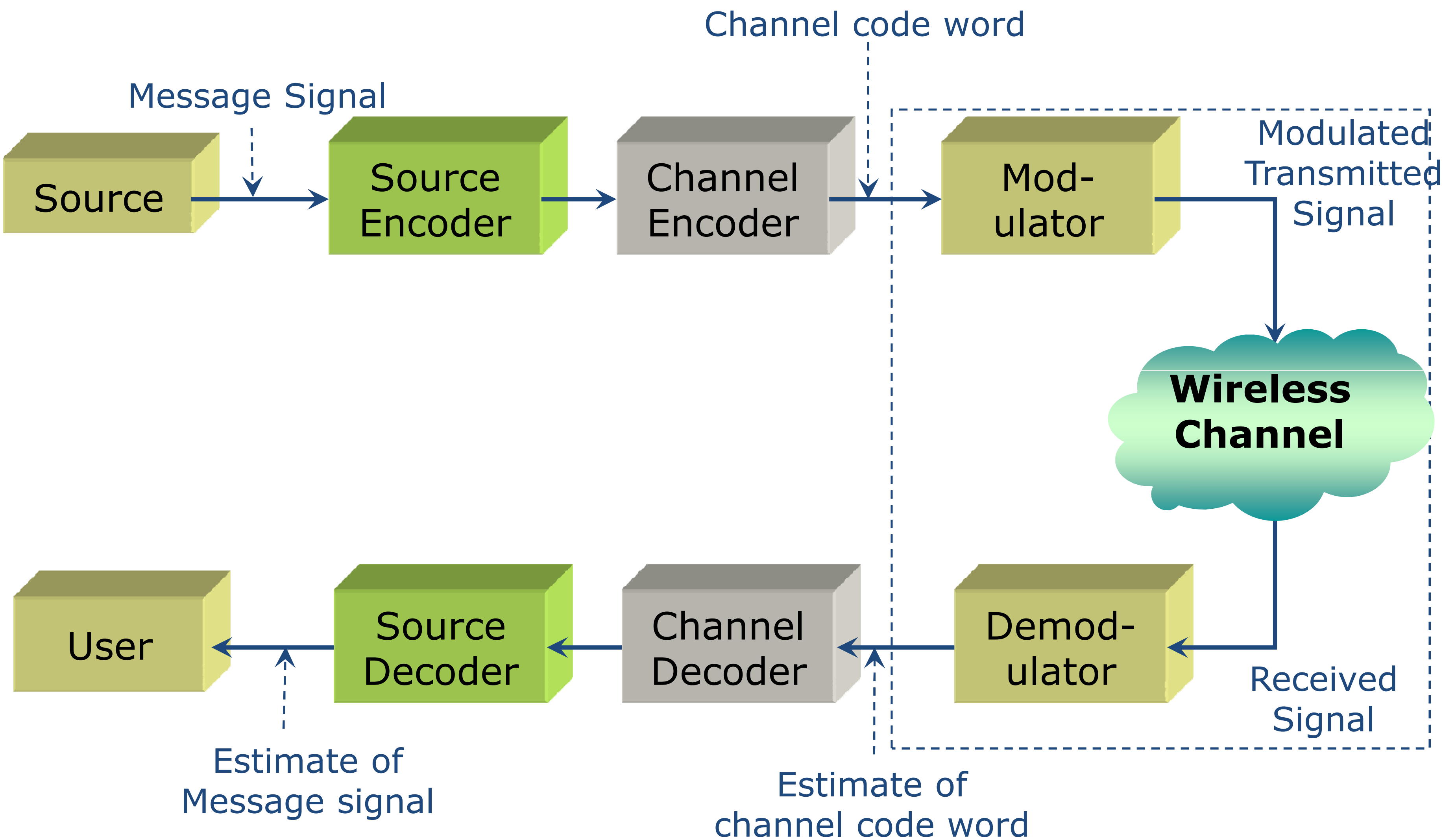
UNIVERSITAS KOMPUTER INDONESIA

Wireless and Mobile Communication

Chap 4
Antennas & Propagation
Signal Encoding

Dr. Yeffry Handoko Putra
Department of Computer Engineering

Wireless Communication System



Introduction

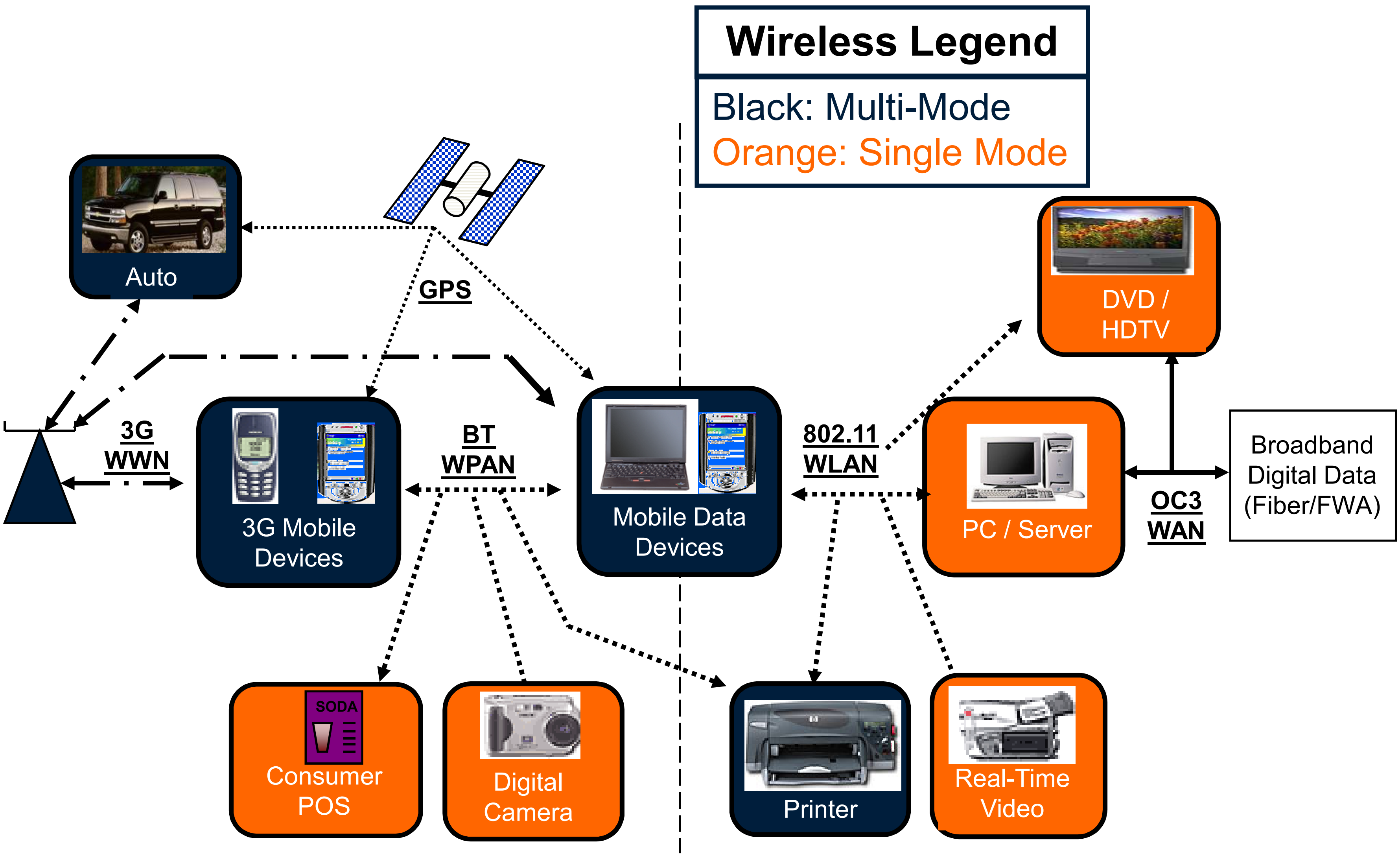
- An antenna is an electrical conductor or system of conductors
  - Transmission - radiates electromagnetic energy into space
  - Reception - collects electromagnetic energy from space
- In two-way communication, the same antenna can be used for transmission and reception

