Wireless Communication

Presented by

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Session2

Antennas and Propagation

1. Introduction
    - Types of Anttenas
    - Free space Propagation
2. Propagation modes
3. Transmission Problems
4. Fading

1. Introduction

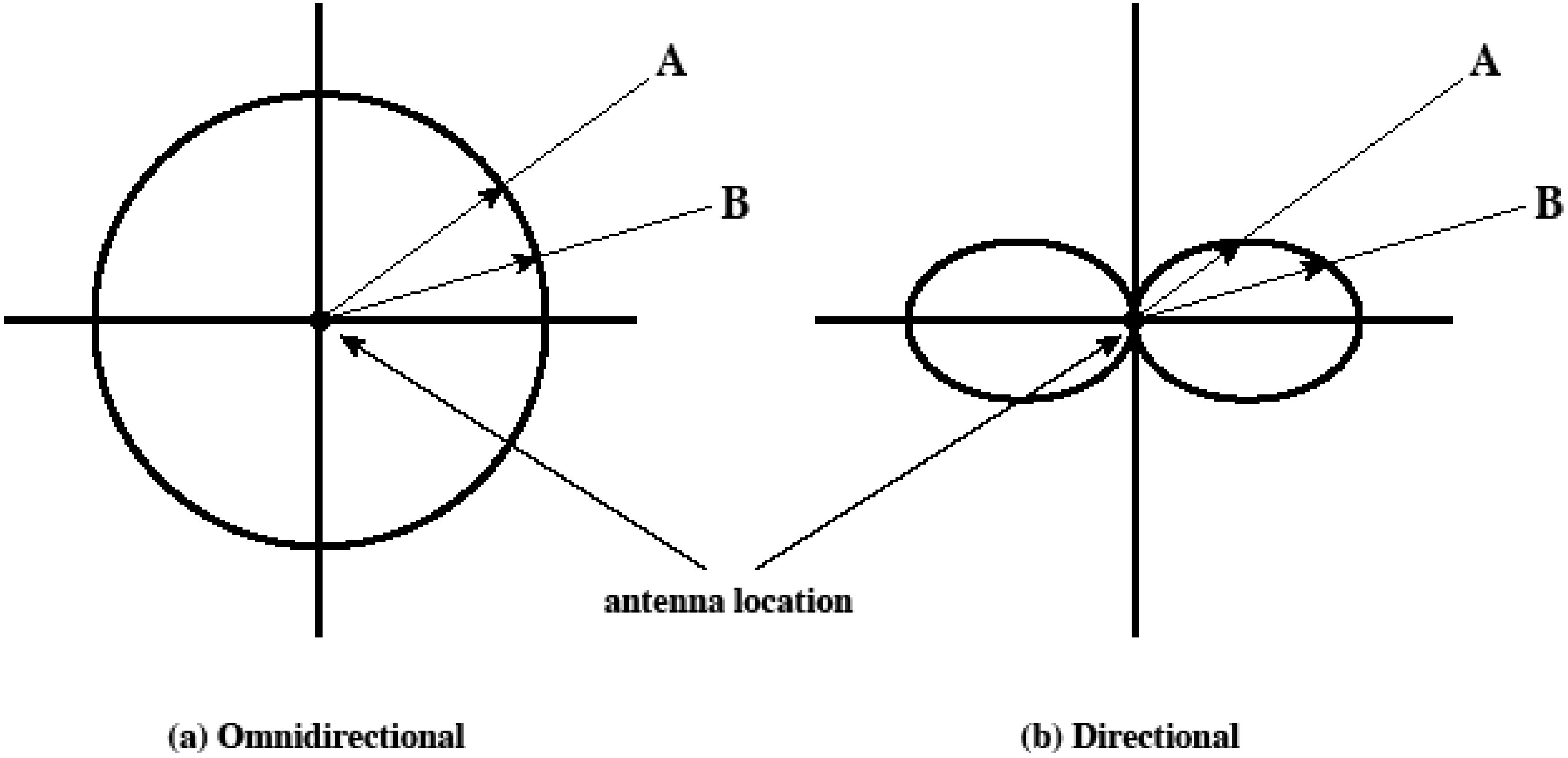
- An antenna is an electrical conductor or system of conductors
  - **Transmission** - radiates electromagnetic energy into space
  - **Reception** - collects electromagnetic energy from space
- In two-way communication, the same antenna can be used for transmission and reception

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
- Reception pattern
  - Receiving antenna’s equivalent to radiation pattern

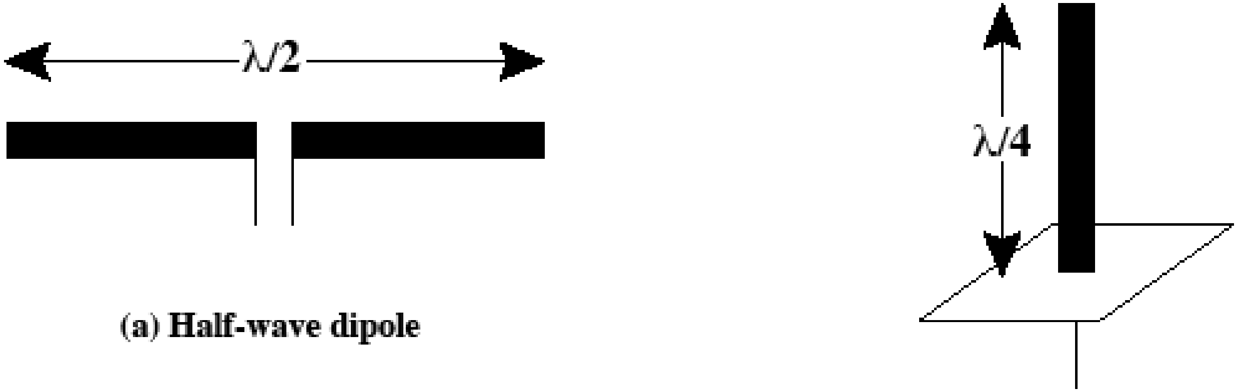
Types of Antennas

- Isotropic antenna (idealized)
  - Radiates power equally in all directions
- Dipole antennas
  - Half-wave dipole antenna (or Hertz antenna)
  - Quarter-wave vertical antenna (or Marconi antenna)
- Parabolic Reflective Antenna



(a) Omnidirectional (b) Directional

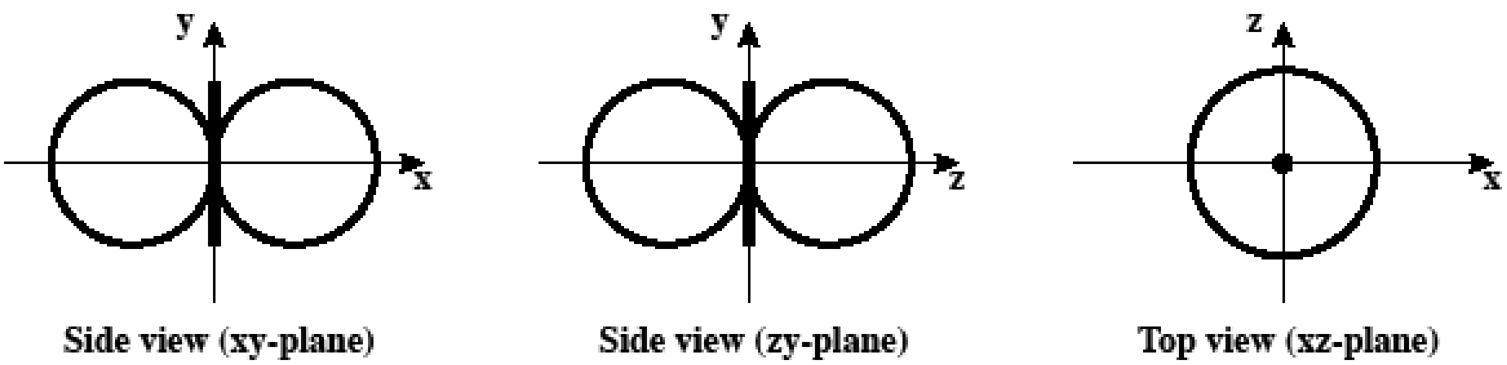
Figure 5.1 Idealized Radiation Patterns



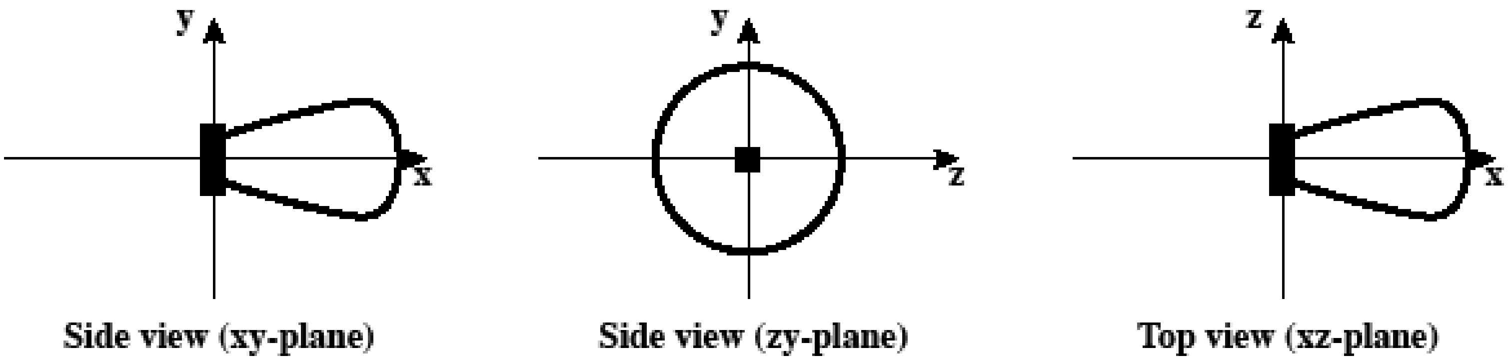
(a) Half-wave dipole

(b) Quarter-wave antenna

Figure 5.2 Simple Antennas

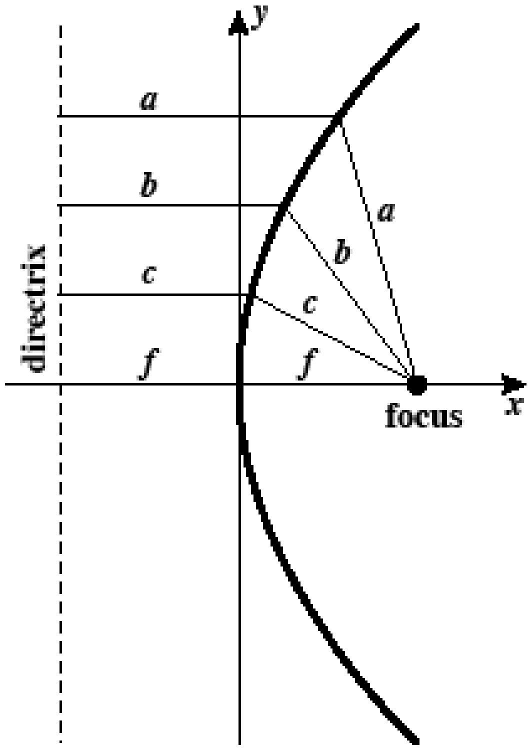


(a) Simple dipole

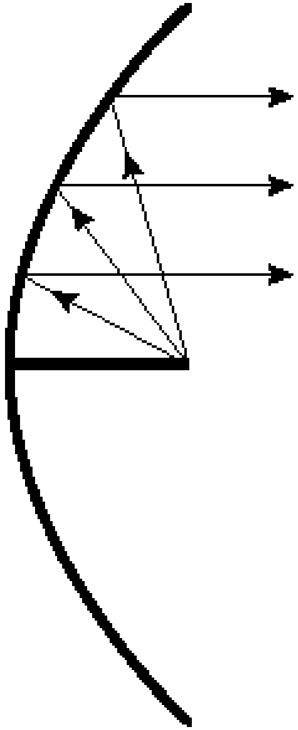


(b) Directed antenna

Figure 5.3 Radiation Patterns in Three Dimensions [SCHI00]



