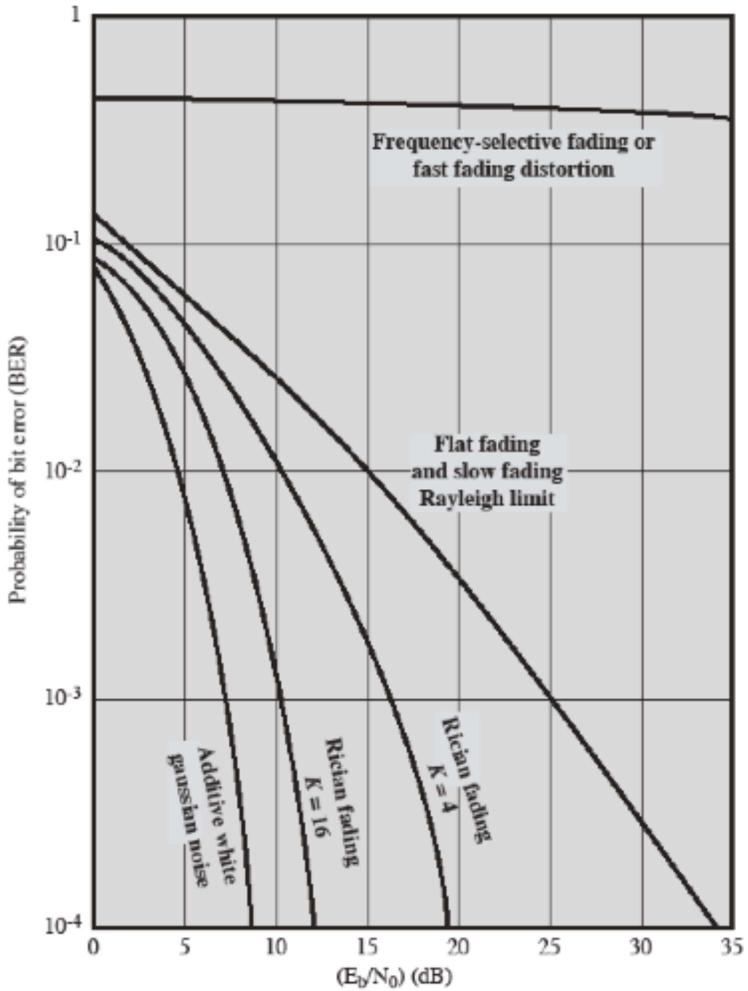
$$SNR = \frac{Signal\ Power}{Noise\ Power} = \frac{R_b E_b}{N_0 W} = \frac{R_s E_s}{N_0 W}$$

R_b and R_s is the maximum bit rate and symbol rate of the modulation scheme respectively, E_b and E_s is the energy of bit and symbol respectively

BER vs E_b/N_0: A General Shape



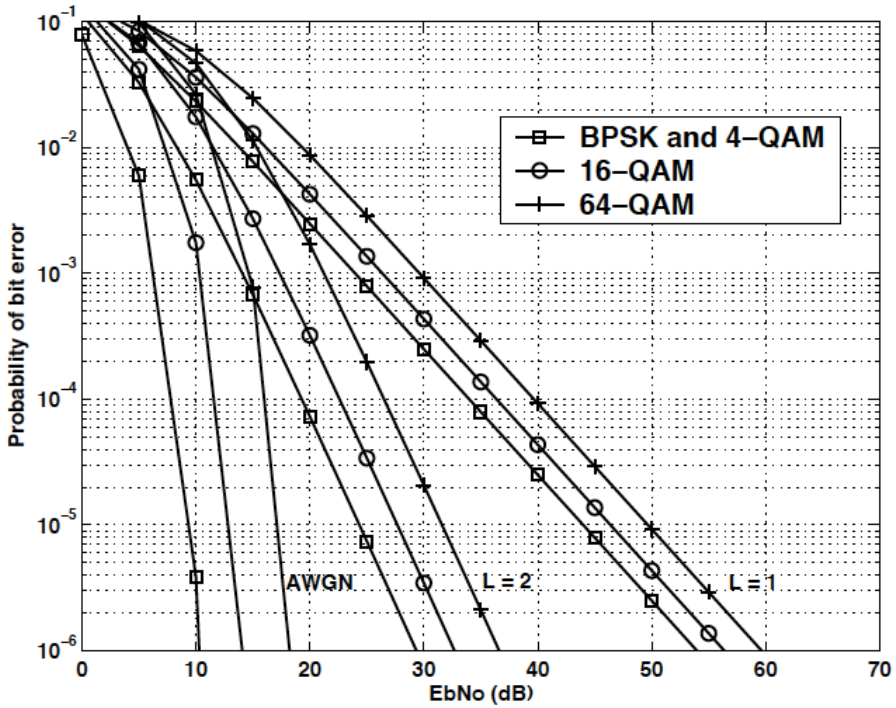
Theoretical BER for various Fading Condition