Antenna Evolution

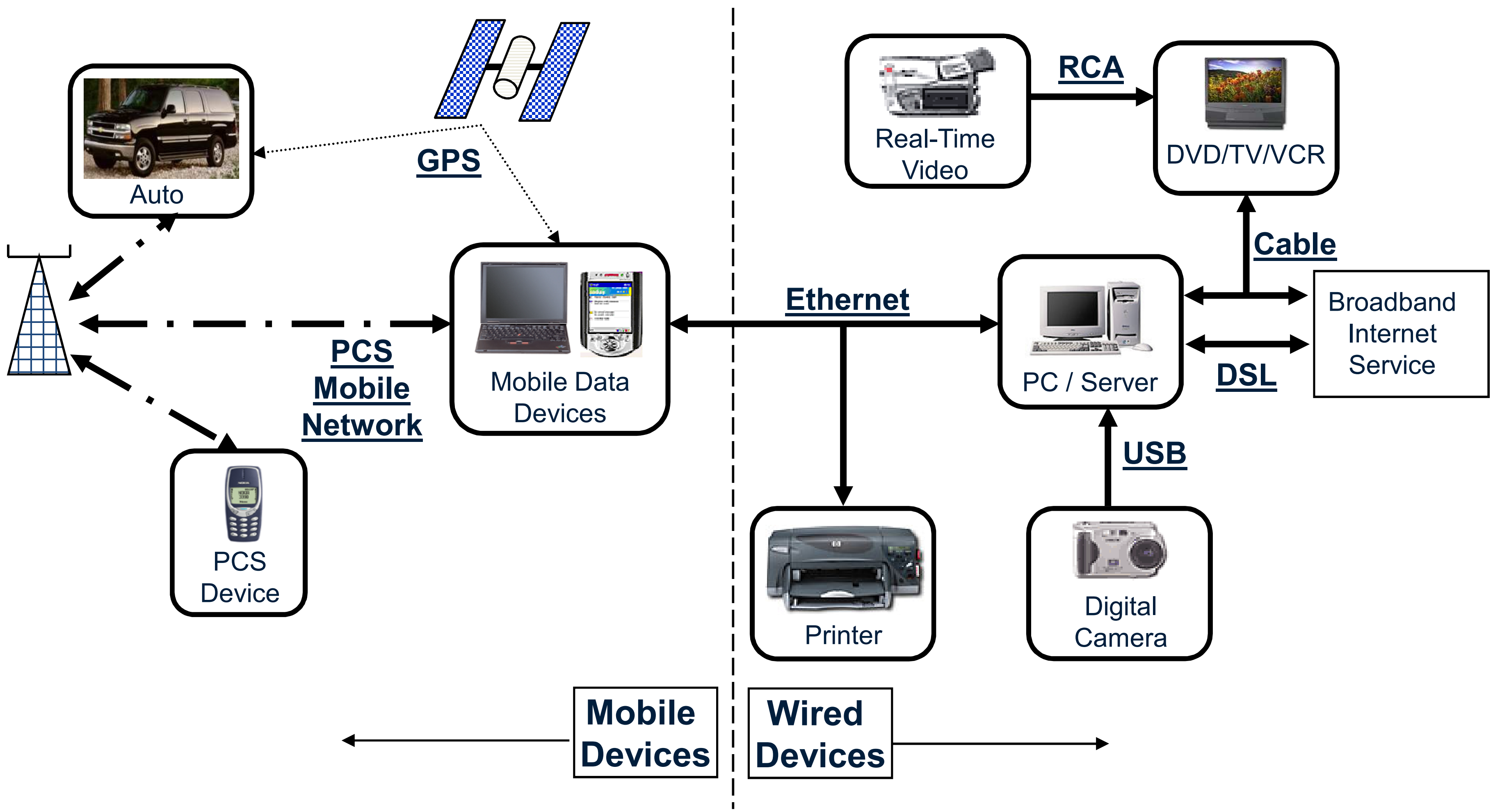
- Antennas Have Always Been the Part That Makes a Wireless Device *Wireless*
- Have Traditionally Been External, Connectorized Components
  - Misunderstood, considered *"black magic"*
  - Gangly, obtrusive
  - Added on at the end of the design
- Antennas for Mobile Devices Have Evolved Since Their Introduction
  - Whips → Retractables → Stubbies → Embedded




Future of the Wired/Wireless World

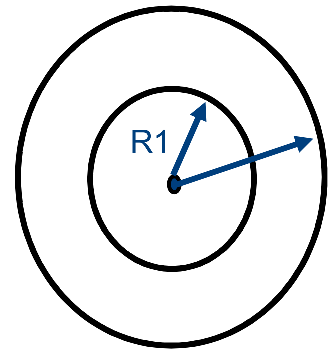


Wired/Wireless Networks of Today

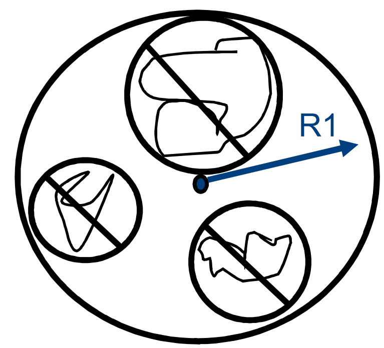


Antenna Performance

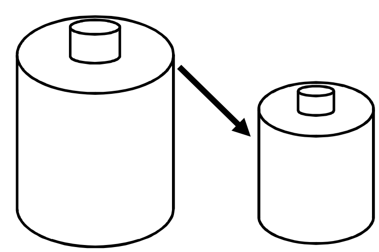
- Better Performance is Usually Achieved by Increased S/N in the Wireless Link
  - Performance improvements can be realized by higher gain antenna (if beam is properly focused)
    - <u>Example</u>: Want horizontal beam for cell phone, zenith beam for GPS
- Increased Gain Can be Used in Different Ways
  - Better cell coverage area
    - Increase cell size / range
    - Given all mobiles at max power, then less dropouts
  - Less battery power
    - Given strong signal area, then reduced Tx Battery
    - Especially critical in CDMA networks
  - Some combination of above