(a) Parabola

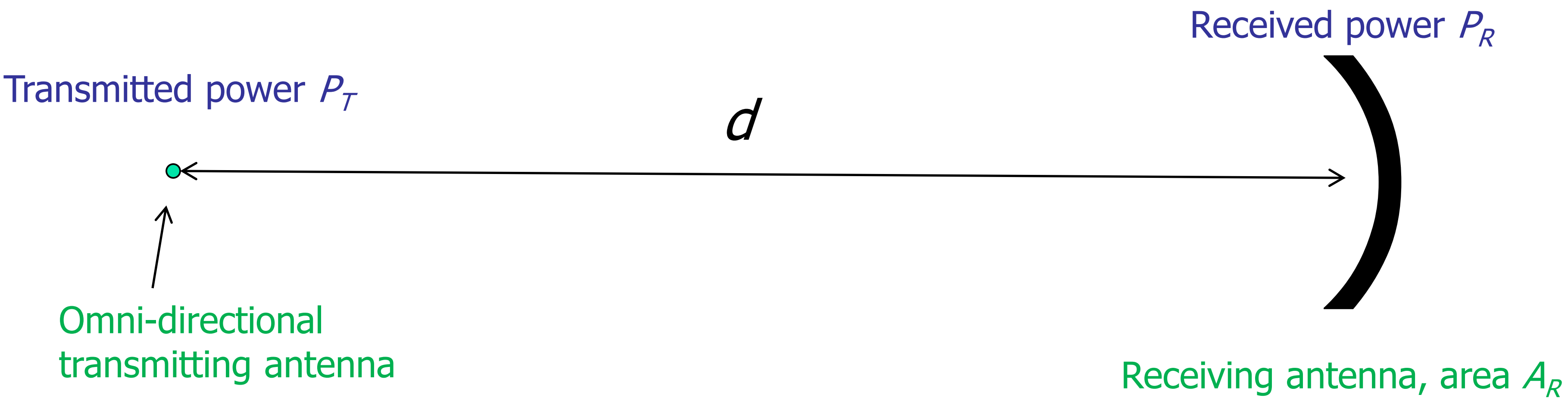


(b) Cross-section of parabolic antenna showing reflective property

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

Free-space propagation



$$P_R = P_T \frac{A_R}{4\pi d^2} \eta_R$$

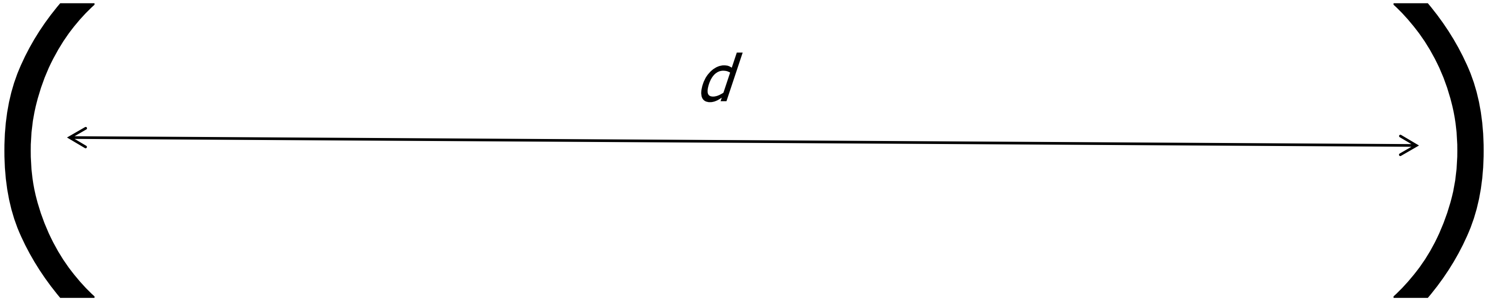
where $\eta_R < 1$ is an efficiency parameter

Focusing capability: determined by the antenna size in wavelenths (the wavelength is λ):

$$G_T = 4\pi \eta_T A_T / \lambda^2$$

where $\eta_T < 1$ is the transmitting antenna efficiency factor

Directional antenna



Transmitted power P_T

Received power P_R

Transmitting antenna, area A_T

Receiving antenna, area A_R

Directional antenna → gain $G_T > 1$

$$P_R = P_T G_T \frac{A_R}{4\pi d^2} \eta_R$$

Similarly to what done on previous slide: $G_R = 4\pi \eta_R A_R / \lambda^2$

Hence: free-space received power: $P_R = P_T G_T G_R (\frac{\lambda}{4\pi d})^2$

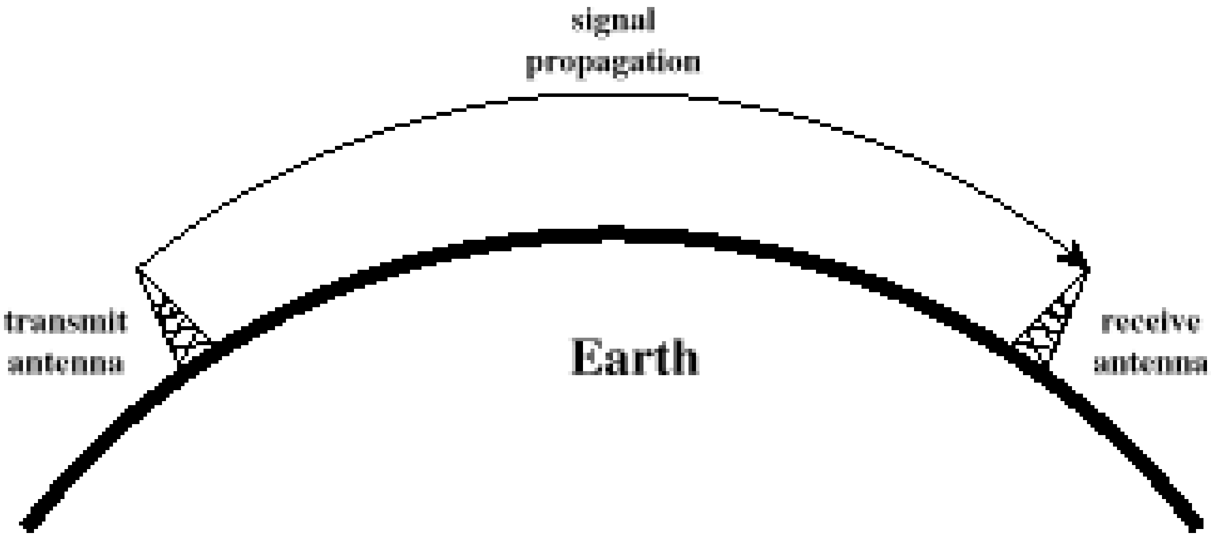
2. Propagation Modes

- Ground-wave propagation
- Sky-wave propagation
- Line-of-sight propagation

Table 5.3 Frequency Bands

Band	Frequency Range	Free-Space Wavelength Range	Propagation Characteristics	Typical Use
ELF (extremely low frequency)	30 to 300 Hz	10,000 to 1,000 km	GW	Power line frequencies; used by some home control systems.
VF (voice frequency)	300 to 3000 Hz	1,000 to 100 km	GW	Used by the telephone system for analog subscriber lines.
VLF (very low frequency)	3 to 30 kHz	100 to 10 km	GW; low attenuation day and night; high atmospheric noise level	Long-range navigation; submarine communication
LF (low frequency)	30 to 300 kHz	10 to 1 km	GW; slightly less reliable than VLF; absorption in daytime	Long-range navigation; marine communication radio beacons
MF (medium frequency)	300 to 3000 kHz	1,000 to 100 m	GW and night SW; attenuation low at night, high in day; atmospheric noise	Maritime radio; direction finding; AM broadcasting.
HF (high frequency)	3 to 30 MHz	100 to 10 m	SW; quality varies with time of day, season, and frequency.	Amateur radio; international broadcasting, military communication; long-distance aircraft and ship communication
VHF (very high frequency)	30 to 300 MHz	10 to 1 m	LOS; scattering because of temperature inversion; cosmic noise	VHF television; FM broadcast and two-way radio, AM aircraft communication; aircraft navigational aids
UHF (ultra high frequency)	300 to 3000 MHz	100 to 10 cm	LOS; cosmic noise	UHF television; cellular telephone; radar; microwave links; personal communications systems
SHF (super high frequency)	3 to 30 GHz	10 to 1 cm	LOS; rainfall attenuation above 10 GHz; atmospheric attenuation due to oxygen and water vapor	Satellite communication; radar; terrestrial microwave links; wireless local loop
EHF (extremely high frequency)	30 to 300 GHz	10 to 1 mm	LOS; atmospheric attenuation due to oxygen and water vapor	Experimental; wireless local loop
Infrared	300 GHz to 400 THz	1 mm to 770 nm	LOS	Infrared LANs; consumer electronic applications
Visible light	400 THz to 900 THz	770 nm to 330 nm	LOS	Optical communication

