Antennas and Propagation

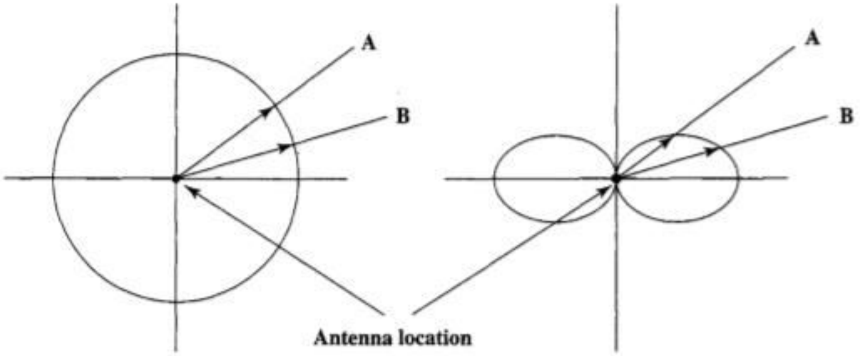
Chapter 5

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



(a) Omnidirectional

(b) Directional

Figure 5.1 Idealized Radiation Patterns

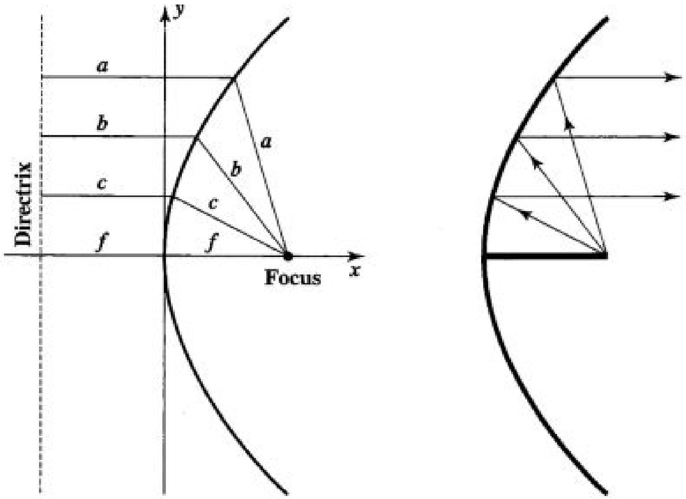
Types of Antennas

- 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)

Figure 5.2 Simple Antennas

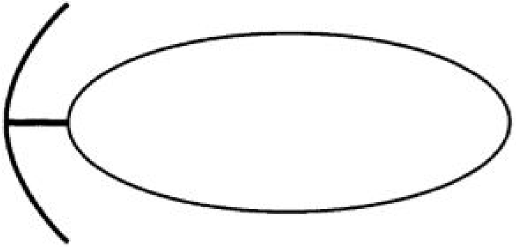
Types of Antennas

- Parabolic Reflective Antenna



(a) Parabola

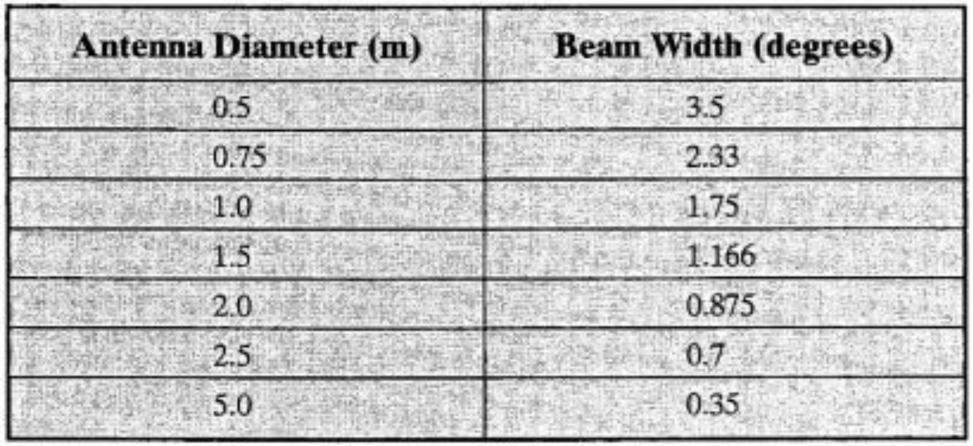
(b) Cross section of parabolic antenna showing reflective property



(c) Cross section of parabolic antenna showing radiation pattern

Figure 5.4 Parabolic Reflective Antenna

Table 5.1 Antenna Beamwidths for Various Diameter Parabolic Reflective Antennas at f = 12 GHz [FREE97]



Antenna Diameter (m)	Beam Width (degrees)
0.5	3.5
0.75	2.33
1.0	1.75
1.5	1.166
2.0	0.875
2.5	0.7
5.0	0.35

Antenna Gain

- Antenna gain
  - Power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna (isotropic antenna)
  - if an antenna has a gain of 3dB, then it improves upon the isotropic antenna in that direction by 3dB, or a factor of 2
  - At the expense of other directions.
- Effective area
  - Related to physical size and shape of antenna

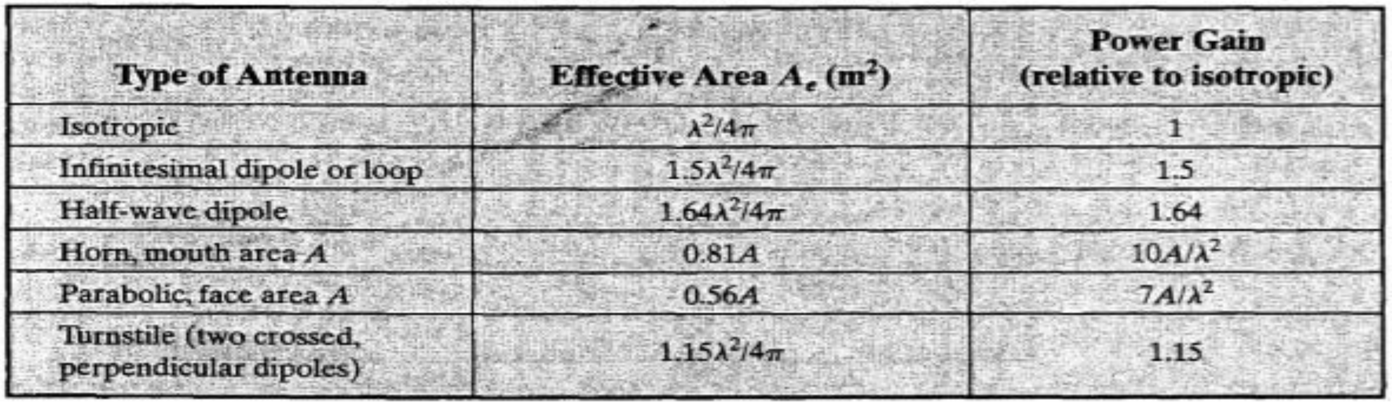
Antenna Gain

- Relationship between antenna gain and effective area:

$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$

  - G = antenna gain
  - A_e = effective area
  - f = carrier frequency
  - c = speed of light ($\leq 3 \times 10^8$ m/s)
  - λ = carrier wavelength

Table 5.2 Antenna Gains and Effective Areas [COUC01]

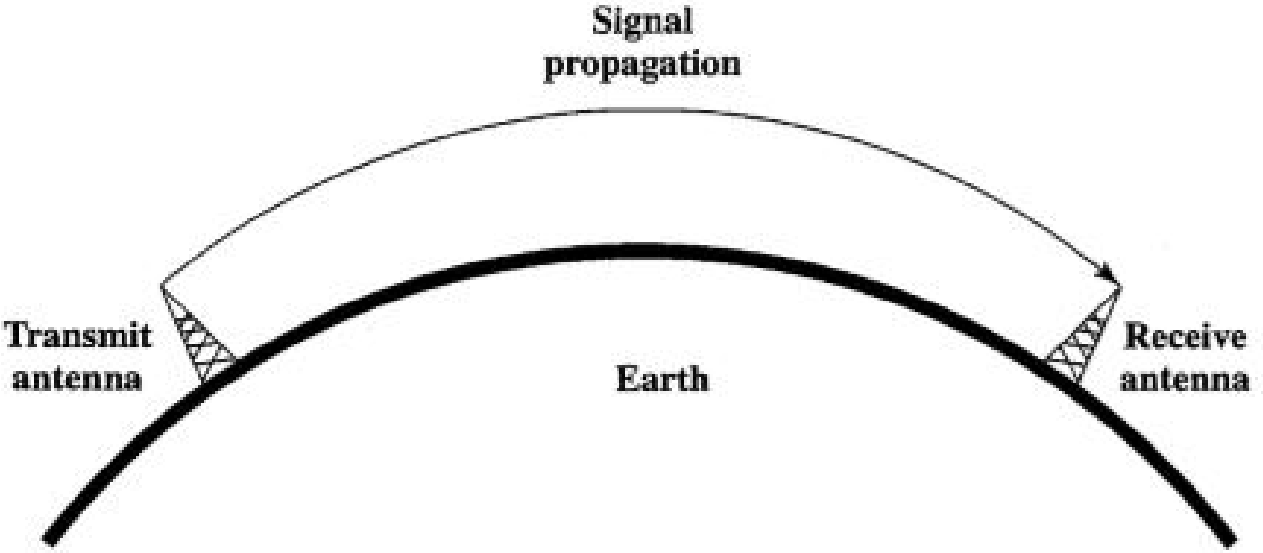


Type of Antenna	Effective Area A_e (m^2)	Power Gain (relative to isotropic)
Isotropic	$\lambda^2/4\pi$	1
Infinitesimal dipole or loop	$1.5\lambda^2/4\pi$	1.5
Half-wave dipole	$1.64\lambda^2/4\pi$	1.64
Horn, mouth area A	$0.81A$	$10A/\lambda^2$
Parabolic, face area A	$0.56A$	$7A/\lambda^2$
Turnstile (two crossed, perpendicular dipoles)	$1.15\lambda^2/4\pi$	1.15

Propagation Modes

1) Ground-wave propagation
2) Sky-wave propagation
3) Line-of-sight propagation

Ground Wave Propagation

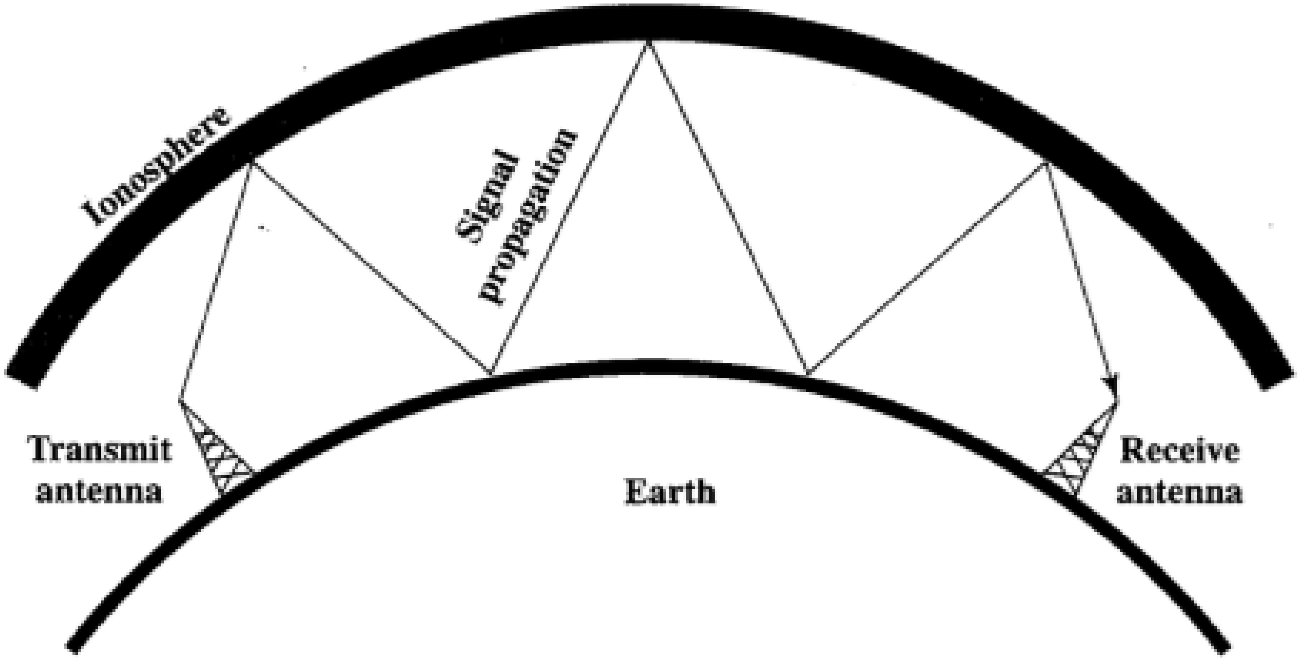


(a) Ground wave propagation (below 2 MHz)