Increase Cell Coverage



Reduce Dropouts


Reduce Battery Size

THEORY OF ANTENNA

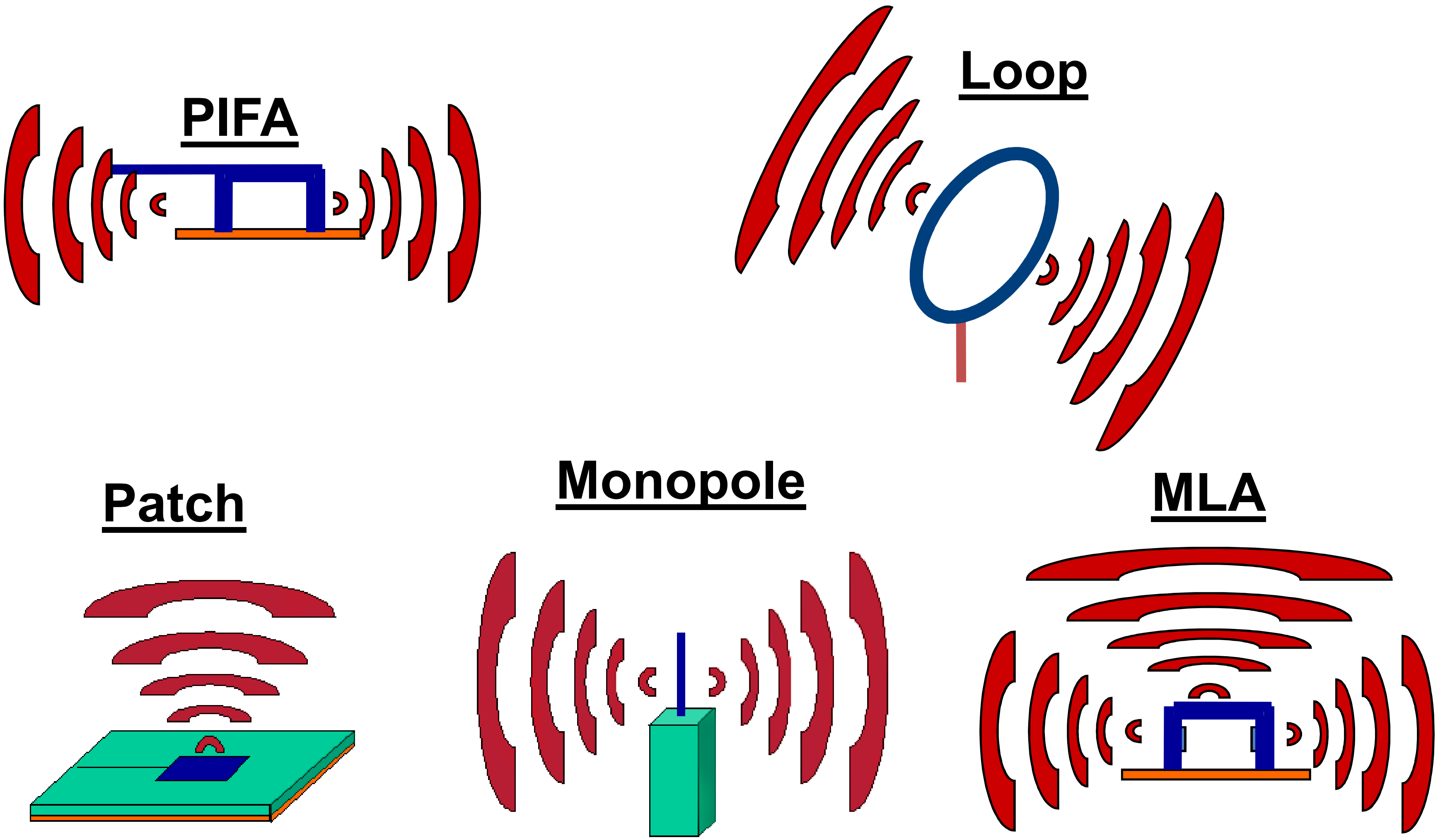
Radiation Patterns

- 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
  - Angle within which power radiated is at least half of that in most preferred direction
- Reception pattern
  - Receiving antenna's equivalent to radiation pattern
- Omnidirectional vs. directional antenna

Types of Antennas

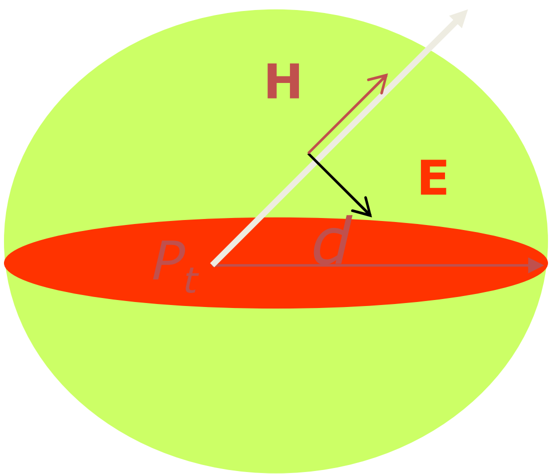
- Isotropic antenna (idealized)
  - Radiates power equally in all directions
- Dipole antennas
  - Half-wave dipole antenna (or Hertz antenna)
  - Quarter-wave vertical antenna (or Marconi antenna)
- Parabolic Reflective Antenna
  - Used for terrestrial microwave and satellite applications
  - Larger the diameter, the more tightly directional is the beam

Wireless Device Antenna Choices

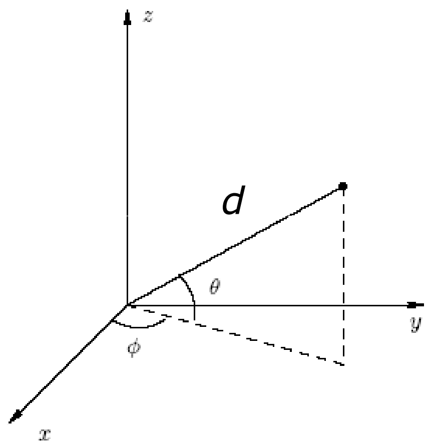


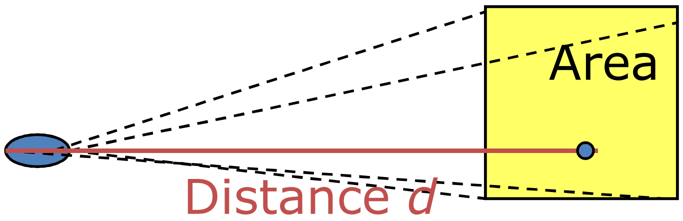
Antenna - Ideal

- Isotropics antenna: In free space radiates power equally in all direction. Not realizable physically



EM fields around a transmitting antenna , a polar coordinate





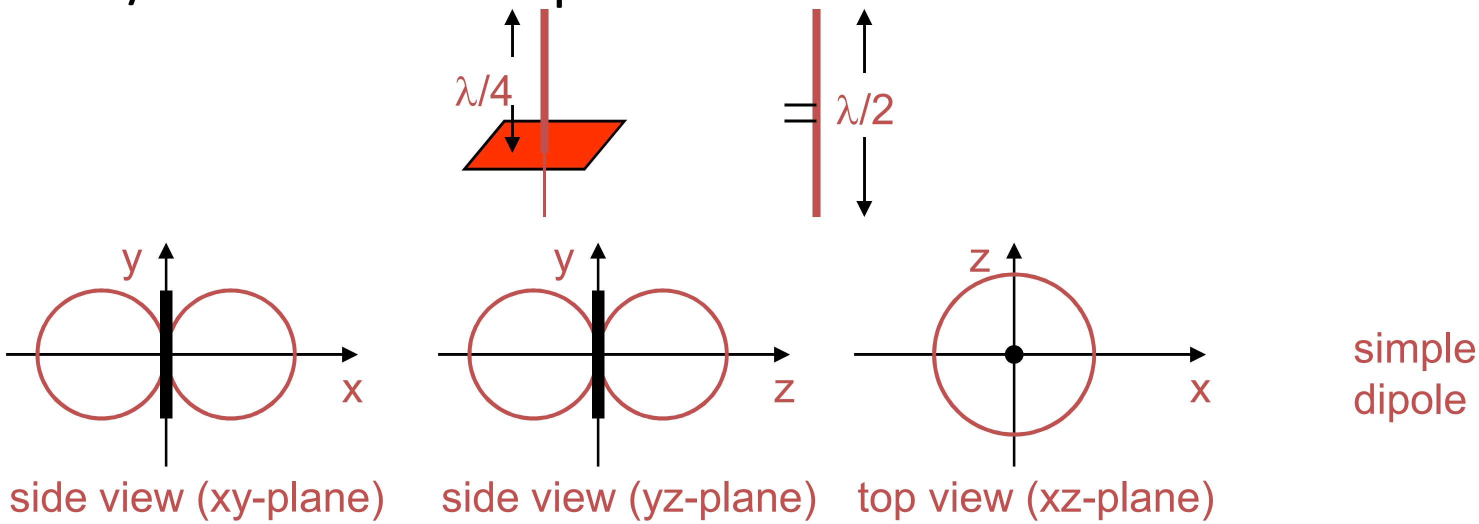
- *d*- distance directly away from the antenna.
- ϕ is the azimuth, or angle in the horizontal plane.
- θ is the zenith, or angle above the horizon.