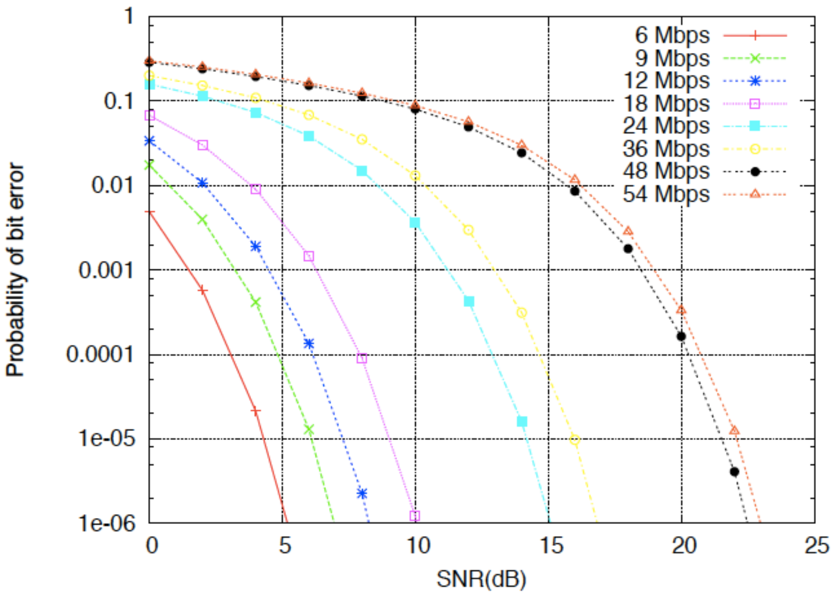
$$K = \frac{\text{Power in the dominant path}}{\text{Power in the scattered paths}}$$