Ground Wave Propagation

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

Sky Wave Propagation

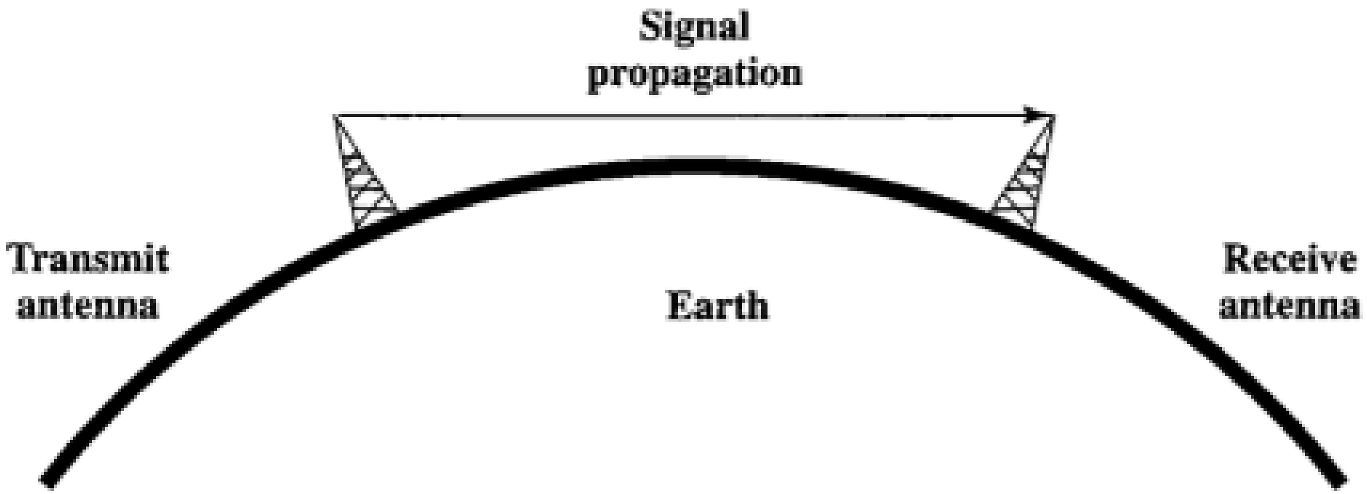


(b) Sky wave propagation (2 to 30 MHz)

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
- Frequencies up to 30 MHz
- Examples
  - Amateur radio
  - International Broadcast radio