Antenna - Real

- Not isotropic radiators, but always have directive effects (vertically and/or horizontally)
- A well defined radiation pattern measured around an antenna
- Patterns are visualised by drawing the set of constant-intensity surfaces

Antenna – Real - Simple Dipoles

- Not isotropic radiators, e.g., dipoles with lengths λ/4 on car roofs or λ/2 as Hertzian dipole

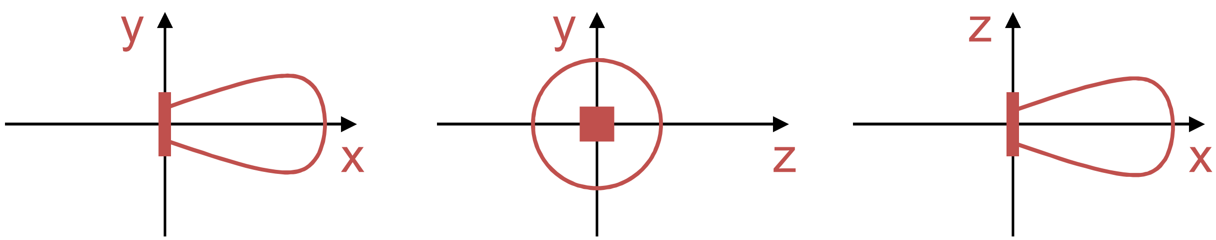


- Example: Radiation pattern of a simple Hertzian dipole

shape of antenna is proportional to the wavelength

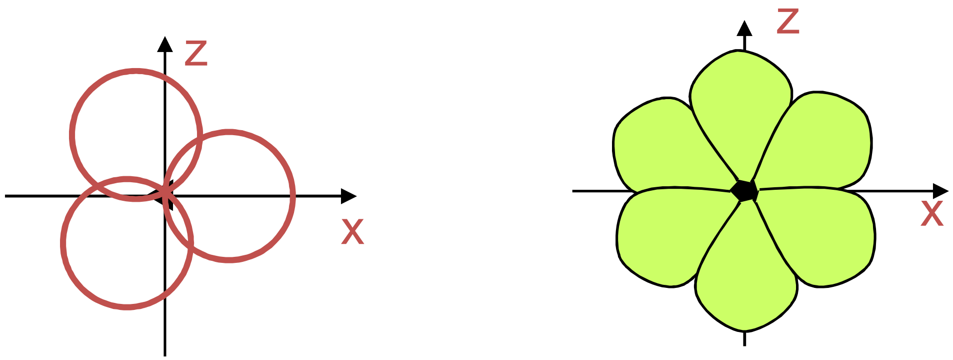
Antenna – Real - Sdirected and Sectorized

- Used for microwave or base stations for mobile phones (e.g., radio coverage of a valley)



side view (xy-plane) side view (yz-plane) top view (xz-plane)

Directed



top view, 3 sector

top view, 6 sector

Sectorized

Antenna Gain

- Antenna gain
  - Power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna (isotropic antenna)
- Expressed in terms of 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 ($\approx 3 \times 10^8$ m/s)
  - λ = carrier wavelength

Antenna - Ideal - *contd.*

- The power density of an ideal loss-less antenna at a distance *d* away from the transmitting antenna:

$$P_a = \frac{P_t G_t}{4\pi d^2} \quad \text{W/m}^2$$

Note: the area is for a sphere.

- G_t is the transmitting antenna gain
- The product $P_t G_t$: **Equivalent Isotropic Radiation Power (EIRP)**

which is the power fed to a perfect isotropic antenna to get the same output power of the practical antenna in hand.

Antenna - Ideal - *contd.*

- The strength of the signal is often defined in terms of its Electric Field Intensity *E*, because it is easier to measure.

$P_a = E^2/R_m$ *where R_m is the impedance of the medium. For free space R_m = 377 Ohms.*

$$E^2 = \frac{P_t R_m}{4\pi d^2} \quad and \quad E = \sqrt{\frac{P_t R_m}{4\pi d^2}}$$

V/m

Antenna - Ideal - *contd.*

- The receiving antenna is characterized by its effective aperture A_e, which describes how well an antenna can pick up power from an incoming electromagnetic wave
- The effective aperture A_e is related to the gain G_r as follows:

$$A_e = P_r / P_a \Rightarrow A_e = G_r \lambda^2 / 4\pi$$

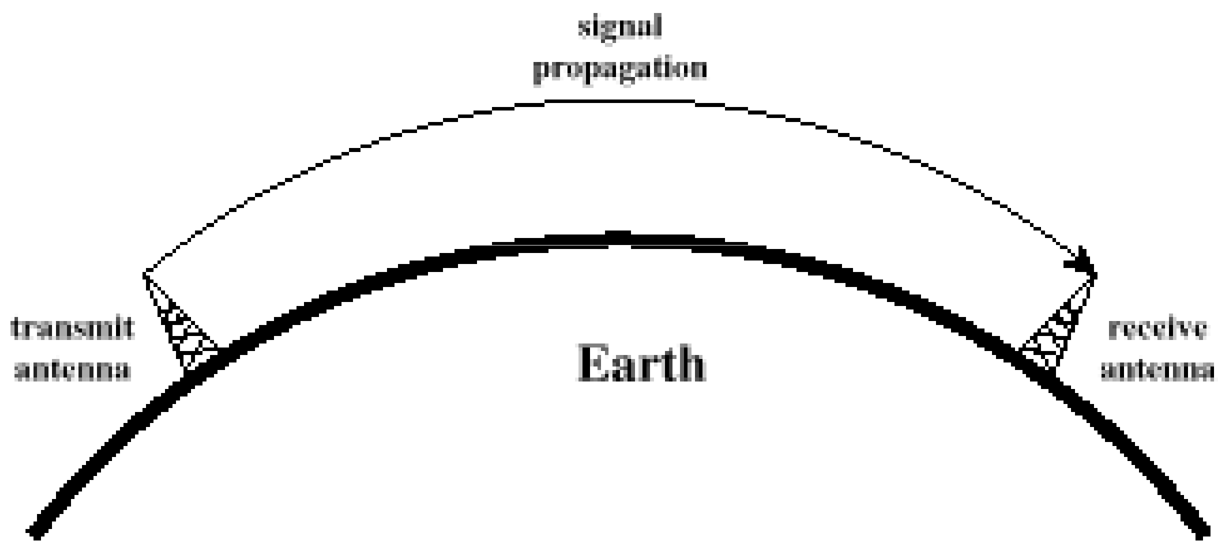
which is the equivalent power absorbing area of the antenna.

G_r is the receiving antenna gain and $\lambda = c/f$

Propagation Modes

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

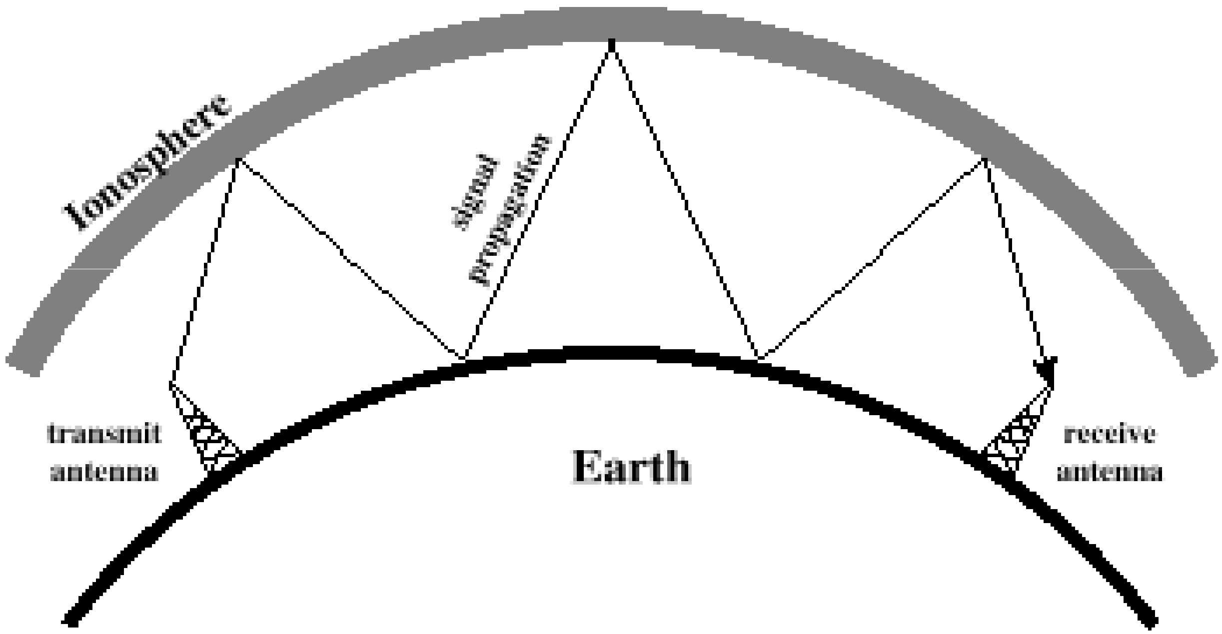
Ground Wave Propagation



Ground Wave Propagation

- Follows contour of the earth
- Can Propagate considerable distances
- Frequencies up to 2 MHz
- Example
  - AM radio