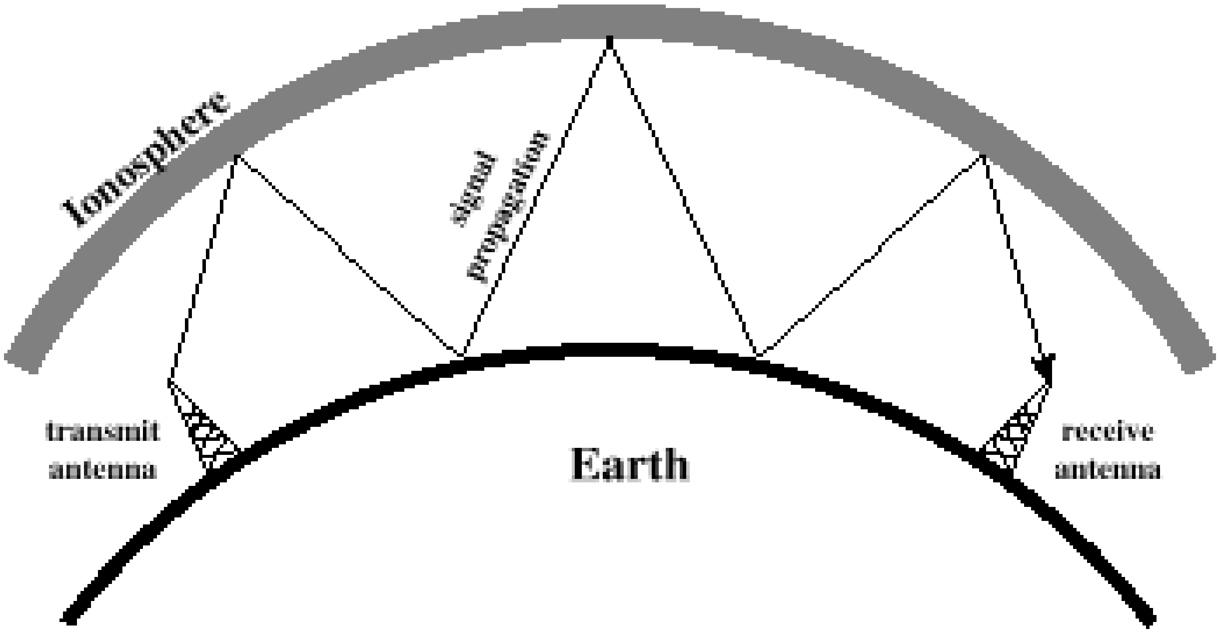
Ground Wave Propagation



Ground Wave Propagation

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

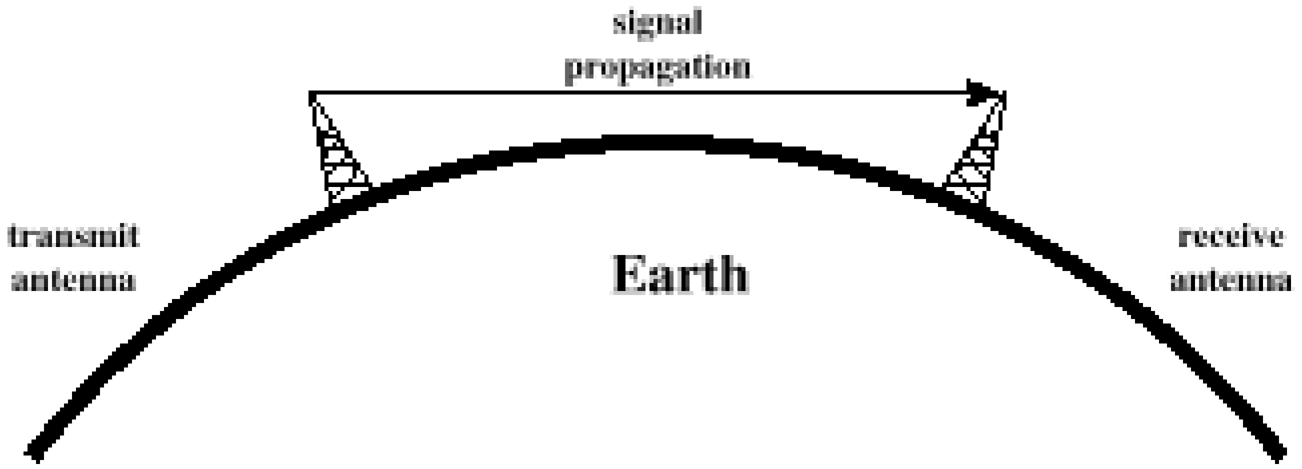
Sky Wave Propagation



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
- Reflection effect caused by refraction
- Examples
    - Amateur radio
    - CB radio

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
- Refraction – bending of microwaves by the atmosphere
  - Velocity of electromagnetic wave is a function of the density of the medium
  - When wave changes medium, speed changes
  - Wave bends at the boundary between mediums

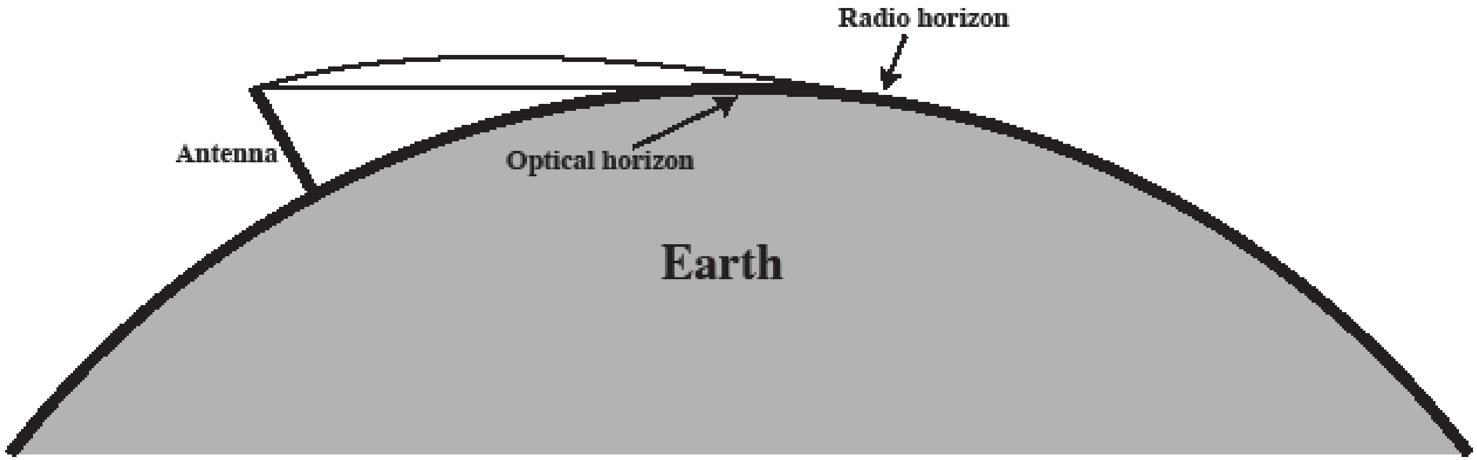


Figure 5.7 Optical and Radio Horizons

Line-of-Sight Equations

- 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

Line-of-Sight Equations

- 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

3. Transmission problems

- Attenuation
  - Free space loss
  - attenuation distortion
- Noise
- Atmospheric absorption
- Multipath
- Refraction

Attenuation

- Strength of signal falls off with distance over transmission medium
- Attenuation factors for unguided media:
  - Received signal must have sufficient strength so that circuitry in the receiver can interpret the signal
  - Signal must maintain a level sufficiently higher than noise to be received without error
  - Attenuation is greater at higher frequencies, causing distortion

Free Space Loss

- Free space loss, ideal isotropic antenna

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}$$

  - P_t = signal power at transmitting antenna
  - P_r = signal power at receiving antenna
  - λ = carrier wavelength
  - d = propagation distance between antennas
  - c = speed of light ($\approx 3 \times 10$ 8 m/s)

where d and λ are in the same units (e.g., meters)

Free Space Loss

- Free space loss equation can be recast:

$$L_{dB} = 10\log\frac{P_t}{P_r} = 20\log\left(\frac{4\pi d}{\lambda}\right)$$

$$= -20\log(\lambda) + 20\log(d) + 21.98\,\mathrm{dB}$$

$$= 20\log\left(\frac{4\pi f d}{c}\right) = 20\log(f) + 20\log(d) - 147.56\,\mathrm{dB}$$

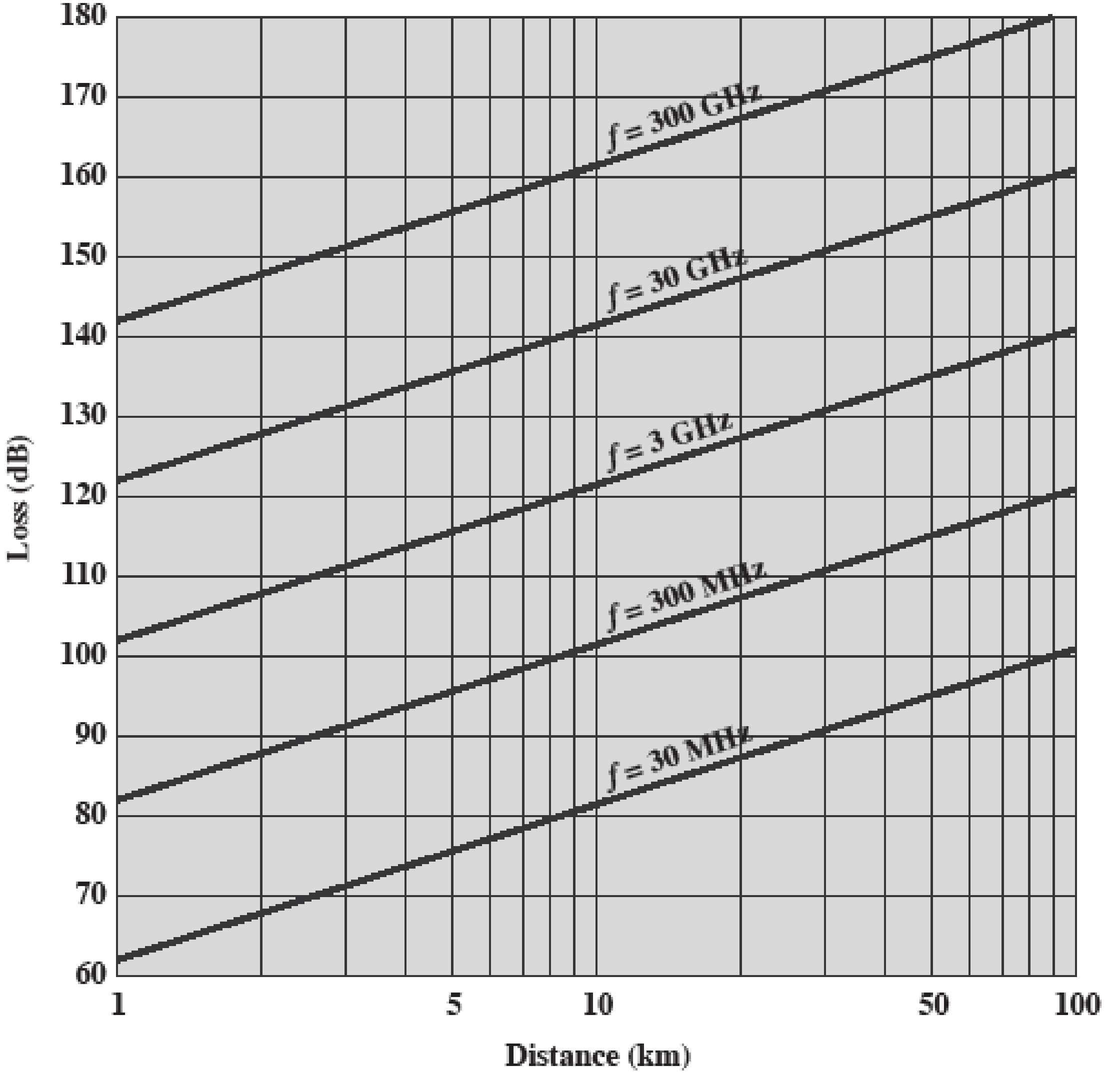


Figure 5.8 Free Space Loss

Free Space Loss

- Free space loss accounting for gain of other kinds of antennas

$$\frac{P_t}{P_r} = \frac{(4\pi)^2 (d)^2}{G_r G_t \lambda^2} = \frac{(\lambda d)^2}{A_r A_t} = \frac{(cd)^2}{f^2 A_r A_t}$$