K=0 : Rayleigh
K=∞: Additive White Gaussian Noise

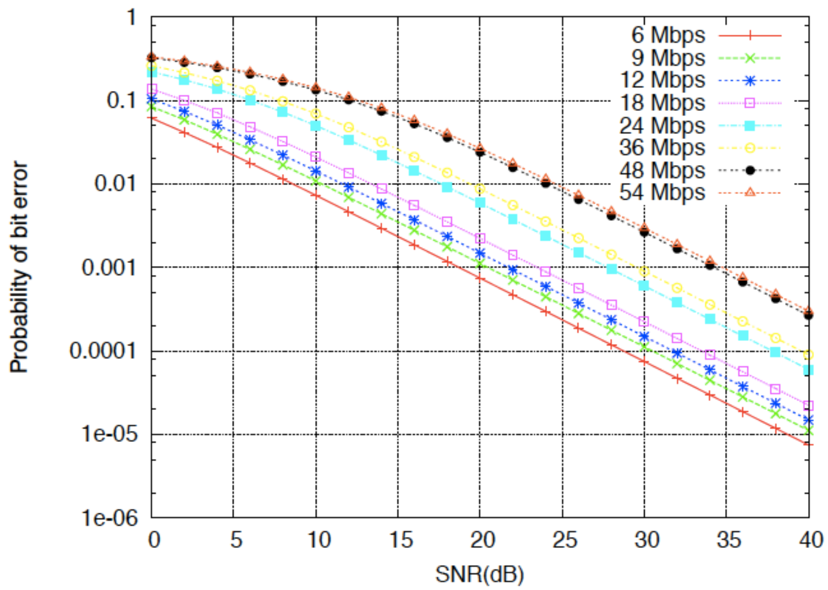
BER vs EbN0 AWGN and Rayleigh



AWGN vs Rayleigh



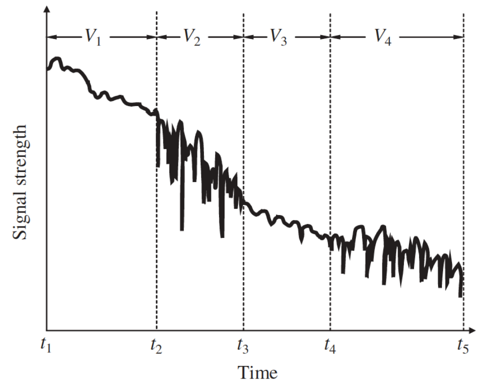
AWGN



Rayleigh (L=1)