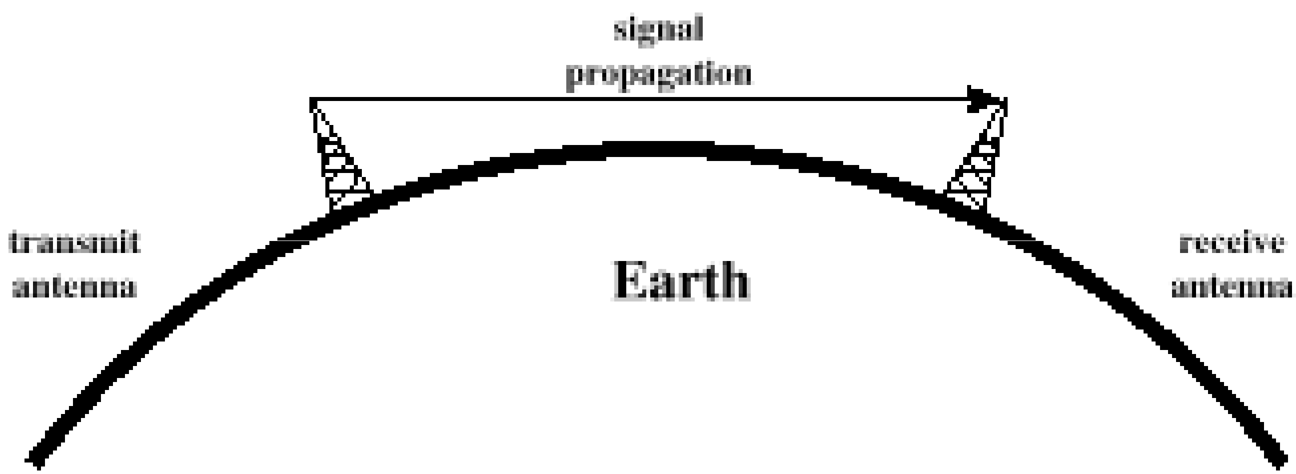
Sky Wave Propagation



Sky Wave Propagation

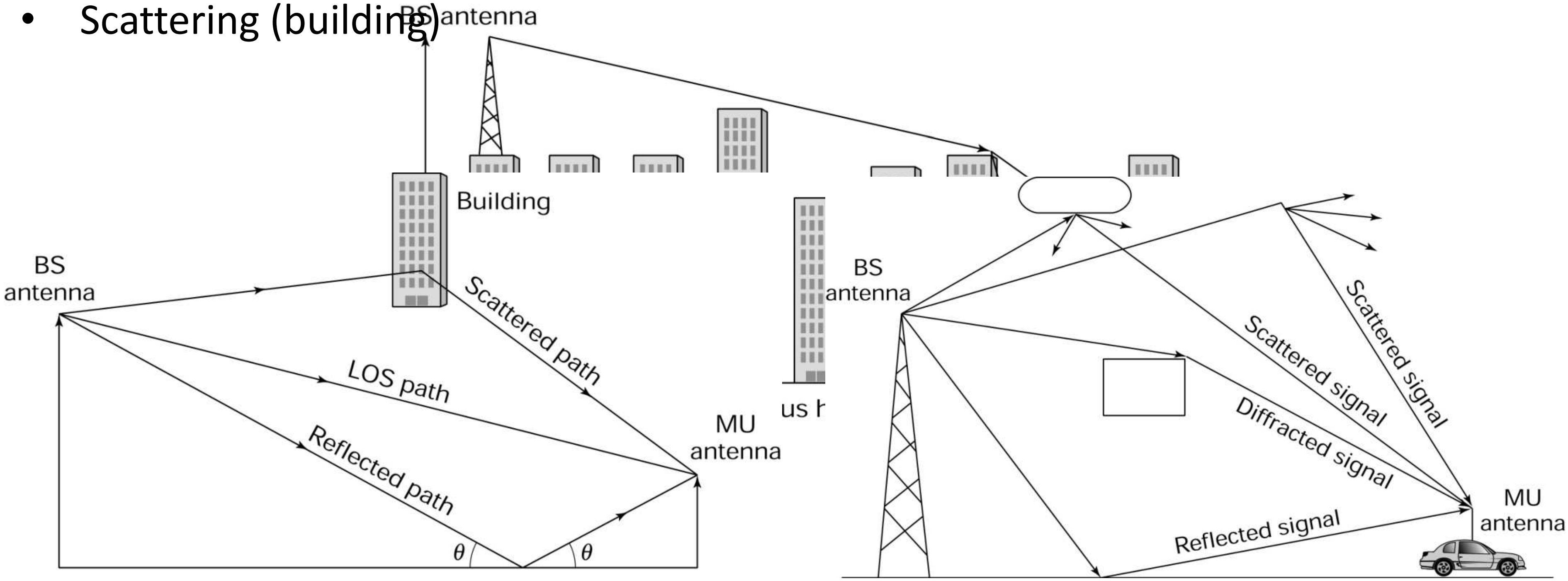
- Signal reflected from ionized layer of atmosphere back down to earth
- Signal can travel a number of hops, back and forth between ionosphere and earth's surface
- Reflection effect caused by refraction
- Examples
  - Amateur radio
  - CB radio

Line-of-Sight Propagation



Propagation Non line of sight

- Reflection (rough terrain, moving vehicle)
- Diffraction (edge of Building)
- Scattering (building)



Source: P M Shankar

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:

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

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

LOS Wireless Transmission Impairments

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

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:

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

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

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

Free Space Loss

- Free space loss accounting for gain 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 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

- Thermal 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:

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

  - 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

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

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

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
  - Primary source of error for digital data transmission

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 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

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

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 is in the order of the wavelength of the signal or less