  - G_t = gain of transmitting antenna
  - G_r = gain of receiving antenna
  - A_t = effective area of transmitting antenna
  - A_r = effective area of receiving antenna

Free Space Loss

- Free space loss accounting for gain of other kinds of antennas can be recast as

$$L_{dB} = 20\log(\lambda) + 20\log(d) - 10\log(A_t A_r)$$

$$= -20\log(f) + 20\log(d) - 10\log(A_t A_r) + 169.54\text{dB}$$

Categories of Noise

- Thermal Noise
- Intermodulation noise
- Crosstalk
- Impulse Noise

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)

Thermal Noise

- Noise is assumed to be independent of frequency
- Thermal noise present in a bandwidth of *B* Hertz (in watts):

$$N = \mathrm{k}TB$$

or, in decibel-watts

$$N = 10\log \mathrm{k} + 10\log T + 10\log B$$

$$= -228.6\,\mathrm{dBW} + 10\log T + 10\log B$$

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

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

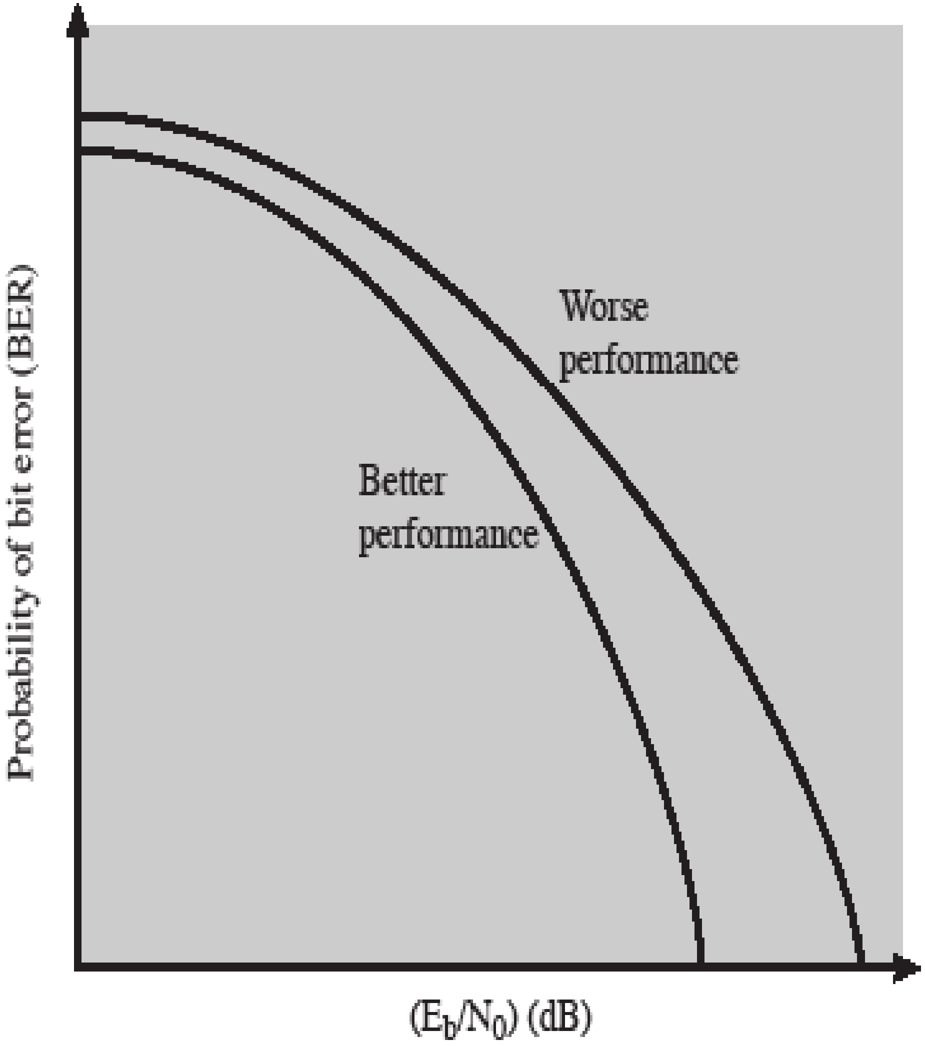


Figure 5.9 General Shape of BER vs E_b/N_0 Curves

Other Impairments

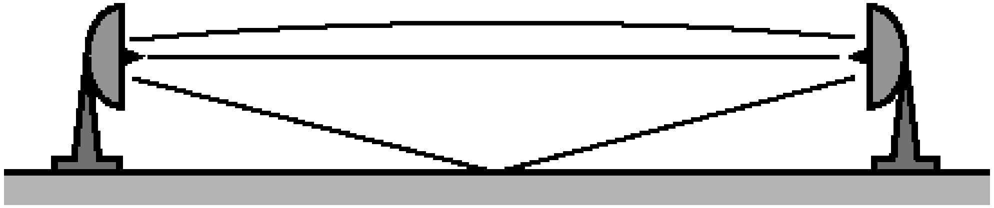
- Atmospheric absorption – water vapor and oxygen contribute to attenuation
- Multipath – obstacles reflect signals so that multiple copies with varying delays are received
- Refraction – bending of radio waves as they propagate through the atmosphere

4. Fading

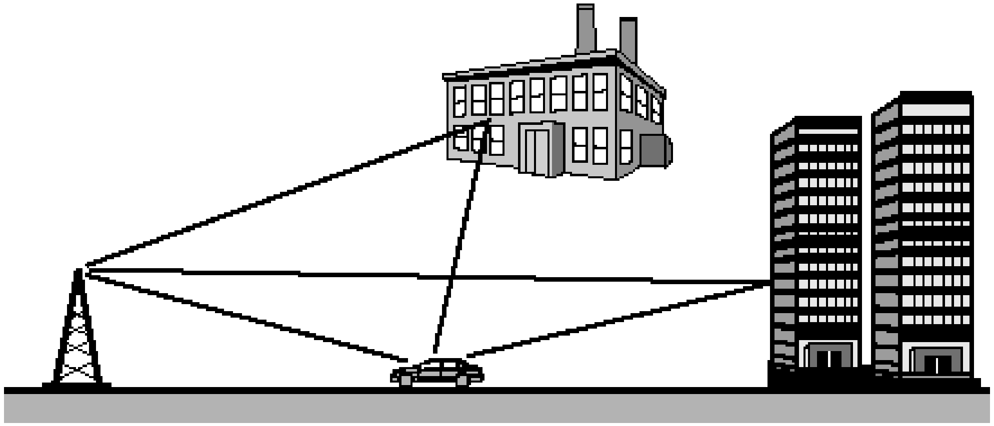
Fading: time variation of received signal power due to changes in the transmission medium or path(s)

Kinds of fading:

- Fast fading
- Slow fading
- Flat fading → independent from frequency
- Selective fading → frequency-dependent
- Rayleigh fading → no dominant path
- Rician fading → Line Of Sight (LOS) is dominating + presence of indirect multipath signals



(a) Microwave line of sight



(b) Mobile radio

Figure 5.10 Examples of Multipath Interference

Multipath Propagation

- Reflection - occurs when signal encounters a surface that is large relative to the wavelength of the signal
- Diffraction - occurs at the edge of an impenetrable body that is large compared to wavelength of radio wave
- Scattering – occurs when incoming signal hits an object whose size in the order of the wavelength of the signal or less