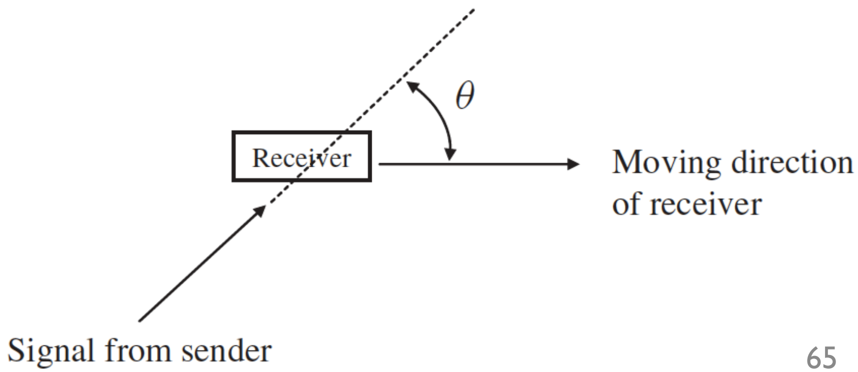
Doppler Effect

- The frequency of the received signal will not be the same as the source



$$f_r = f_c - f_d$$

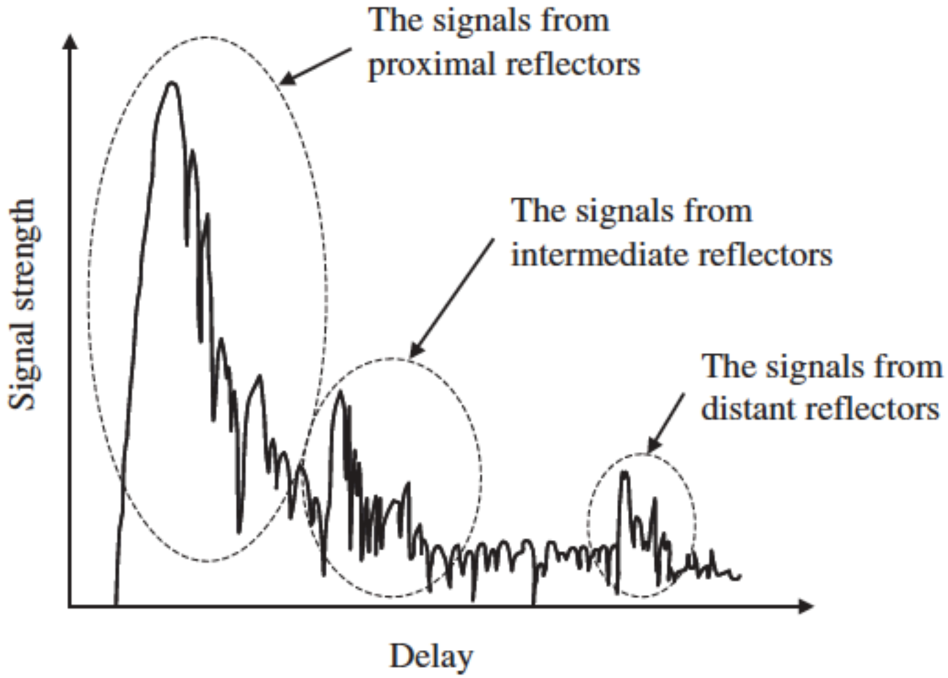
$$f_d = \frac{v}{\lambda} \cos \theta$$



Delay Spread

- Each path has a different path length, the time of arrival for each path is different ➔ ISI
- **Exponential Model:**

$$p(t) = \frac{1}{\tau_m} e^{-\frac{t}{\tau_m}}$$

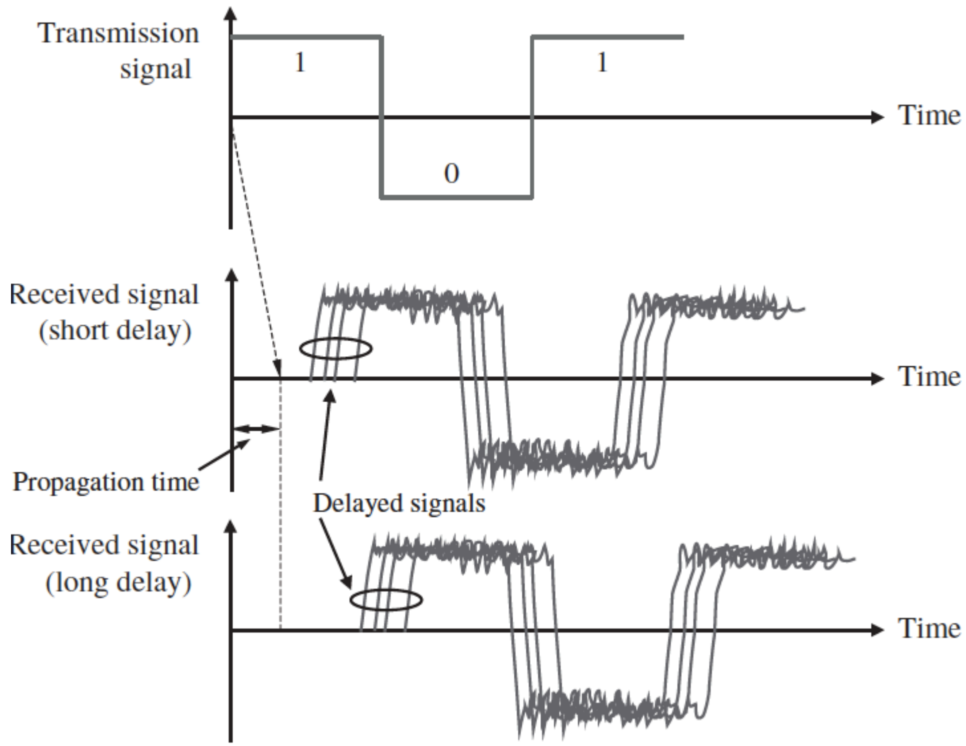


- **Uniform Model:**

$$p(t) = \begin{cases} \frac{1}{2\tau_m}, & 0 \leq t \leq 2\tau_m, \\ 0, & \text{elsewhere.} \end{cases}$$

InterSymbol Interference (ISI)