Line-of-Sight Propagation



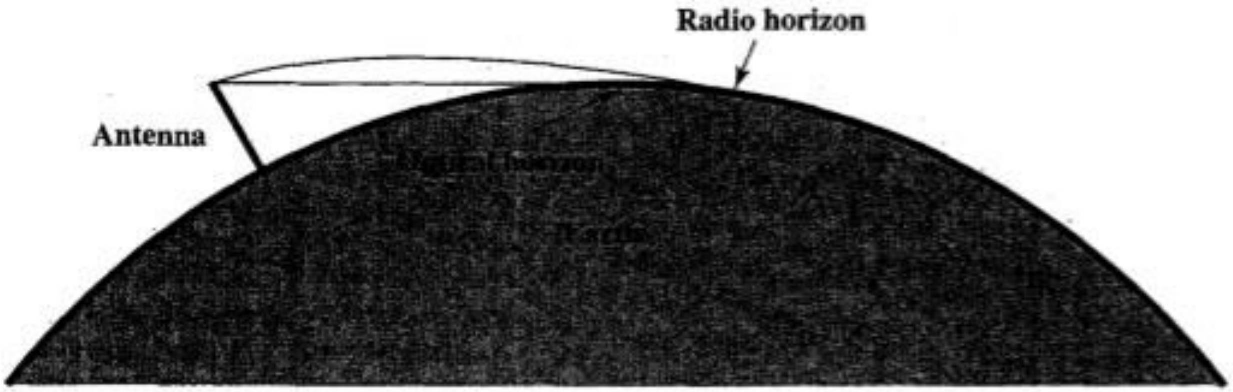


Figure 5.7 Optical and Radio Horizons

Line-of-Sight Propagation

- 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

Line-of-Sight Equations

- Optical line of sight

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

- Effective, or radio, line of sight

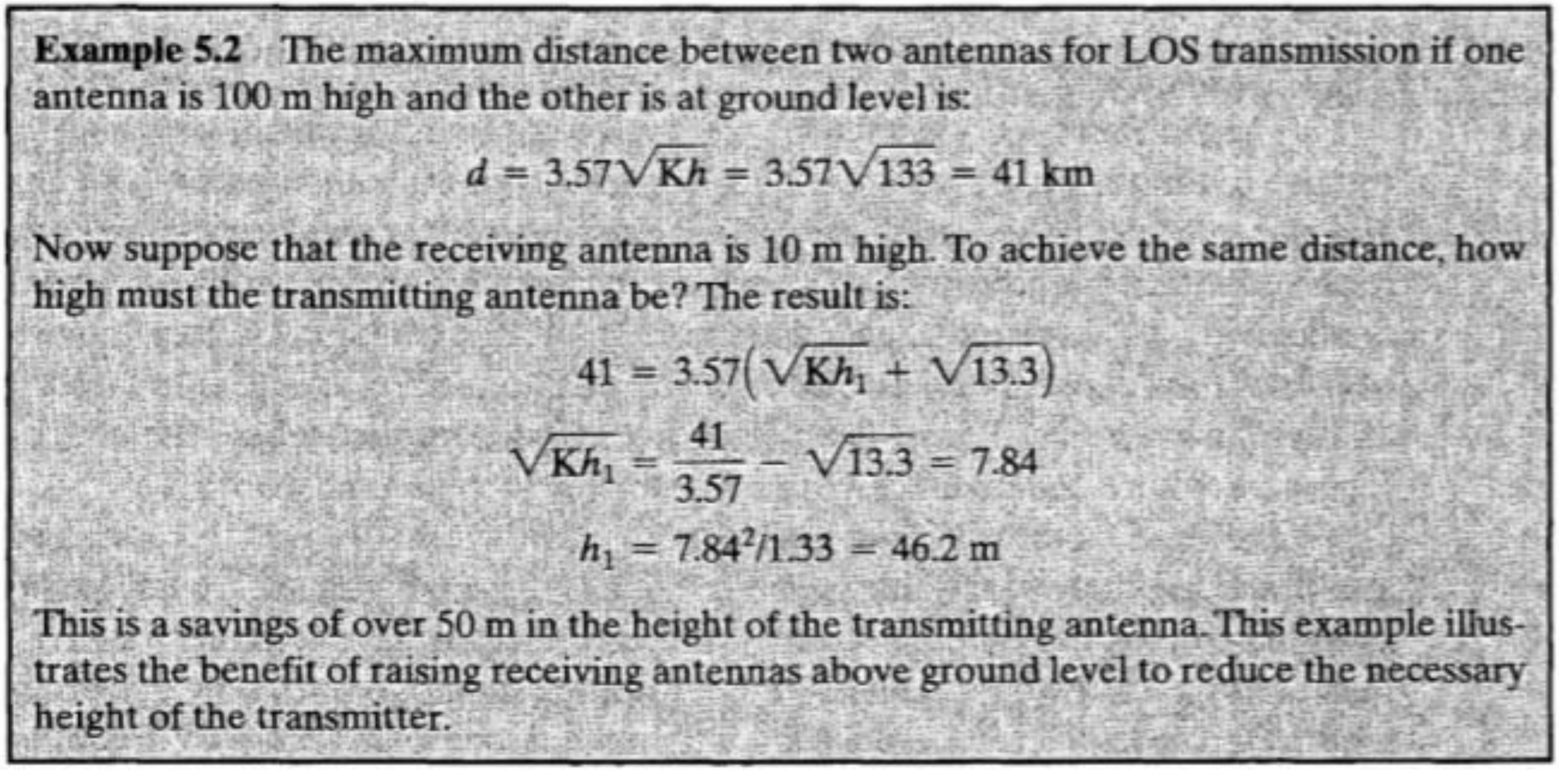
$$d = 3.57\sqrt{\mathrm{K}h}$$

  - 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:

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



Example 5.2 The maximum distance between two antennas for LOS transmission if one antenna is 100 m high and the other is at ground level is:

$$d = 3.57\sqrt{\mathrm{K}h} = 3.57\sqrt{133} = 41 \text{ km}$$

Now suppose that the receiving antenna is 10 m high. To achieve the same distance, how high must the transmitting antenna be? The result is:

$$41 = 3.57\left(\sqrt{\mathrm{K}h_1} + \sqrt{13.3}\right)$$

$$\sqrt{\mathrm{K}h_1} = \frac{41}{3.57} - \sqrt{13.3} = 7.84$$

$$h_1 = 7.84^2/1.33 = 46.2 \text{ m}$$

This is a savings of over 50 m in the height of the transmitting antenna. This example illustrates the benefit of raising receiving antennas above ground level to reduce the necessary height of the transmitter.

LOS Wireless Transmission Impairments

- Attenuation and attenuation distortion
- Free space loss
- 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
    - Use repeaters or amplifiers
  - Attenuation is greater at higher frequencies, causing distortion
    - Amplify high frequencies more than lower frequencies.

Free Space Loss

- Signal dispersion (spreading) with distance.
- Free space loss, ideal isotropic antenna:

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

- Free space loss equation can be recast:

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

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

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

Free Space Loss

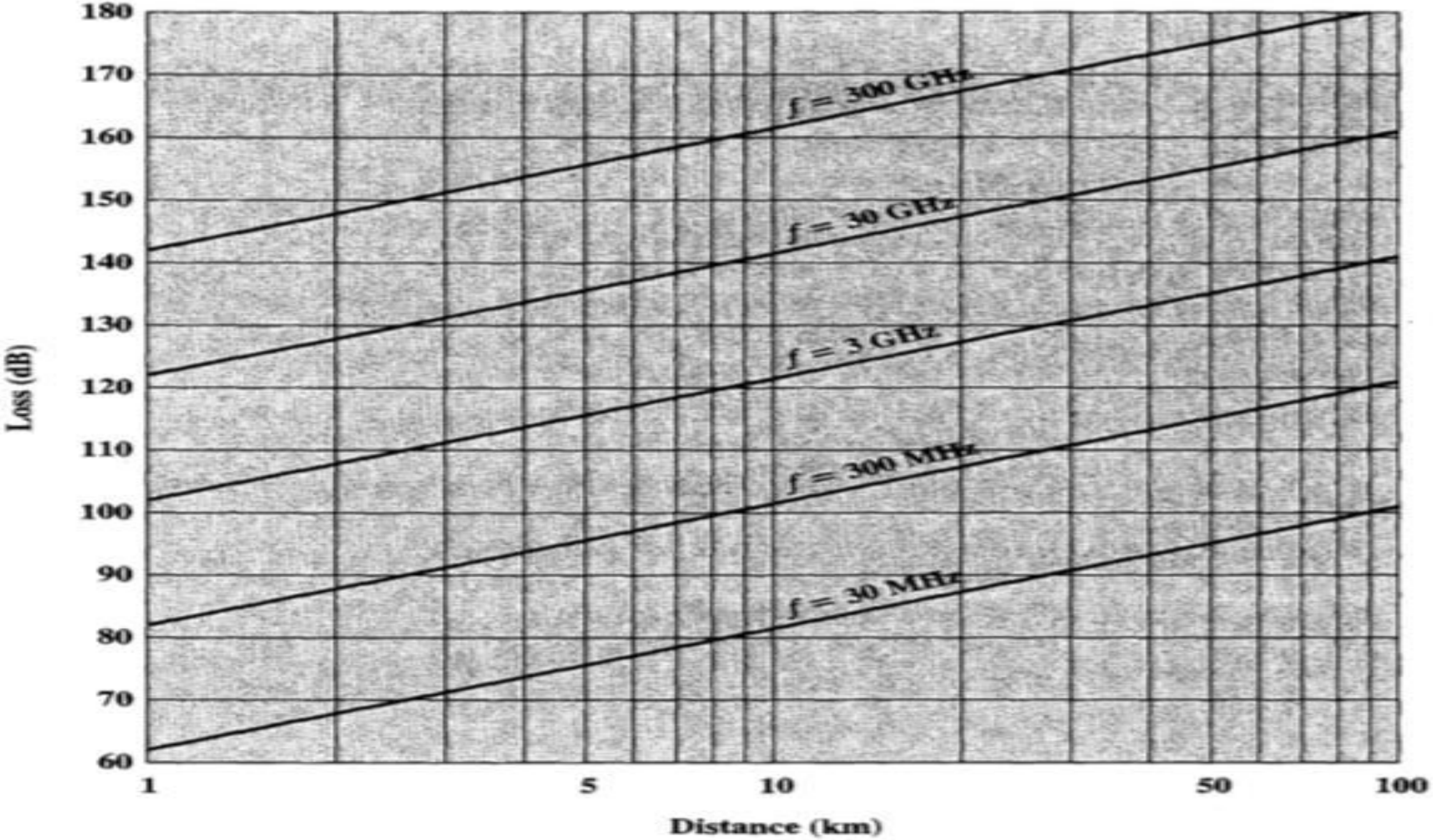
- Free space loss accounting for gain of other antennas:

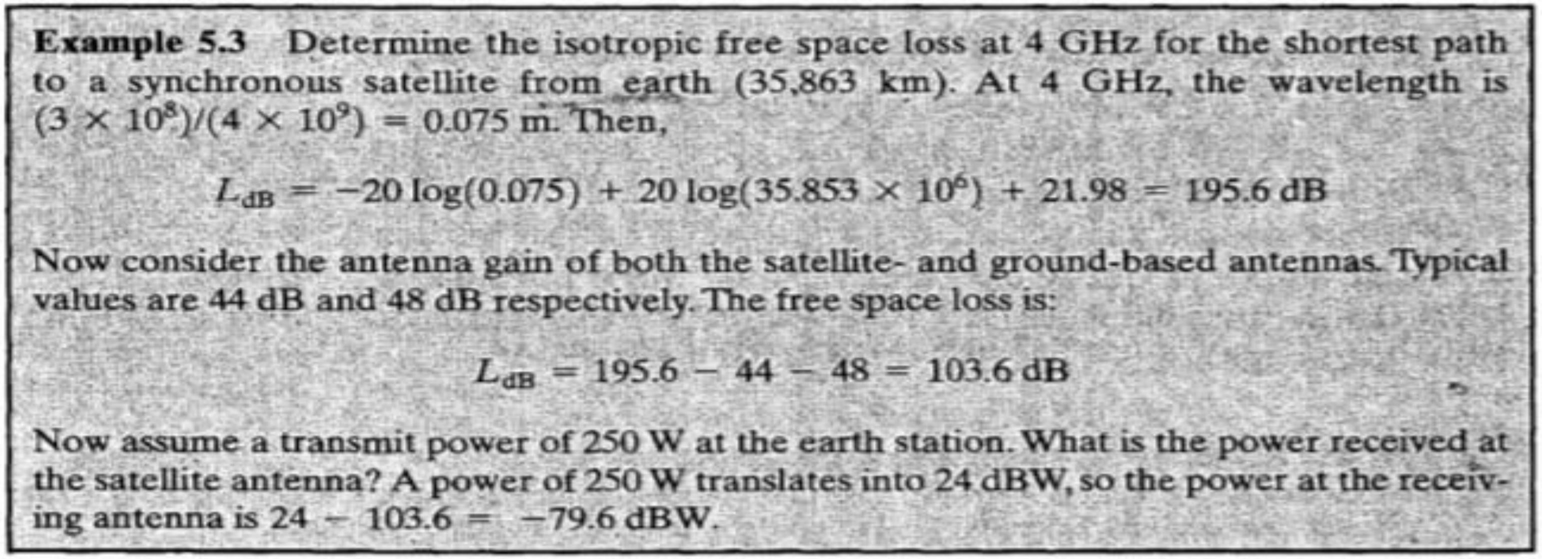
$$\frac{P_t}{P_r}=\frac{(4\pi)^2(d)^2}{G_rG_t\lambda^2}=\frac{(\lambda d)^2}{A_rA_t}=\frac{(cd)^2}{f^2A_rA_t}$$

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

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

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





Example 5.3 Determine the isotropic free space loss at 4 GHz for the shortest path to a synchronous satellite from earth (35,863 km). At 4 GHz, the wavelength is $(3 \times 10^8)/(4 \times 10^9) = 0.075$ m. Then,

$$L_{dB} = -20 \log(0.075) + 20 \log(35.853 \times 10^6) + 21.98 = 195.6 \text{ dB}$$

Now consider the antenna gain of both the satellite- and ground-based antennas. Typical values are 44 dB and 48 dB respectively. The free space loss is:

$$L_{dB} = 195.6 - 44 - 48 = 103.6 \text{ dB}$$

Now assume a transmit power of 250 W at the earth station. What is the power received at the satellite antenna? A power of 250 W translates into 24 dBW, so the power at the receiving antenna is 24 − 103.6 = −79.6 dBW.