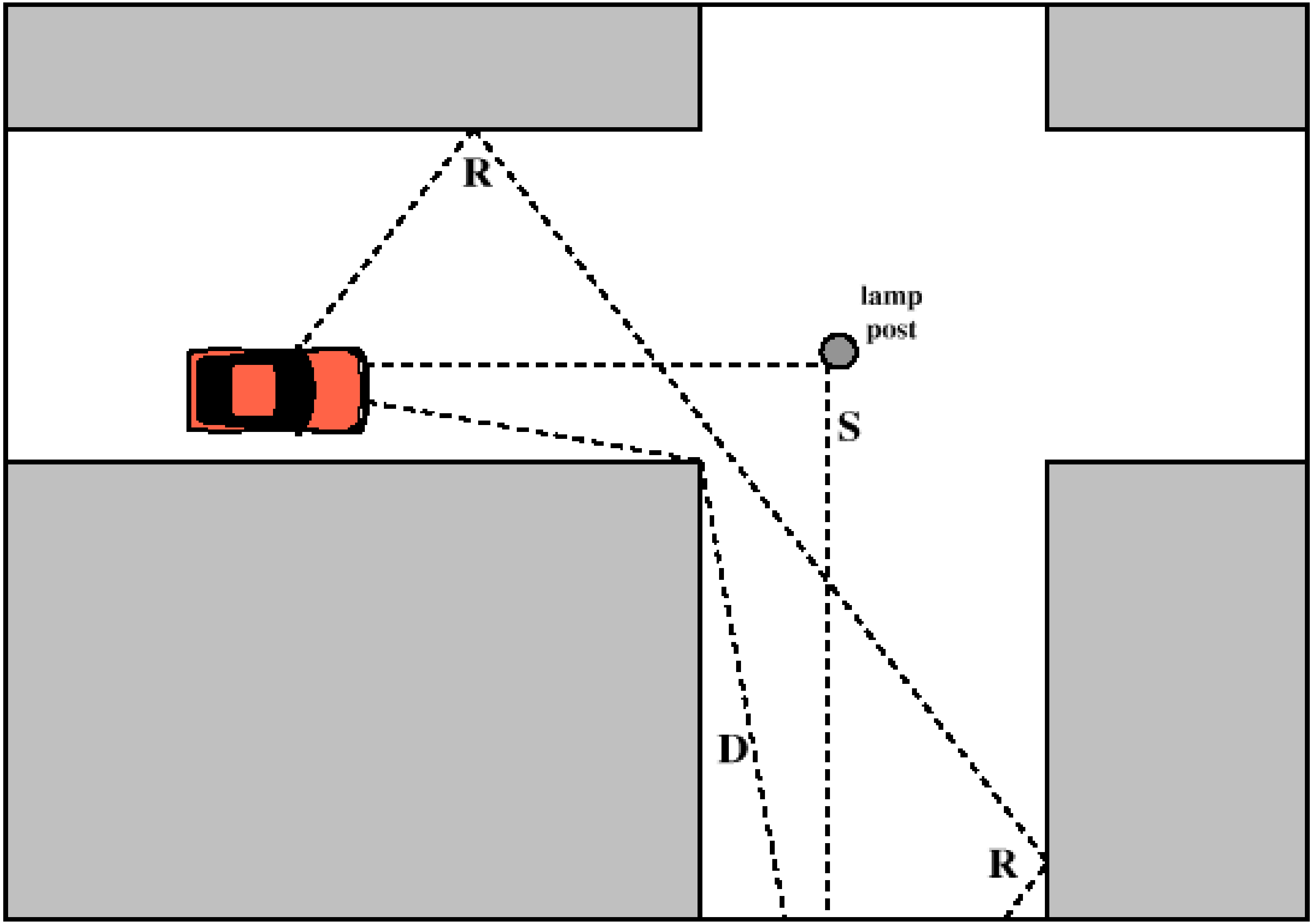


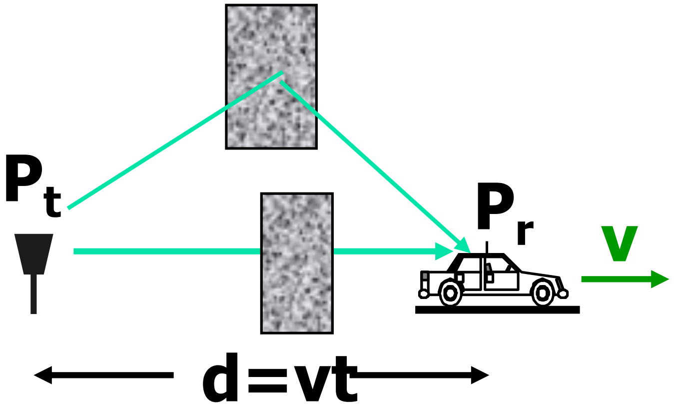
Figure 5.10 Sketch of Three Important Propagation Mechanisms: Reflection (R), Scattering (S), Diffraction (D) [ANDE95]

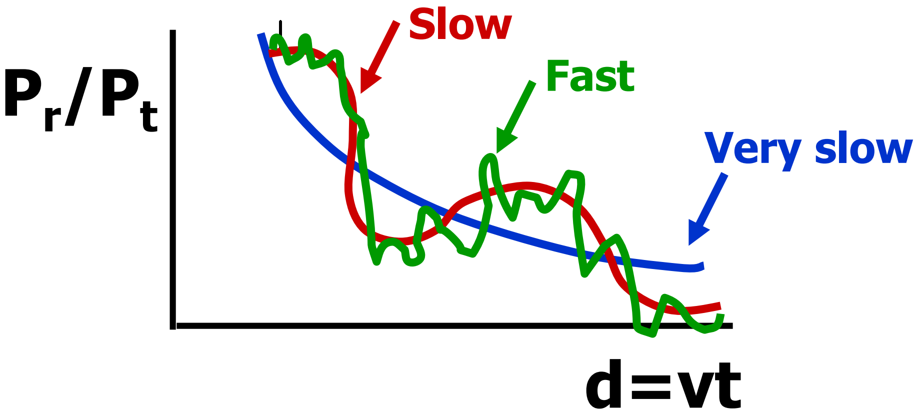
The Effects of Multipath Propagation

- Multiple copies of a signal may arrive at different phases
  - If phases add destructively, the signal level relative to noise declines, making detection more difficult
- Intersymbol interference (ISI)
  - One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit

Propagation Characteristics

- Path Loss (includes average shadowing)
- Shadowing (due to obstructions)
- Multipath Fading





Path Loss Modeling

- Maxwell’s equations
    - Complex and impractical
- Free space path loss model
    - Too simple
- Ray tracing models
    - Requires site-specific information
- Empirical Models
    - Don’t always generalize to other environments
- Simplified power falloff models
    - Main characteristics: good for high-level analysis

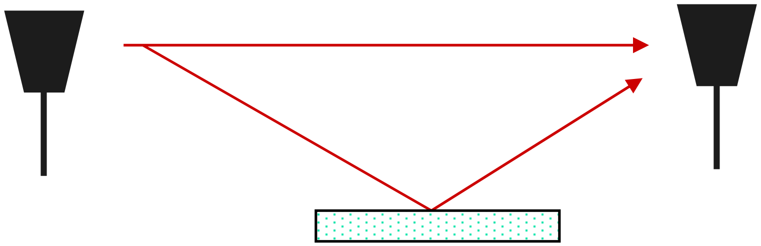
Free Space (LOS) Model

- Path loss for unobstructed LOS path
- Power falls off :
  - Proportional to d^2
  - Proportional to λ^2 (inversely proportional to f^2)

Ray Tracing Approximation

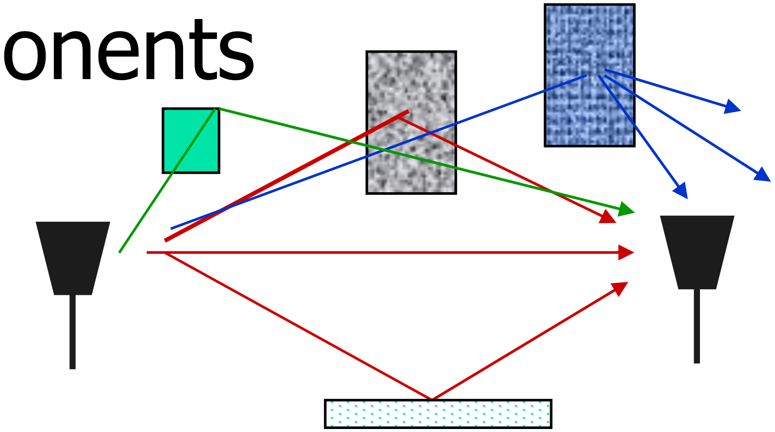
- Represent wavefronts as simple particles
- Geometry determines received signal from each signal component
- Typically includes reflected rays, can also include scattered and defracted rays.
- Requires site parameters
  - Geometry
  - Dielectric properties

Two Path Model



- Path loss for one LOS path and 1 ground (or reflected) bounce
- Ground bounce approximately cancels LOS path above critical distance
- Power falls off
  - Proportional to d^2 (small d)
  - Proportional to d^4 $(d>d_c)$
  - Independent of λ (f)

General Ray Tracing



- Models all signal components
  - Reflections
  - Scattering
  - Diffraction
- Requires detailed geometry and dielectric properties of site
  - Similar to Maxwell, but easier math.
- Computer packages often used

Simplified Path Loss Model

- Used when path loss dominated by reflections.
- Most important parameter is the path loss exponent γ, determined empirically.

$$P_r = P_t K \left[\frac{d_0}{d} \right]^{\gamma}, \qquad 2 \le \gamma \le 8$$

Empirical Models

- Okumura model
  - Empirically based (site/freq specific)
  - Awkward (uses graphs)
- Hata model
  - Analytical approximation to Okumura model
- Cost 136 Model:
  - Extends Hata model to higher frequency (2 GHz)
- Walfish/Bertoni:
  - Cost 136 extension to include diffraction from rooftops

Commonly used in cellular system simulations

Main Points

- Path loss models simplify Maxwell's equations
- Models vary in complexity and accuracy
- Power falloff with distance is proportional to d^2 in free space, d^4 in two path model
- General ray tracing computationally complex
- Empirical models used in 2G simulations
- Main characteristics of path loss captured in simple model $P_r=P_tK[d_0/d]^\gamma$