- Caused by time-delayed multipath signals



Antenna

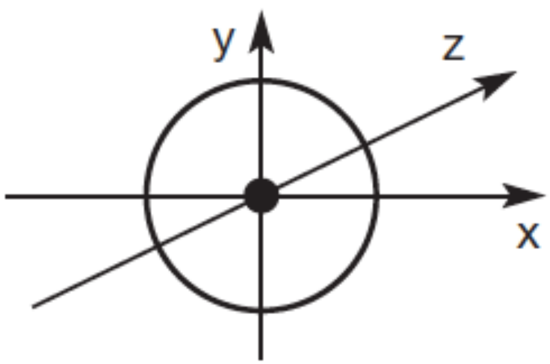
- **An antenna** is an electrical conductor or system of conductors
  - **Transmission**: radiates electromagnetic energy into space
  - **Reception:** collects electromagnetic energy from space
- In two-way communication, the same antenna can be used for transmission and reception

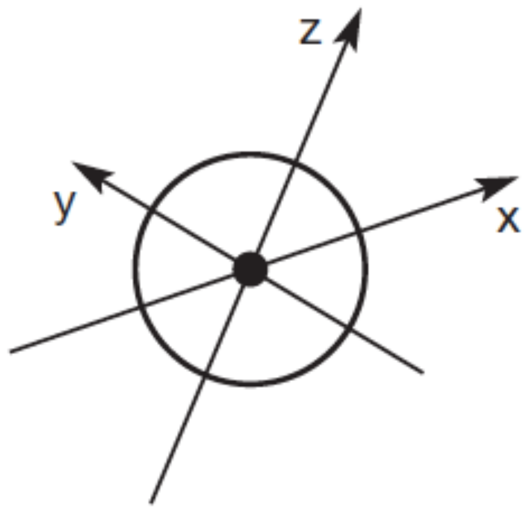
Radiation Patterns

- **Radiation pattern**
  - Graphical representation of radiation properties of an antenna
  - Depicted as two-dimensional cross section
- **Beam width** (or half-power beam width)
  - Measure of directivity of antenna (the angle within which the power radiated by the antenna is at least half of what it is in the most preferred direction)
- **Reception pattern**
  - Receiving antenna’s equivalent to radiation pattern

Types of Antennas

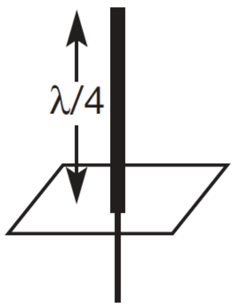
- **Isotropic antenna** (idealized)
  - Radiates power equally in all directions



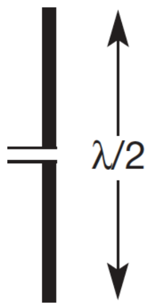


Types of Antennas

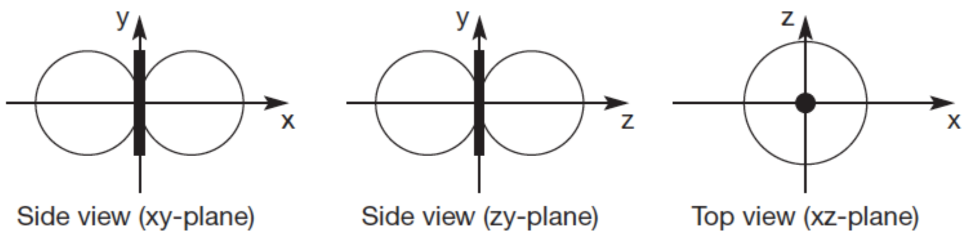
- **Dipole antennas**
  - *Half-wave* dipole antenna (or Hertz antenna)
  - *Quarter-wave* vertical antenna (or Marconi antenna)