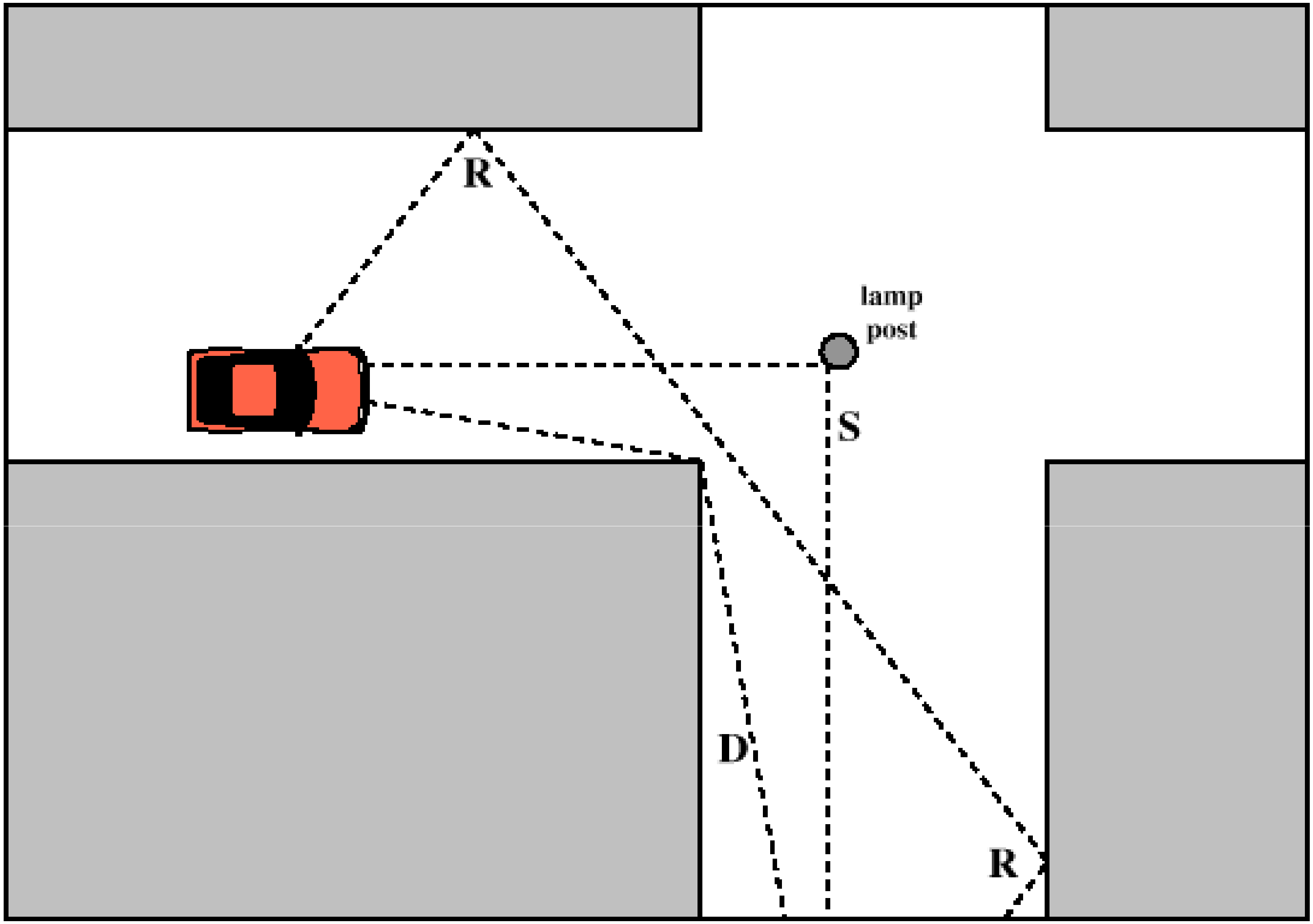


Figure 5.10 Sketch of Three Important Propagation Mechanisms: Reflection (R), Scattering (S), Diffraction (D) [ANDE95]

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

Fading

- Time variation of received signal power caused by changes in the transmission medium or path(s)
- In a fixed environment:
  - Changes in atmospheric conditions
- In a mobile environment:
  - Multipath propagation

Types of Fading

- Fast fading
- Slow fading
- Flat fading
- Selective fading
- Rayleigh fading
- Rician fading

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

Diversity Techniques

- Space diversity:
  - Use multiple nearby antennas and combine received signals to obtain the desired signal
  - Use collocated multiple directional antennas
- Frequency diversity:
  - Spreading out signal over a larger frequency bandwidth
  - Spread spectrum
- Time diversity:
  - Noise often occurs in bursts
  - Spreading the data out over time spreads the errors and hence allows FEC techniques to work well
  - TDM
  - Interleaving

Signal Encoding Techniques

Reasons for Choosing Encoding Techniques

- Digital data, digital signal
  – Equipment less complex and expensive than digital-to-analog modulation equipment
- Analog data, digital signal
  – Permits use of modern digital transmission and switching equipment

Reasons for Choosing Encoding Techniques

- Digital data, analog signal
  - Some transmission media will only propagate analog signals
  - E.g., unguided media
- Analog data, analog signal
  - Analog data in electrical form can be transmitted easily and cheaply
  - Done with voice transmission over voice-grade lines

Signal Encoding Criteria

- What determines how successful a receiver will be in interpreting an incoming signal?
  - Signal-to-noise ratio
  - Data rate
  - Bandwidth
- An increase in data rate increases bit error rate
- An increase in SNR decreases bit error rate
- An increase in bandwidth allows an increase in data rate

Comparing Encoding Schemes

- Signal spectrum
  - With lack of high-frequency components, less bandwidth required
  - With no dc component, ac coupling via transformer possible
  - Transfer function of a channel is worse near band edges
- Clocking
  - Ease of determining beginning and end of each bit position

Comparing Encoding Schemes

- Signal interference and noise immunity
  - Performance in the presence of noise
- Cost and complexity
  - The higher the signal rate to achieve a given data rate, the greater the cost

Digital Data to Analog Signals

- Amplitude-shift keying (ASK)
  - Amplitude difference of carrier frequency
- Frequency-shift keying (FSK)
  - Frequency difference near carrier frequency
- Phase-shift keying (PSK)
  - Phase of carrier signal shifted

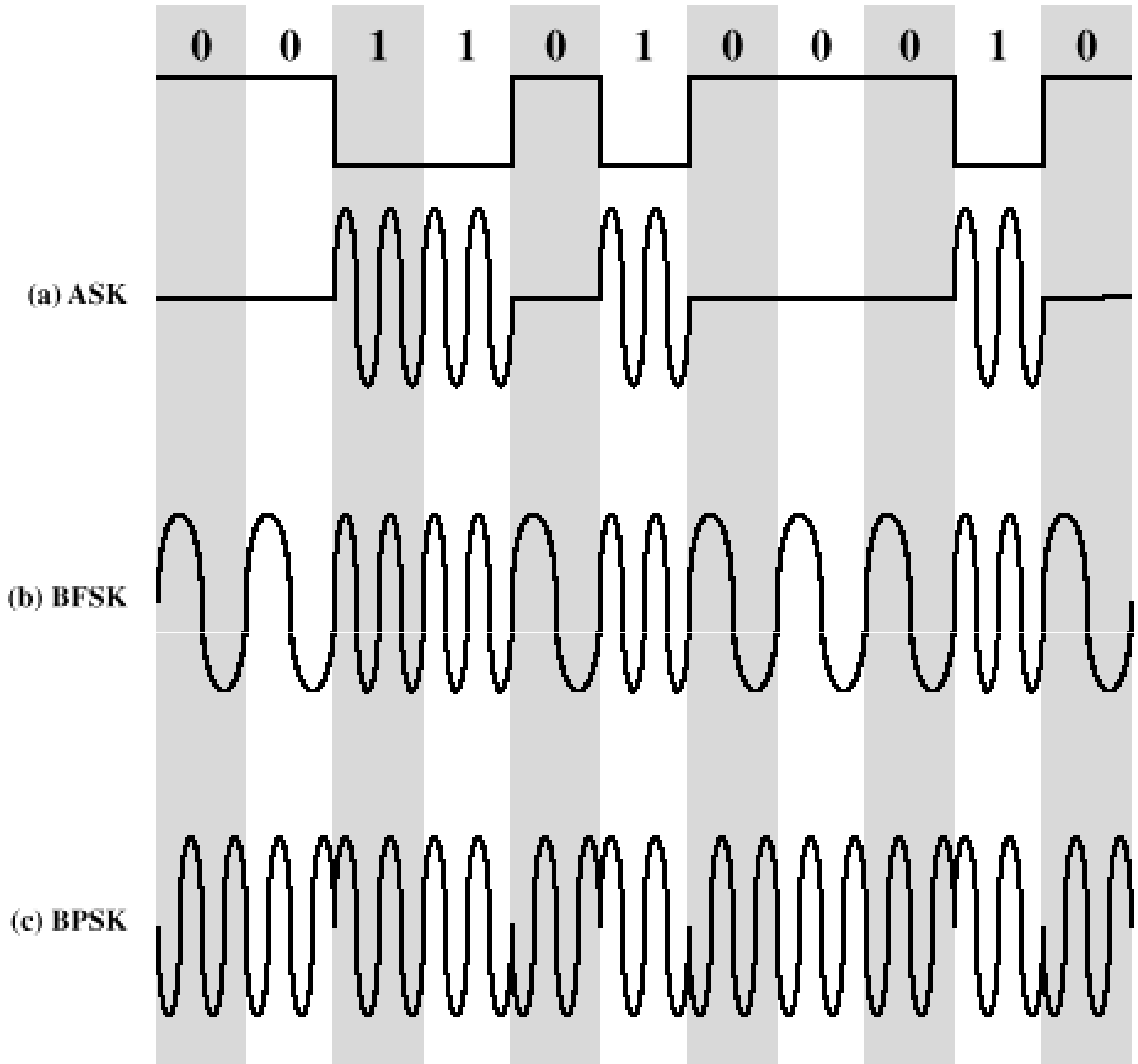


Figure 6.2 Modulation of Analog Signals for Digital Data

Amplitude-Shift Keying

- One binary digit represented by presence of carrier, at constant amplitude
- Other binary digit represented by absence of carrier

$$s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ 0 & \text{binary } 0 \end{cases}$$

- where the carrier signal is $A\cos(2\pi f_c t)$

Amplitude-Shift Keying

- Susceptible to sudden gain changes
- Inefficient modulation technique
- On voice-grade lines, used up to 1200 bps
- Used to transmit digital data over optical fiber

Binary Frequency-Shift Keying (BFSK)

- Two binary digits represented by two different frequencies near the carrier frequency

$$s(t) = \begin{cases} A\cos(2\pi f_1 t) & \text{binary } 1 \\ A\cos(2\pi f_2 t) & \text{binary } 0 \end{cases}$$