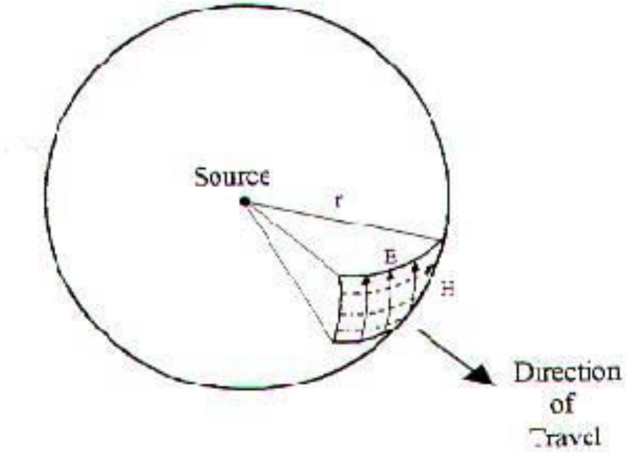
Free Space Propagation

- Isotropic Source creates electromagnetic energy of power P.
  - A spherical wave is created towards all directions
  - The energy of the source is equally distributed over the surface area of the sphere,

$$A = 4\pi r^2$$

- Therefore, at any point on the sphere, the power is equal to

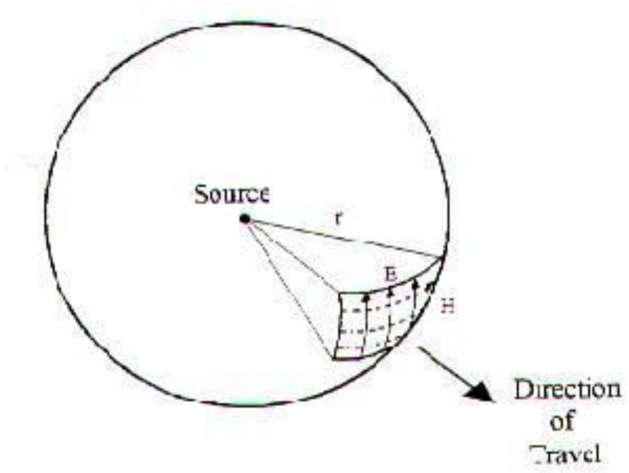
$$P_r = \frac{P}{4\pi r^2}$$



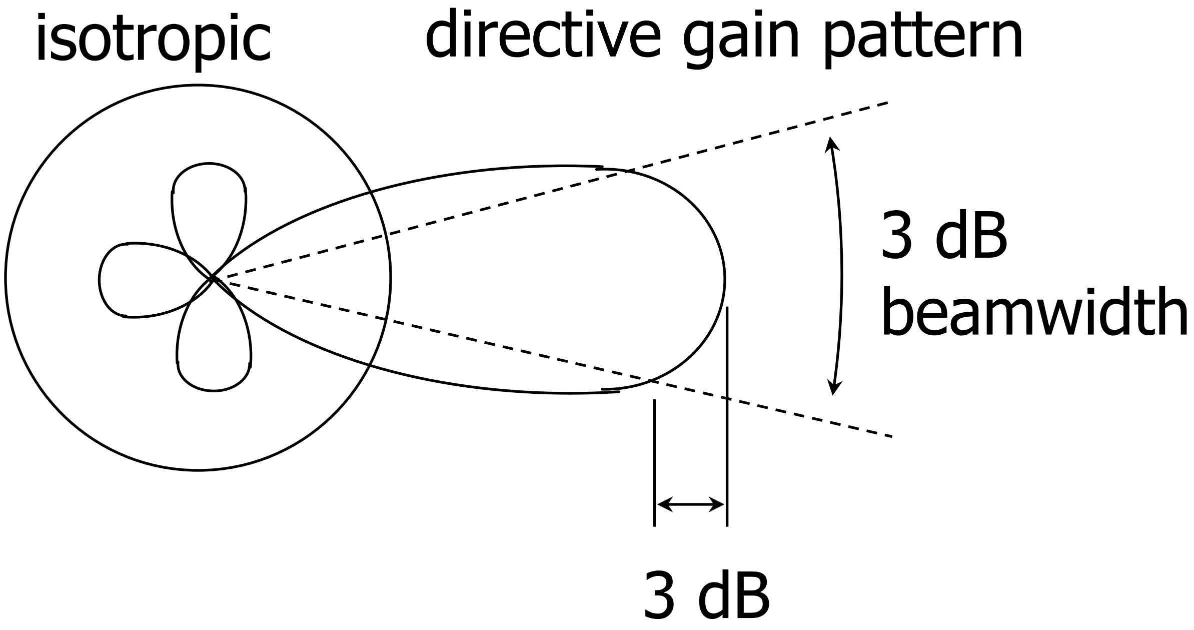
Free Space Propagation

- If the receiver has an effective area A_e , then the received power will be:

$$P_r = \frac{P}{4\pi r^2} \cdot A_e$$



Free Space Propagation



- Effective Isotropic Radiated Power *(EIRP)*$=P_t\,G_t$
- Effective area of an antenna: $$A_e=\left(\frac{\lambda^2}{4\pi}\right)G$$

Free Space Propagation

- Received power is equal to

$$P_r = P_t G_t \left[\frac{\lambda}{4\pi r} \right]^2 G_r$$

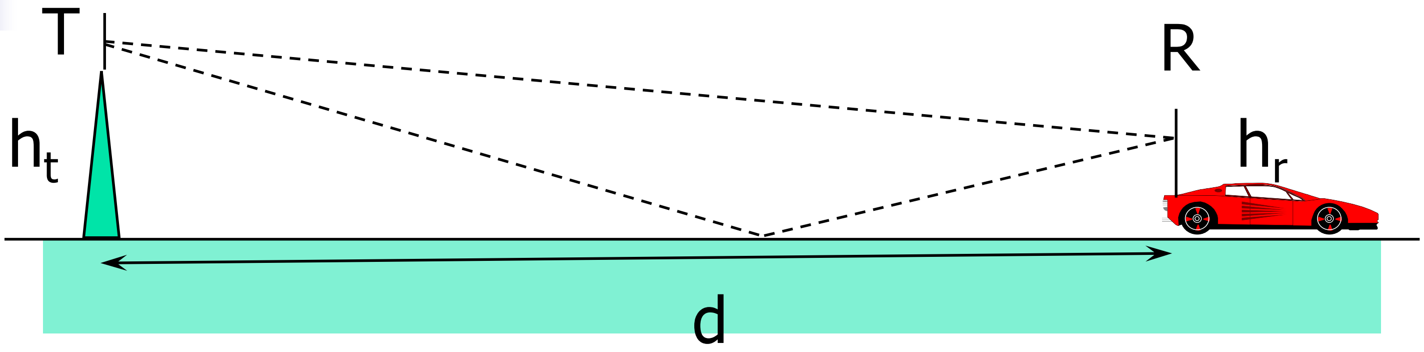
- Attenuation is equal to

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi r} \right)^2$$

- or

$$PL[dB] = 20 \log_{10} \left(\frac{\lambda}{4\pi r} \right)$$

2-Ray Ground Reflection Model



- then $$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}$$
- Note:
  - No longer depends on wavelength (d>>ht)
  - Drops off as 1/r4 instead of 1/r2