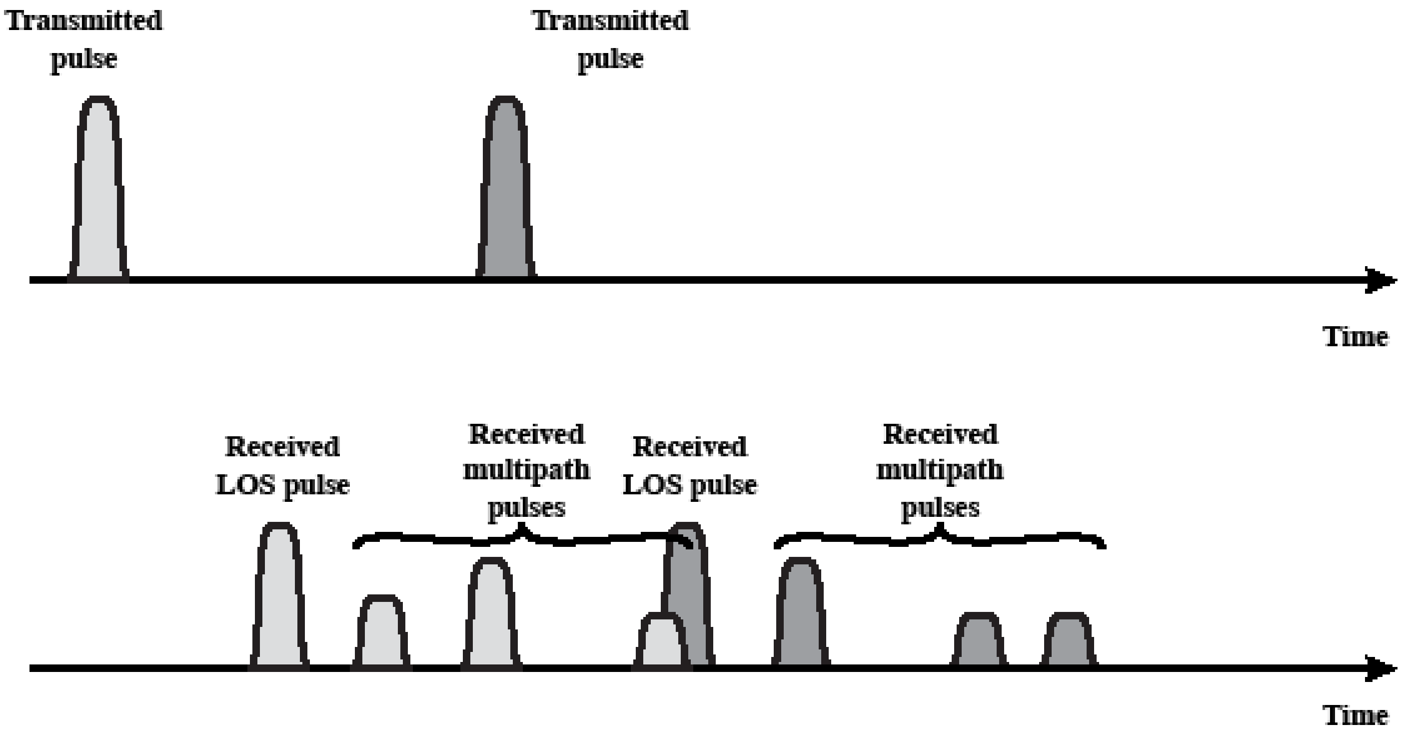


Figure 5.12 Two Pulses in Time-Variant Multipath

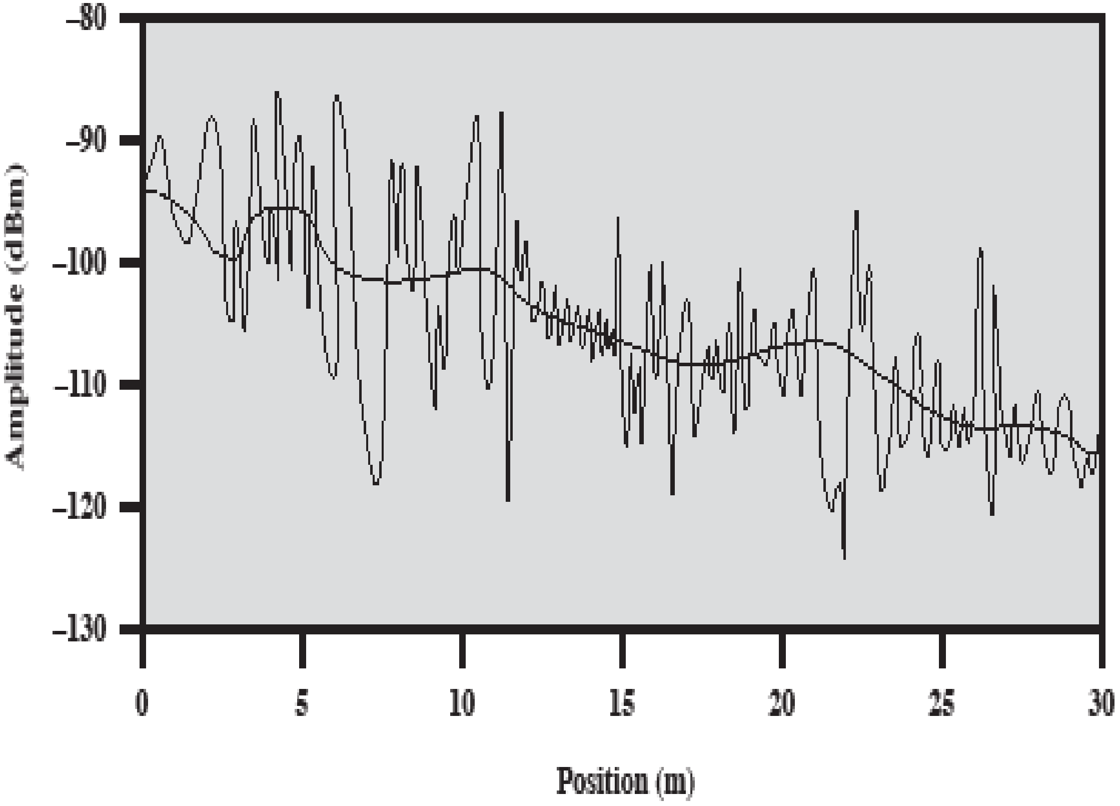
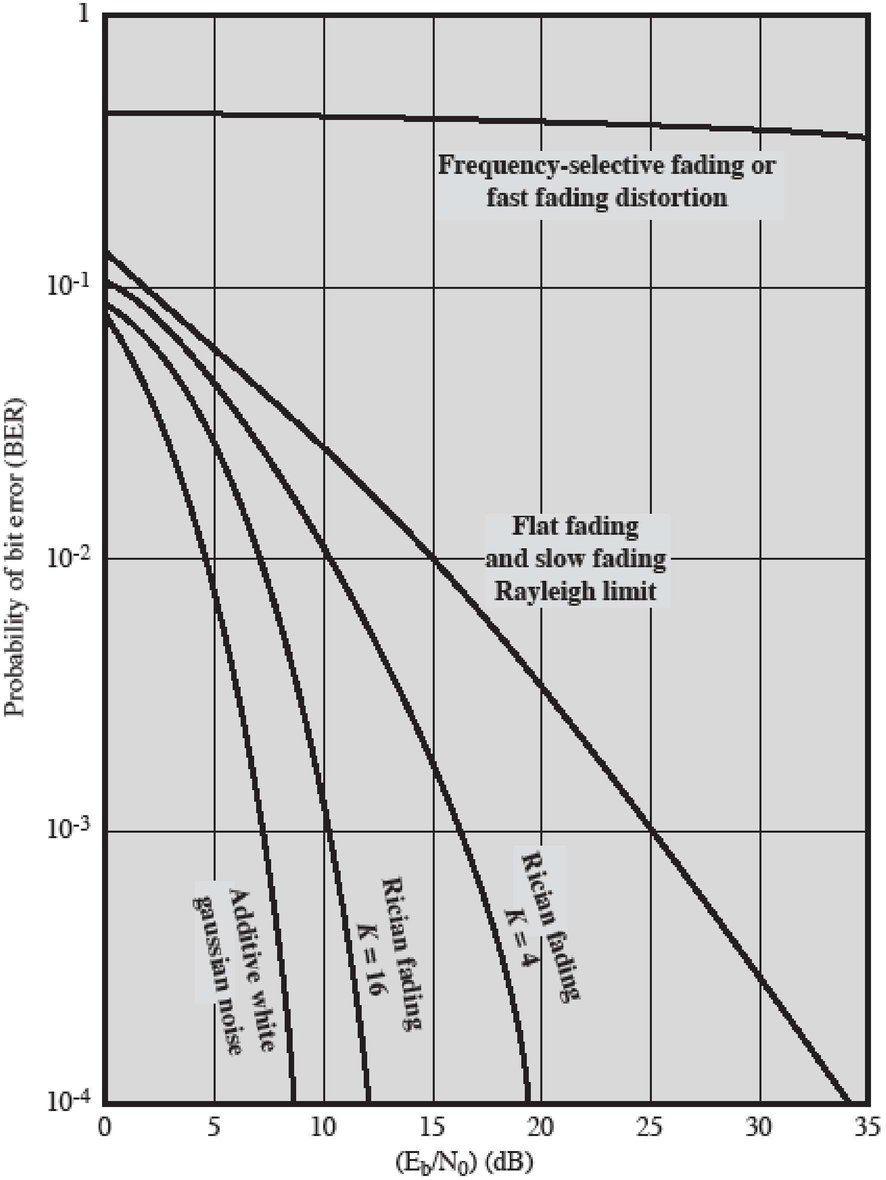


Figure 5.13 Typical Slow and Fast Fading in an Urban Mobile Environment

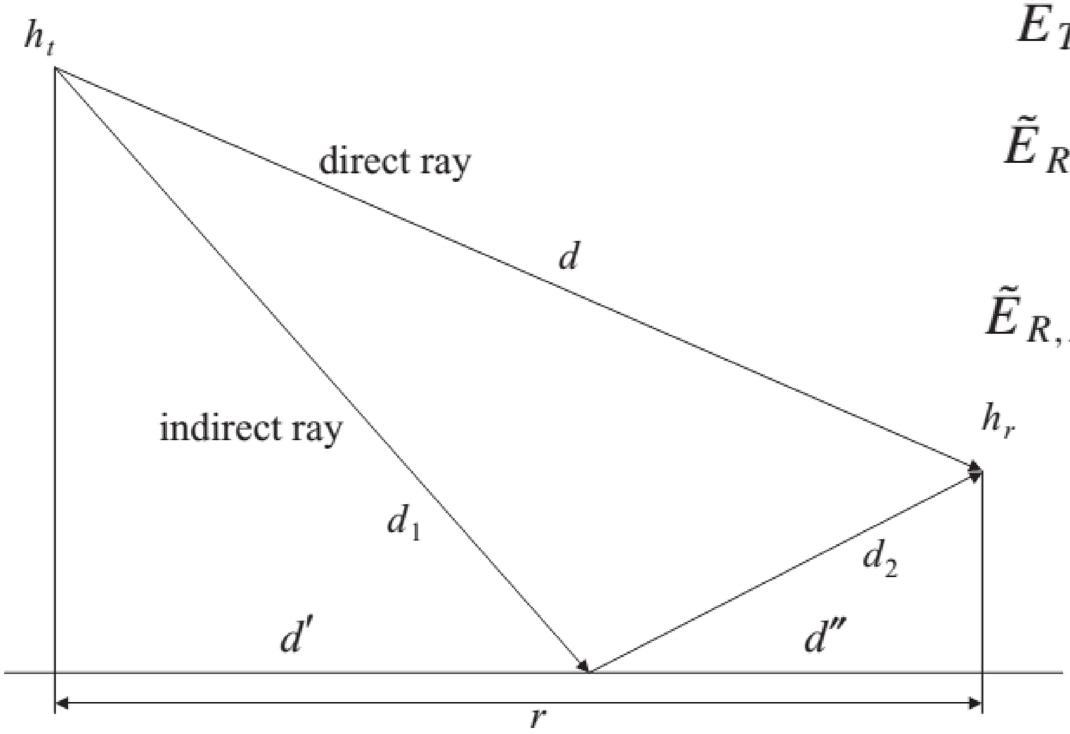


$$K = \frac{\text{Power in the dominant path}}{\text{Power in the scattered paths}}$$

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

Figure 5.14 Theoretical Bit Error Rate for Various Fading Conditions

2 Rays Analysis



$$\tilde{E}_T = E_T e^{j\omega_c t}$$

$$\tilde{E}_{R,D} = \frac{E_T}{d} e^{j\left[\omega_c\left(t-\frac{d}{c}\right)\right]}$$

$$\tilde{E}_{R,I} = -\frac{E_T}{d_1+d_2} e^{j\left[\omega_c\left(t-\frac{d_1+d_2}{c}\right)\right]}$$

$$\tilde{E}_R = \frac{E_T e^{j\omega_c\left(t-\frac{d}{c}\right)}}{d}\left[1-\frac{d}{d_1+d_2}e^{-j\omega_c\left(\frac{d_1+d_2-d}{c}\right)}\right]$$

$$\overline{P}_R = K\left|E_R\right|^2 = P_T G_T G_R\left(\frac{\lambda}{4\pi d}\right)^2\left|1-\left(\frac{d}{d_1+d_2}\right)e^{-j\Delta\phi}\right|^2$$