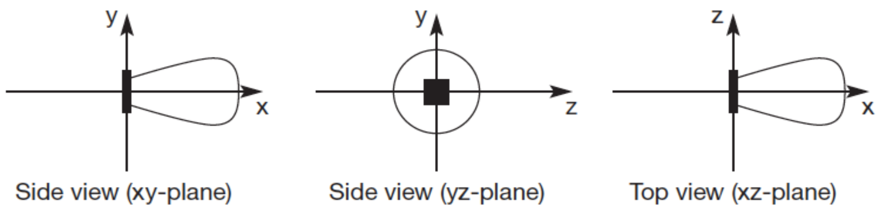
Quarter-wave
Antenna



Half-Wave
Dipole



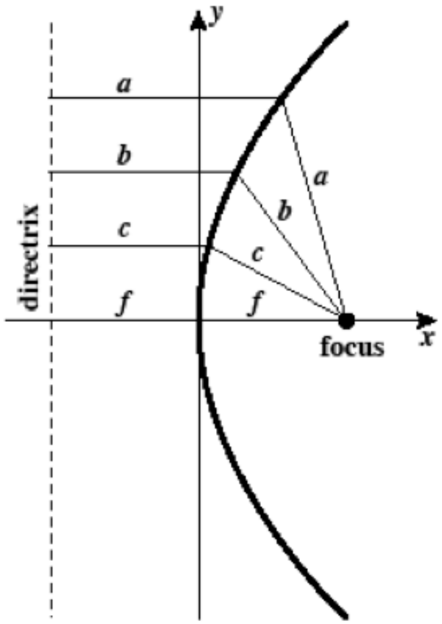
Simple dipole



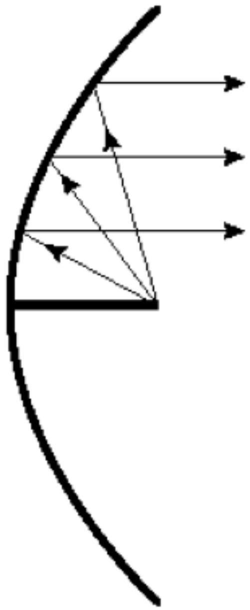
Directional Antenna

Types of Antennas

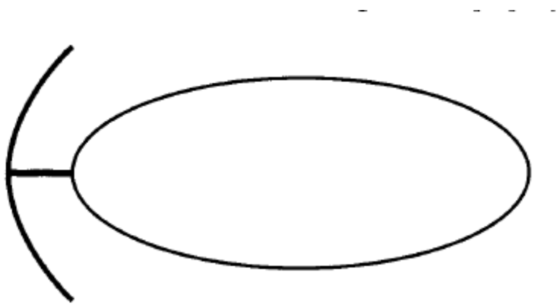
- **Parabolic** Reflective Antenna



(a) Parabola



(b) Cross-section of parabolic antenna



(c) Cross section of parabolic antenna
showing radiation pattern

Antenna Gain

- **Antenna gain**
  - Measure of the directionality of an antenna
  - Power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna (isotropic antenna)
- **Effective area**
  - Related to physical size and shape of antenna

Contents

- Processing at the Transmitter
- The Wireless Channel
- Processing at the Receiver
- Noise
- Mobile Radio Propagation
- Throughput Limit for a Wireless Link

Capacity, bandwidth, and Throughput

THROUGHPUT LIMITS

Capacity: Throughput Limit

- Assume an AWGN channel with bandwidth W
- P: received signal power
- Assume I = 0
- Shannon best available rate of reliable transmission:

$$C = W \log_2 \left(1 + \frac{P}{N_0 W}\right) \qquad \text{bits/second}$$

Capacity: Throughput Limit

- Assume I is the total interference power at the receiver and receivers treats it similar to noise:

$$C = W \log_2 (1 + SINR) \qquad \text{in bits/second}$$

Bandwidth, Capacity, and Throughput

- *Bandwidth*: The amount of spectrum occupied by a signal transmitted on a channel, in units of Hertz (Hz).
- *Capacity:* The maximum possible rate of reliable information delivery.
- *Transmission rate:* The rate at which information is transmitted on the channel.
- *Throughput:* is the rate at which data is reliably delivered between a pair of peers.

- Capacity, transmission rate and throughput can all be expressed in the units of bits-per-second (bps).

The goal is to design the system such that the achieved throughput approaches the capacity.