Categories of Noise

- Thermal Noise
- Intermodulation noise
- Crosstalk
- Impulse Noise

Thermal Noise

- Thermal noise due to agitation of electrons
- Present in all electronic devices and transmission media
- Cannot be eliminated
- Function of temperature
- Uniformly distributed across the frequency spectrum (white noise)
- 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:

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

  - 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:

$$\begin{aligned} N &= 10\log \mathrm{k} + 10\log T + 10\log B \\ &= -228.6\,\mathrm{dBW} + 10\log T + 10\log B \end{aligned}$$

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

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

- The bit error rate (BER) for digital data is a function of E_b/N_0 (inverse relationship)
  - 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 S must increase to maintain required E_b/N_0

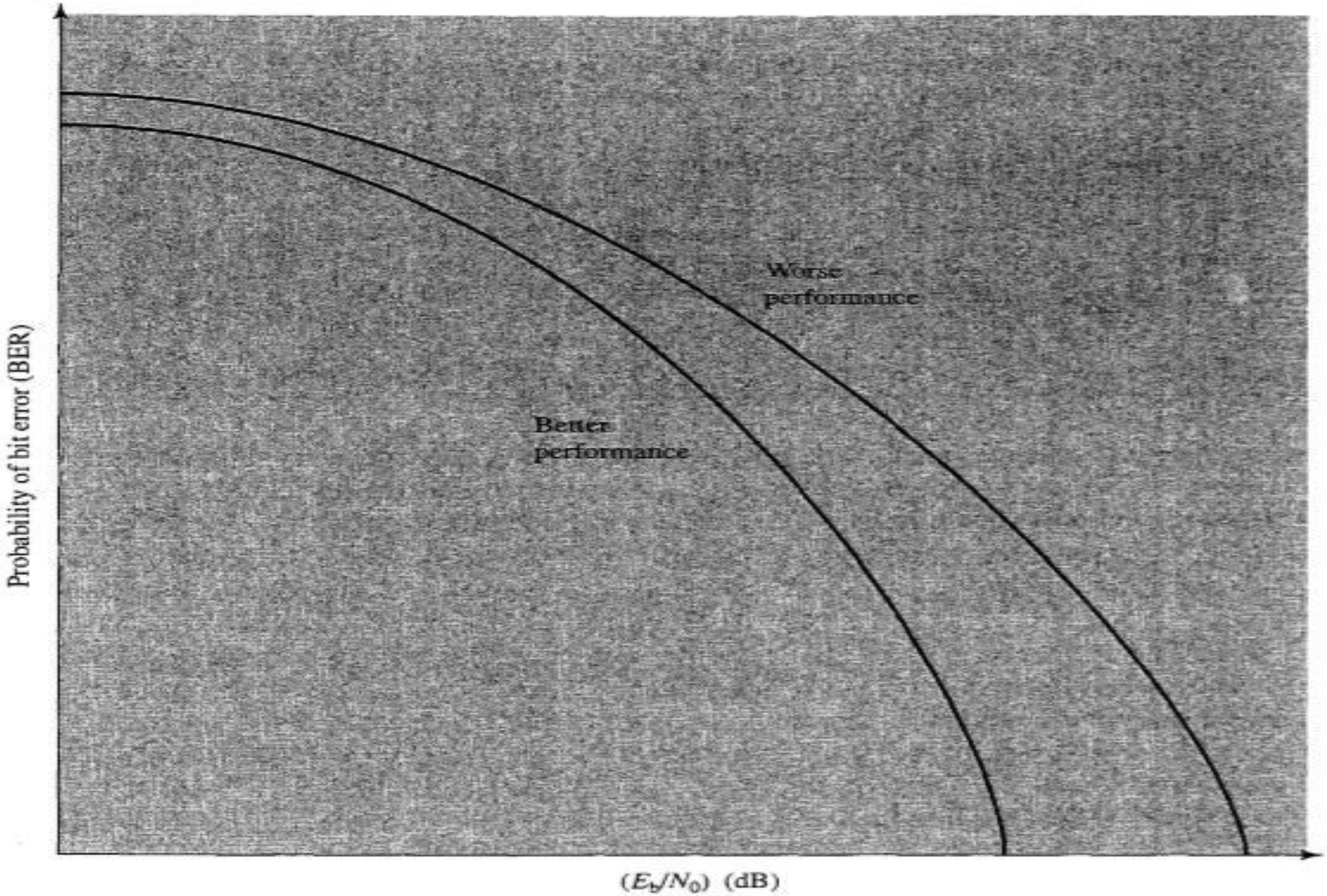


Figure 5.9 General Shape of BER Versus E_b/N_0 Curves

Example 5.6 Suppose a signal encoding technique requires that $E_b/N_0 = 8.4$ dB for a bit error rate of 10^{-4} (one bit error out of every 10,000). If the effective noise temperature is 290°K (room temperature) and the data rate is 2400 bps, what received signal level is required to overcome thermal noise?

We have

$$\begin{aligned} 8.4 &= S_{\text{dBW}} - 10 \log 2400 + 228.6 \text{ dBW} - 10 \log 290 \\ &= S_{\text{dBW}} - (10)(3.38) + 228.6 - (10)(2.46) \\ S &= -161.8 \text{ dBW} \end{aligned}$$

Other Impairments

- Atmospheric absorption – water vapor (22 GHz) and oxygen (60 GHz) 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