2 Rays Analysis

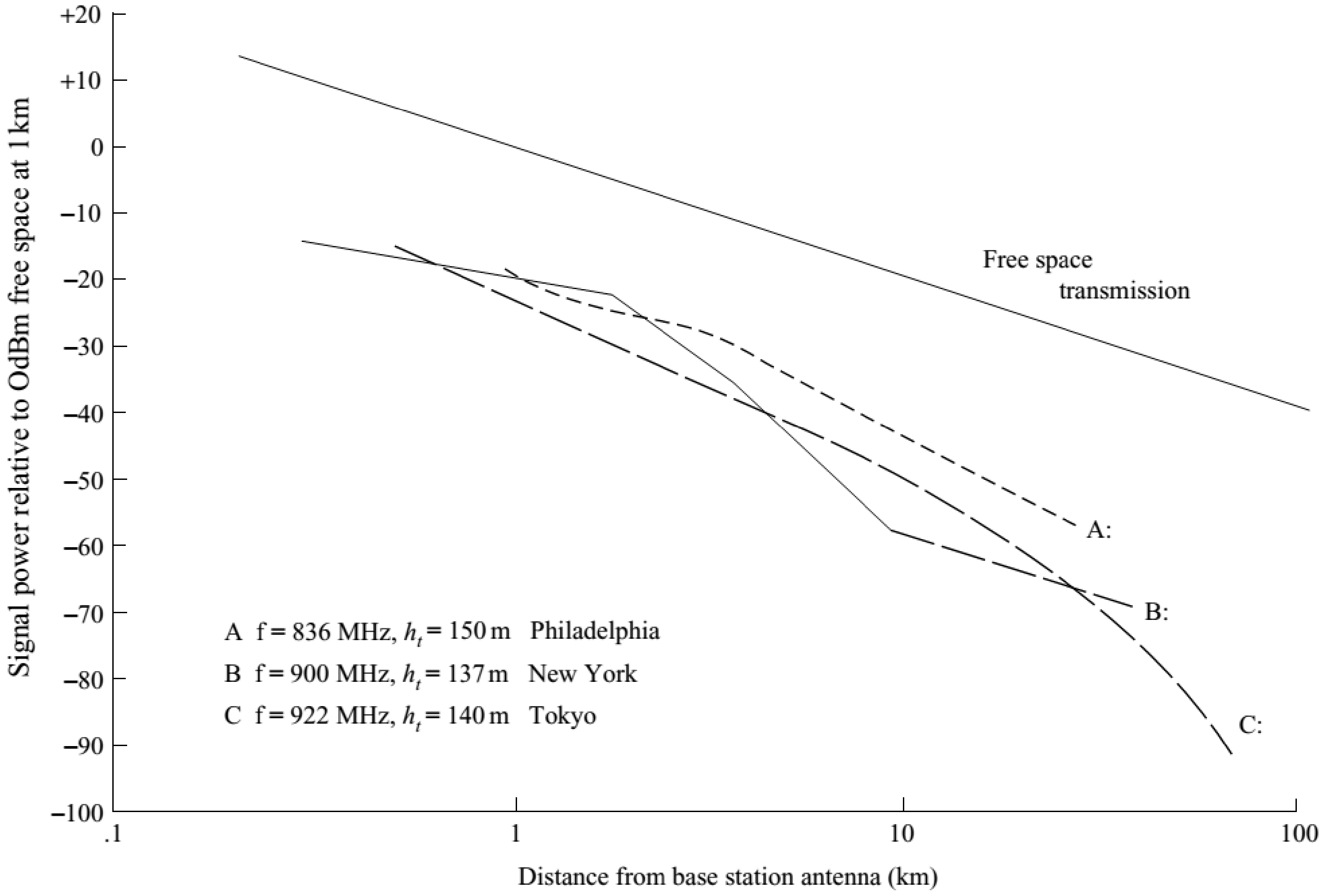
$$d_1 + d_2 = \sqrt{r^2 + (h_t + h_r)^2}$$

$$d_1 + d_2 = d\sqrt{1 + \frac{4h_t h_r}{d^2}}$$

$$\left|1 - \frac{d}{d_1 + d_2} e^{-j\Delta\phi}\right|^2 \cong (\Delta\phi)^2$$

$$\overline{P}_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\Delta\phi\right)^2 = P_T G_T G_R \frac{(h_t h_r)^2}{d^4}$$

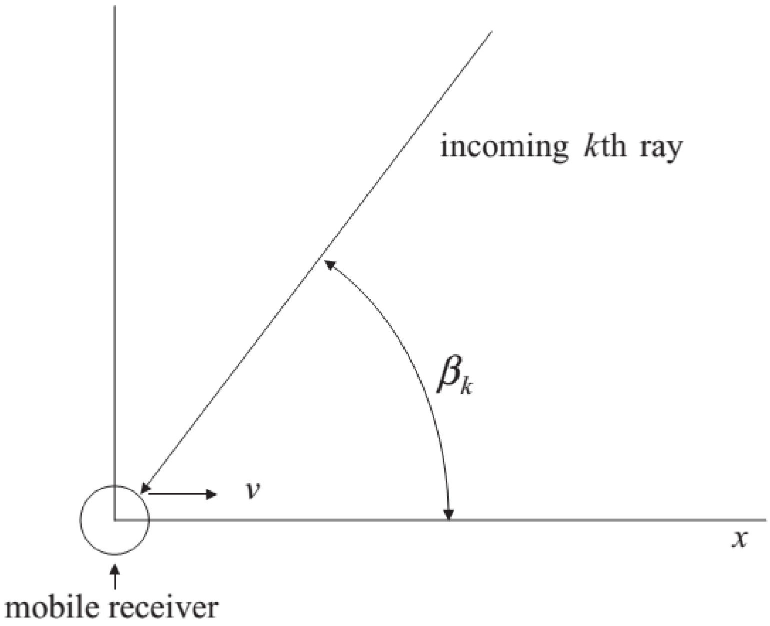
Path Loss


+20
+10
0
−10
−20
−30
−40
−50
−60
−70
−80
−90
−100
Signal power relative to OdBm free space at 1 km
.1
1
10
100
Distance from base station antenna (km)
Free space transmission
A:
B:
C:
A f = 836 MHz, h_t = 150 m Philadelphia
B f = 900 MHz, h_t = 137 m New York
C f = 922 MHz, h_t = 140 m Tokyo

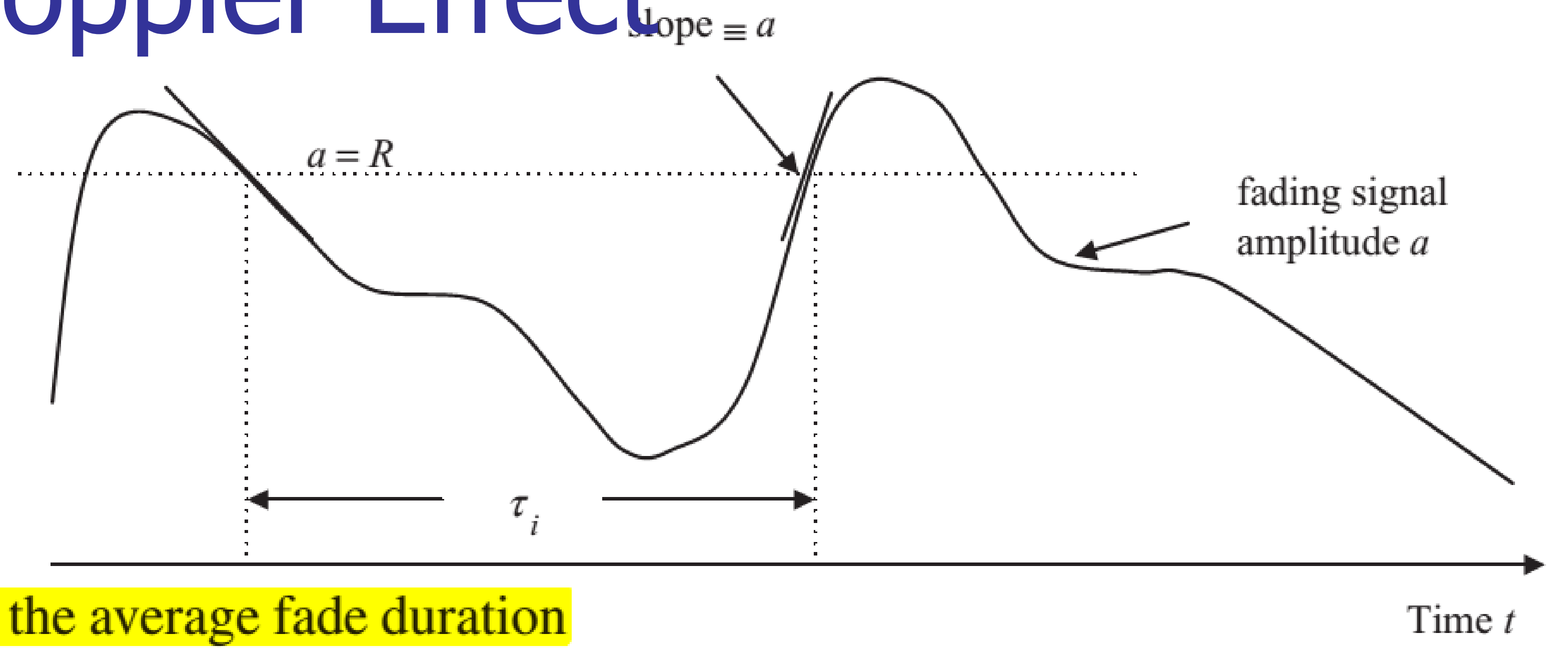
Doppler Effect

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

$$\omega_k t = (2\pi v \cos\beta_k)t/\lambda$$



Doppler Effect



the average fade duration

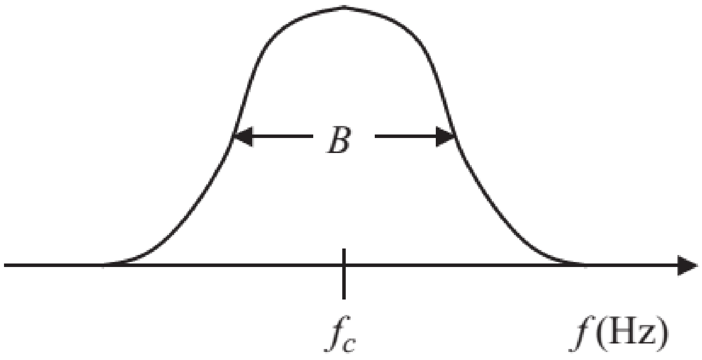
$$\tau_f = \frac{e^{\rho^2} - 1}{\rho f_m \sqrt{2\pi}} \qquad \rho \equiv a/\sqrt{E(a^2)} \qquad f_m \equiv v/\lambda.$$

the average rate R_c of crossing

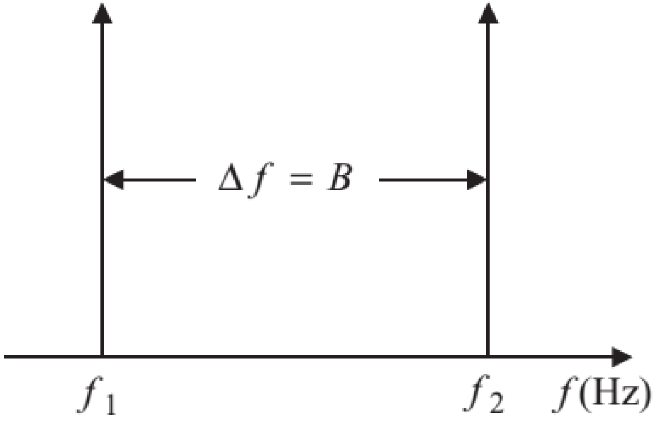
$$\tau_f R_c = 1 - e^{-\frac{R^2}{2\sigma_R^2}}$$

$$R_c \equiv E[\dot{a}/a = R] = \sqrt{2\pi}\, f_m \frac{R}{\sqrt{2}\sigma_R} e^{-\frac{R^2}{2\sigma_R^2}}$$