  - where f_1 and f_2 are offset from carrier frequency f_c by equal but opposite amounts

Binary Frequency-Shift Keying (BFSK)

- Less susceptible to error than ASK
- On voice-grade lines, used up to 1200bps
- Used for high-frequency (3 to 30 MHz) radio transmission
- Can be used at higher frequencies on LANs that use coaxial cable

Multiple Frequency-Shift Keying (MFSK)

- More than two frequencies are used
- More bandwidth efficient but more susceptible to error

$$s_i(t) = A \cos 2\pi f_i t \qquad 1 \le i \le M$$

- $f_i = f_c + (2i - 1 - M)f_d$
- f_c = the carrier frequency
- f_d = the difference frequency
- M = number of different signal elements = 2^L
- L = number of bits per signal element

Multiple Frequency-Shift Keying (MFSK)

- To match data rate of input bit stream, each output signal element is held for:

  $$T_s = LT \text{ seconds}$$

  - where T is the bit period (data rate = $1/T$)
- So, one signal element encodes L bits

Multiple Frequency-Shift Keying (MFSK)

- Total bandwidth required

$$2Mf_d$$

- Minimum frequency separation required $2f_d=1/T_s$
- Therefore, modulator requires a bandwidth of

$$W_d=2^L/LT=M/T_s$$

Multiple Frequency-Shift Keying (MFSK)

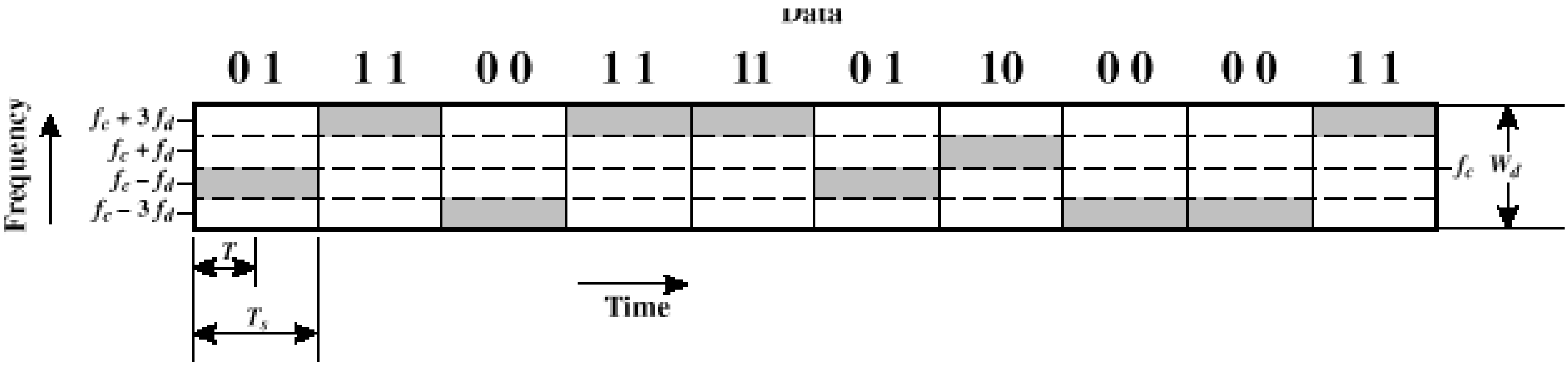


Figure 6.4 MFSK Frequency Use (M = 4)

Phase-Shift Keying (PSK)

- Two-level PSK (BPSK)
  - Uses two phases to represent binary digits

$$s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ A\cos(2\pi f_c t + \pi) & \text{binary } 0 \end{cases}$$

$$= \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ -A\cos(2\pi f_c t) & \text{binary } 0 \end{cases}$$

Phase-Shift Keying (PSK)

- Differential PSK (DPSK)
  - Phase shift with reference to previous bit
    - Binary 0 – signal burst of same phase as previous signal burst
    - Binary 1 – signal burst of opposite phase to previous signal burst

Phase-Shift Keying (PSK)

- Four-level PSK (QPSK)
  - Each element represents more than one bit

$$s(t) = \begin{cases} A\cos\left(2\pi f_c t + \dfrac{\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t + \dfrac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t - \dfrac{3\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t - \dfrac{\pi}{4}\right) & 10 \end{cases}$$

Phase-Shift Keying (PSK)

- Multilevel PSK
  - Using multiple phase angles with each angle having more than one amplitude, multiple signals elements can be achieved

$$D = \frac{R}{L} = \frac{R}{\log_2 M}$$

- D = modulation rate, baud
- R = data rate, bps
- M = number of different signal elements = 2^L
- L = number of bits per signal element

Performance

- Bandwidth of modulated signal (B_T)
  - ASK, PSK $B_T=(1+r)R$
  - FSK $B_T=2DF+(1+r)R$
    - R = bit rate
    - $0 < r < 1$; related to how signal is filtered
    - $DF = f_2-f_c=f_c-f_1$

Performance

- Bandwidth of modulated signal (B_T)
  - MPSK
    $$B_T = \left(\frac{1+r}{L}\right)R = \left(\frac{1+r}{\log_2 M}\right)R$$
  - MFSK
    $$B_T = \left(\frac{(1+r)M}{\log_2 M}\right)R$$

    - L = number of bits encoded per signal element
    - M = number of different signal elements

Quadrature Amplitude Modulation

- QAM is a combination of ASK and PSK
  - Two different signals sent simultaneously on the same carrier frequency