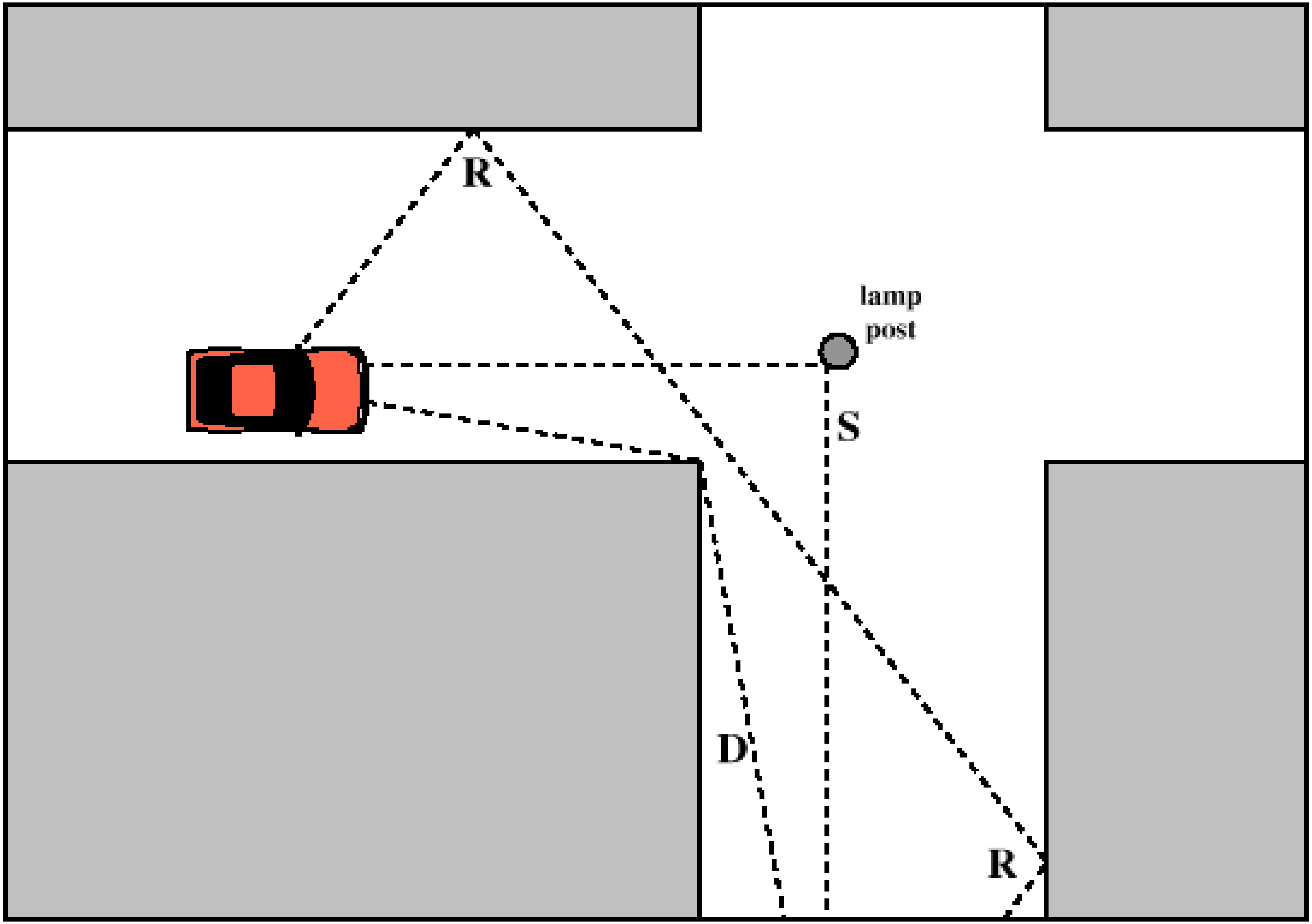


Figure 5.10 Sketch of Three Important Propagation Mechanisms: Reflection (R), Scattering (S), Diffraction (D) [ANDE95]

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

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 S/N 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

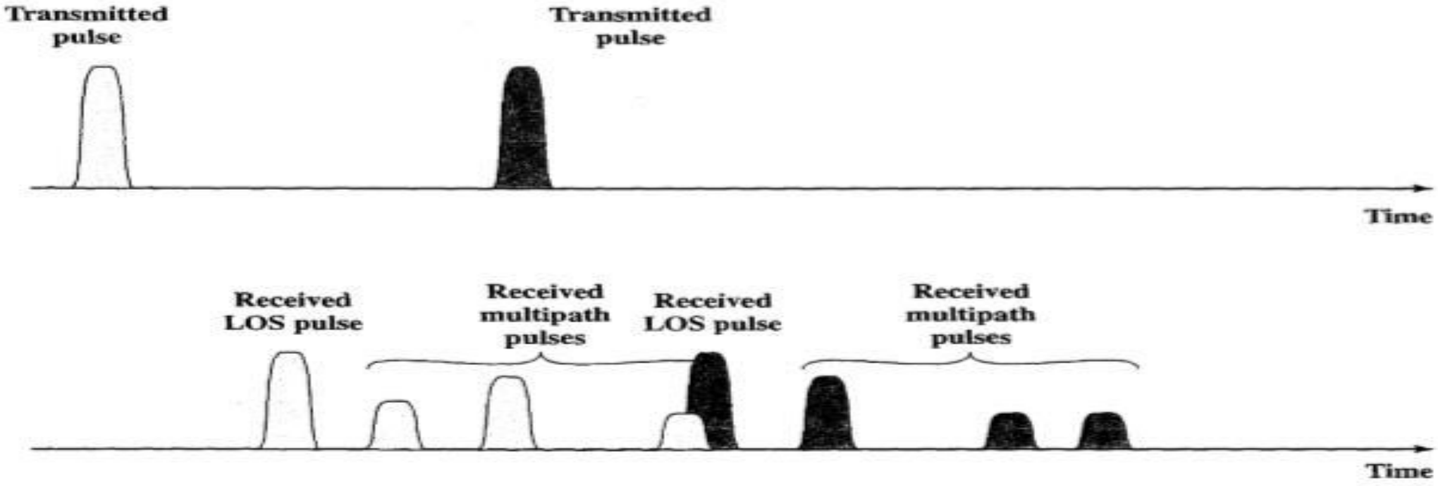


Figure 5.12 Two Pulses in Time-Variant Multipath

Error Compensation Mechanisms

- Forward error correction
- Adaptive equalization
- Diversity techniques

Forward Error Correction

- Transmitter adds error-correcting code to data block
  - Code (FEC) 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

Diversity Techniques

- Diversity is based on the fact that individual channels experience independent fading events:
- Space diversity – techniques involving physical transmission path
- 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