Frequency Selective Fading



(a) Modulated carrier spectrum



(b) Two-carrier model

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

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

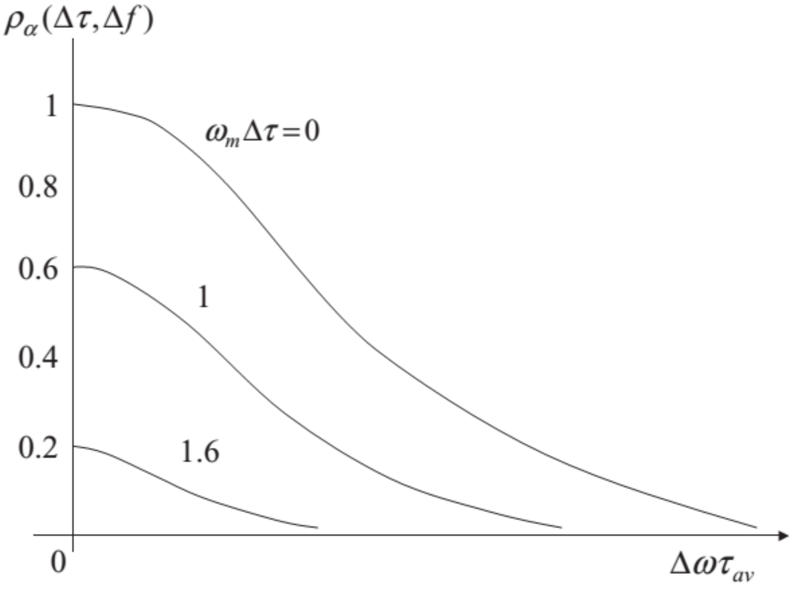
Frequency Selective Fading

The probability density function $f_\tau(\tau)$ of the incremental delay

$$f_\tau(\tau) = \frac{1}{\tau_{av}} e^{-\frac{\tau}{\tau_{av}}}, \quad \tau \geq 0$$

$$\rho_a(\Delta\tau, \Delta f) \approx \frac{J_0^2(\omega_m \Delta\tau)}{1 + (\Delta\omega\tau_{av})^2}$$

$$T < 2\pi\tau_{av}$$



$$\tau_{av} > 1/2\pi B$$

Frequency/Time Selective Fading

Frequency-selective fading/time dispersion

$$B > \text{Coherence bandwidth } = 1/2\pi\tau_{av}$$

Time-selective fading/frequency dispersion

$$T > \text{Coherence time } = 9/16\pi f_m = 0.18/f_m$$

Solution

- Error Compensation Mechanisms
- Adaptive Equalization
- Diversity Techniques

Error Compensation Mechanisms

- Forward error correction
- Adaptive equalization
- Diversity techniques

Forward Error Correction

- Transmitter adds error-correcting code to data block
  - Code is a function of the data bits
- Receiver calculates error-correcting code from incoming data bits
  - If calculated code matches incoming code, no error occurred
  - If error-correcting codes don’t match, receiver attempts to determine bits in error and correct

Adaptive Equalization

- Can be applied to transmissions that carry analog or digital information
  - Analog voice or video
  - Digital data, digitized voice or video
- Used to combat intersymbol interference
- Involves gathering dispersed symbol energy back into its original time interval
- Techniques
  - Lumped analog circuits
  - Sophisticated digital signal processing algorithms

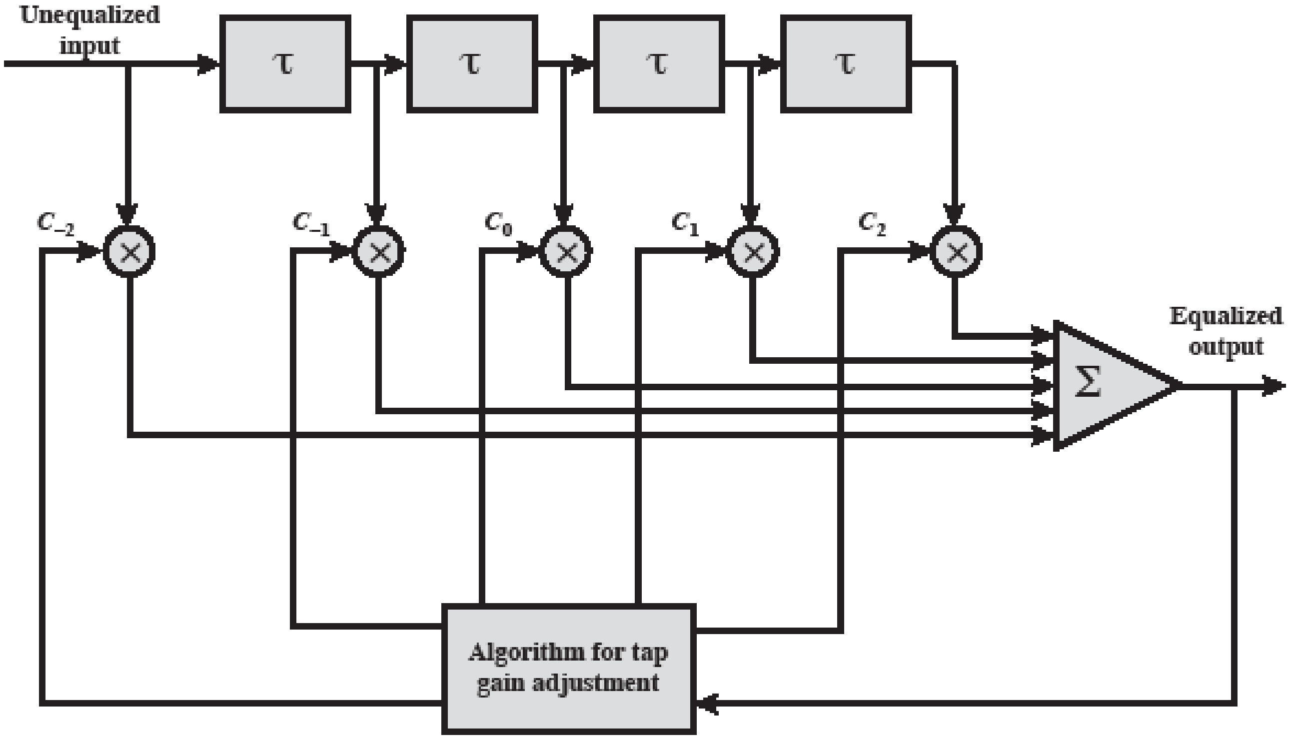
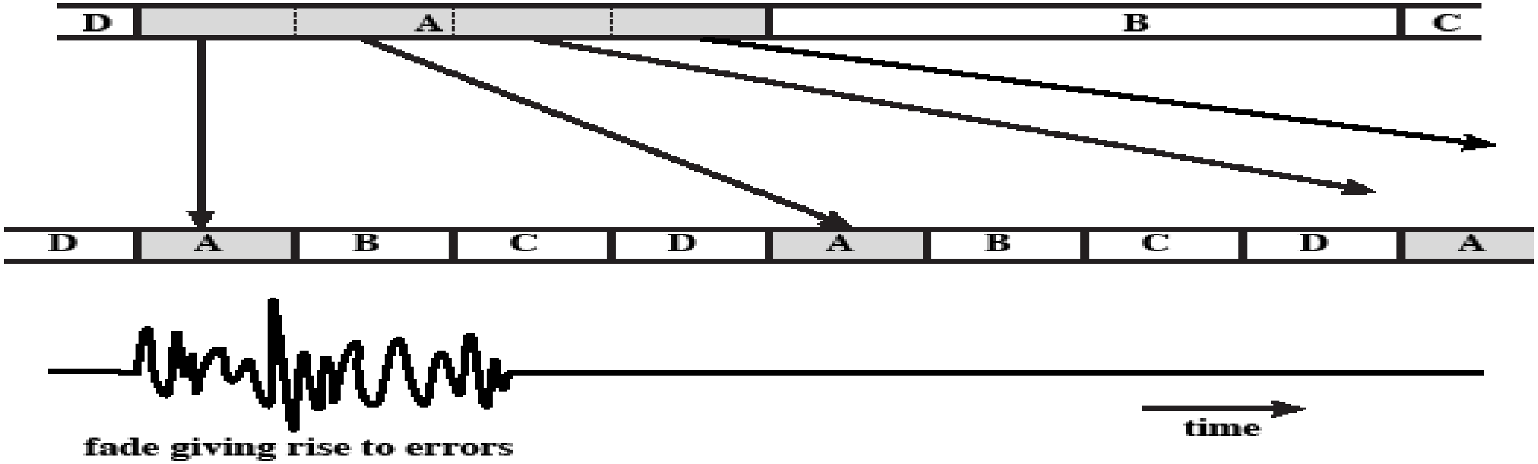


Figure 5.15 Linear Equalizer Circuit [PROA01]

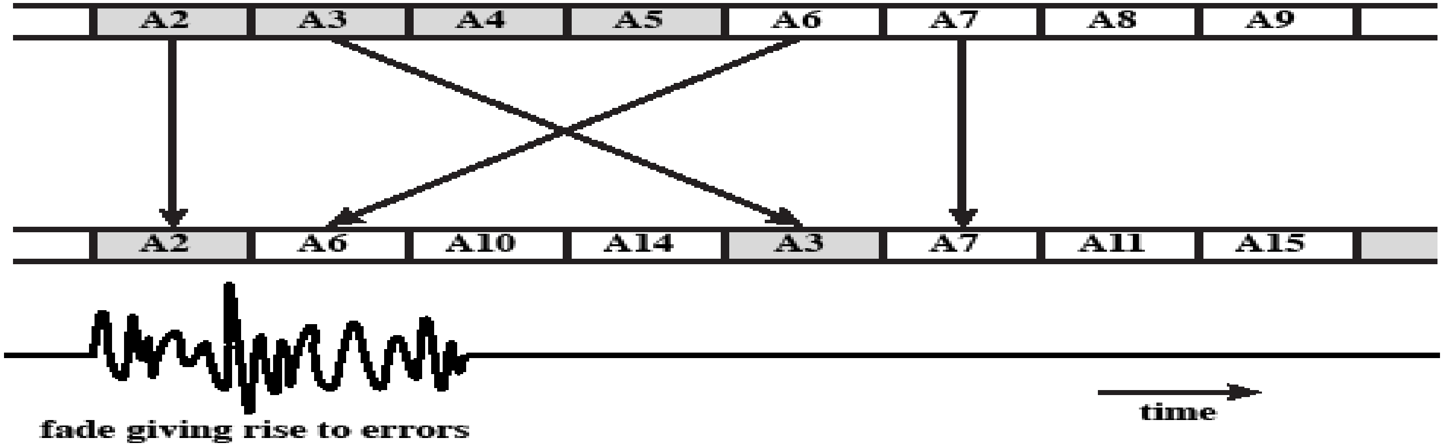
A known training sequence is sent periodically. The receiver fine tunes the coefficients accordingly.

Diversity Techniques

- Diversity is based on the fact that individual channels experience independent fading events
- Space diversity – techniques involving physical transmission path (e.g., multiple antennas)
- Frequency diversity – techniques where the signal is spread out over a larger frequency bandwidth or carried on multiple frequency carriers
- Time diversity – techniques aimed at spreading the data out over time



(a) TDM stream



(b) Interleaving without TDM

Figure 5.16 Interleaving Data Blocks to Spread the Effects of Error Bursts