$$s(t) = d_1(t)\cos 2\pi f_c t + d_2(t)\sin 2\pi f_c t$$

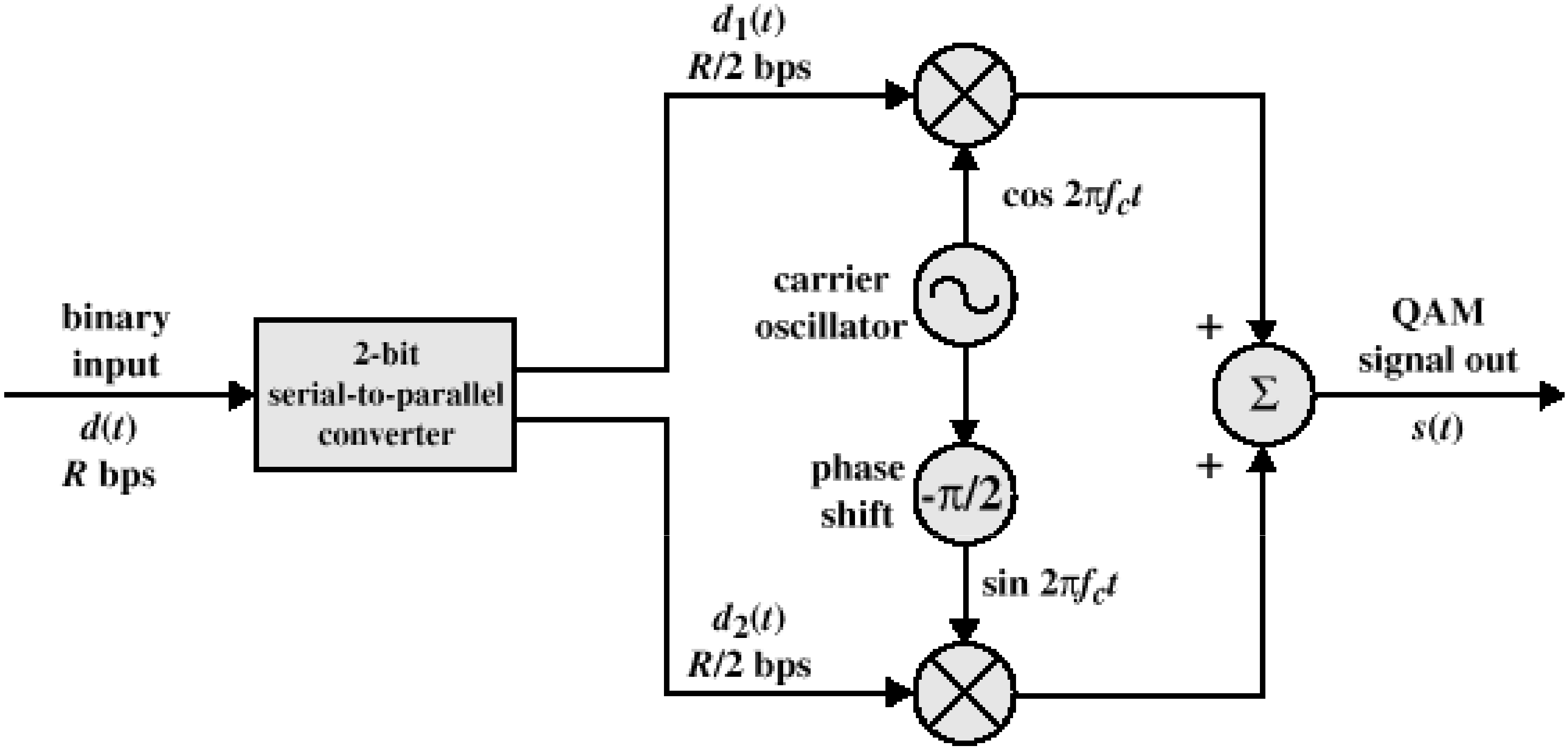


Figure 6.10 QAM Modulator

Analog Data to Analog Signal

- Modulation of digital signals
  - When only analog transmission facilities are available, digital to analog conversion required
- Modulation of analog signals
  - A higher frequency may be needed for effective transmission
  - Modulation permits frequency division multiplexing

Mopdulation Techniques

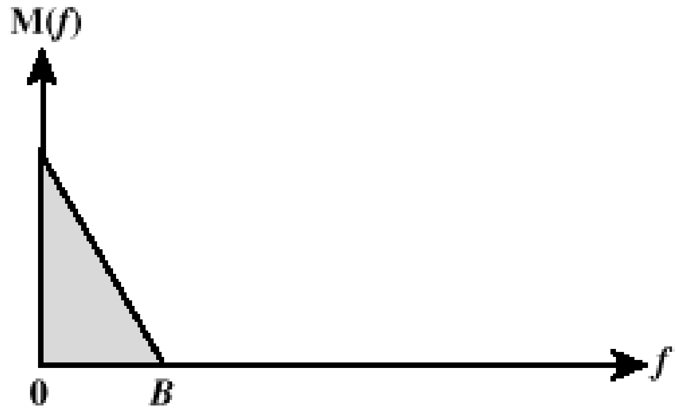
- Amplitude modulation (AM)
- Angle modulation
  - Frequency modulation (FM)
  - Phase modulation (PM)

Amplitude Modulation

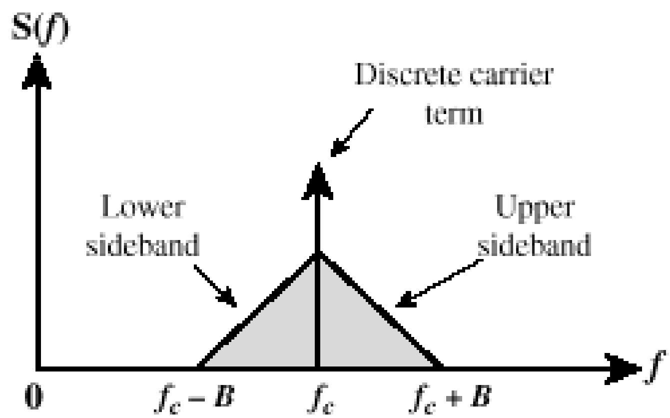
- Amplitude Modulation

$$s(t) = [1 + n_a x(t)]\cos 2\pi f_c t$$

  - $\cos 2\pi f_c t$ = carrier
  - $x(t)$ = input signal
  - n_a = modulation index (< 1)
    - Ratio of amplitude of input signal to carrier
- a.k.a double sideband transmitted carrier (DSBTC)



(a) Spectrum of modulating signal



(b) Spectrum of AM signal with carrier at f_c

Figure 6.12 Spectrum of an AM Signal

Amplitude Modulation

- Transmitted power

$$P_t = P_c\left(1 + \frac{{n_a}^2}{2}\right)$$

  - P_t = total transmitted power in $s(t)$
  - P_c = transmitted power in carrier

Single Sideband (SSB)

- Variant of AM is single sideband (SSB)
  - Sends only one sideband
  - Eliminates other sideband and carrier
- Advantages
  - Only half the bandwidth is required
  - Less power is required
- Disadvantages
  - Suppressed carrier can’t be used for synchronization purposes

Angle Modulation

- Angle modulation

$$s(t) = A_c \cos[2\pi f_c t + \phi(t)]$$

- Phase modulation
  - Phase is proportional to modulating signal

$$\phi(t) = n_p m(t)$$

    - n_p = phase modulation index

Angle Modulation

- Frequency modulation
  - Derivative of the phase is proportional to modulating signal

$$\phi'(t) = n_f m(t)$$

    - n_f = frequency modulation index

Angle Modulation

- Compared to AM, FM and PM result in a signal whose bandwidth:
  - is also centered at f_c
  - but has a magnitude that is much different

- Thus, FM and PM require greater bandwidth than AM

Angle Modulation

- Carson's rule $$B_T = 2(\beta + 1)B$$

  where
  $$\beta = \begin{cases} n_p A_m & \text{for PM} \\ \dfrac{\Delta F}{B} = \dfrac{n_f A_m}{2\pi B} & \text{for FM} \end{cases}$$

- The formula for FM becomes $$B_T = 2\Delta F + 2B$$

Analog Data to Digital Signal

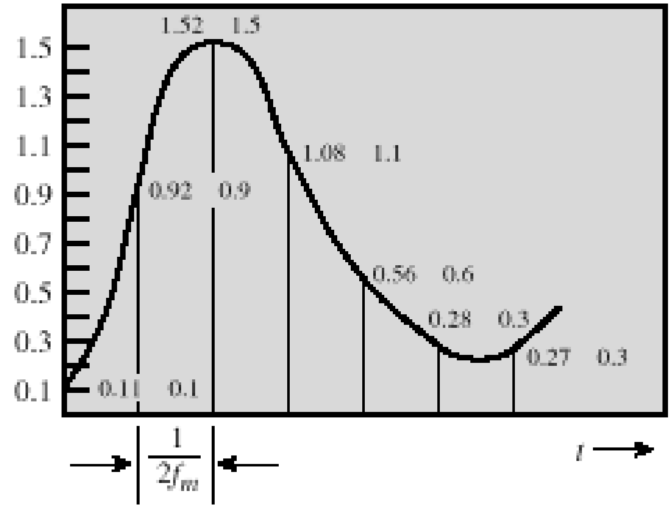
- Digitization: Often analog data are converted to digital form
- Once analog data have been converted to digital signals, the digital data:
  - can be transmitted using NRZ-L
  - can be encoded as a digital signal using a code other than NRZ-L
  - can be converted to an analog signal, using previously discussed techniques

Analog data to digital signal

- Pulse code modulation (PCM)
- Delta modulation (DM)

Pulse Code Modulation

- Based on the sampling theorem
- Each analog sample is assigned a binary code
  - Analog samples are referred to as pulse amplitude modulation (PAM) samples
- The digital signal consists of block of *n* bits, where each *n*-bit number is the amplitude of a PCM pulse



(a)

Digit	Binary Equivalent	PCM waveform
0	0000	
1	0001	
2	0010	
3	0011	
4	0100	
5	0101	
6	0110	
7	0111	

Digit	Binary Equivalent	PCM waveform
8	1000	
9	1001	
10	1010	
11	1011	
12	1100	
13	1101	
14	1110	
15	1111	

(b)

Figure 6.15 Pulse-Code Modulation

Pulse Code Modulation

- By quantizing the PAM pulse, original signal is only approximated
- Leads to quantizing noise
- Signal-to-noise ratio for quantizing noise

$$\text{SNR}_{\text{dB}} = 20\log 2^n + 1.76\,\text{dB} = 6.02n + 1.76\,\text{dB}$$

- Thus, each additional bit increases SNR by 6 dB, or a factor of 4

Delta Modulation

- Analog input is approximated by staircase function
  - Moves up or down by one quantization level (δ) at each sampling interval
- The bit stream approximates derivative of analog signal (rather than amplitude)
  - 1 is generated if function goes up
  - 0 otherwise

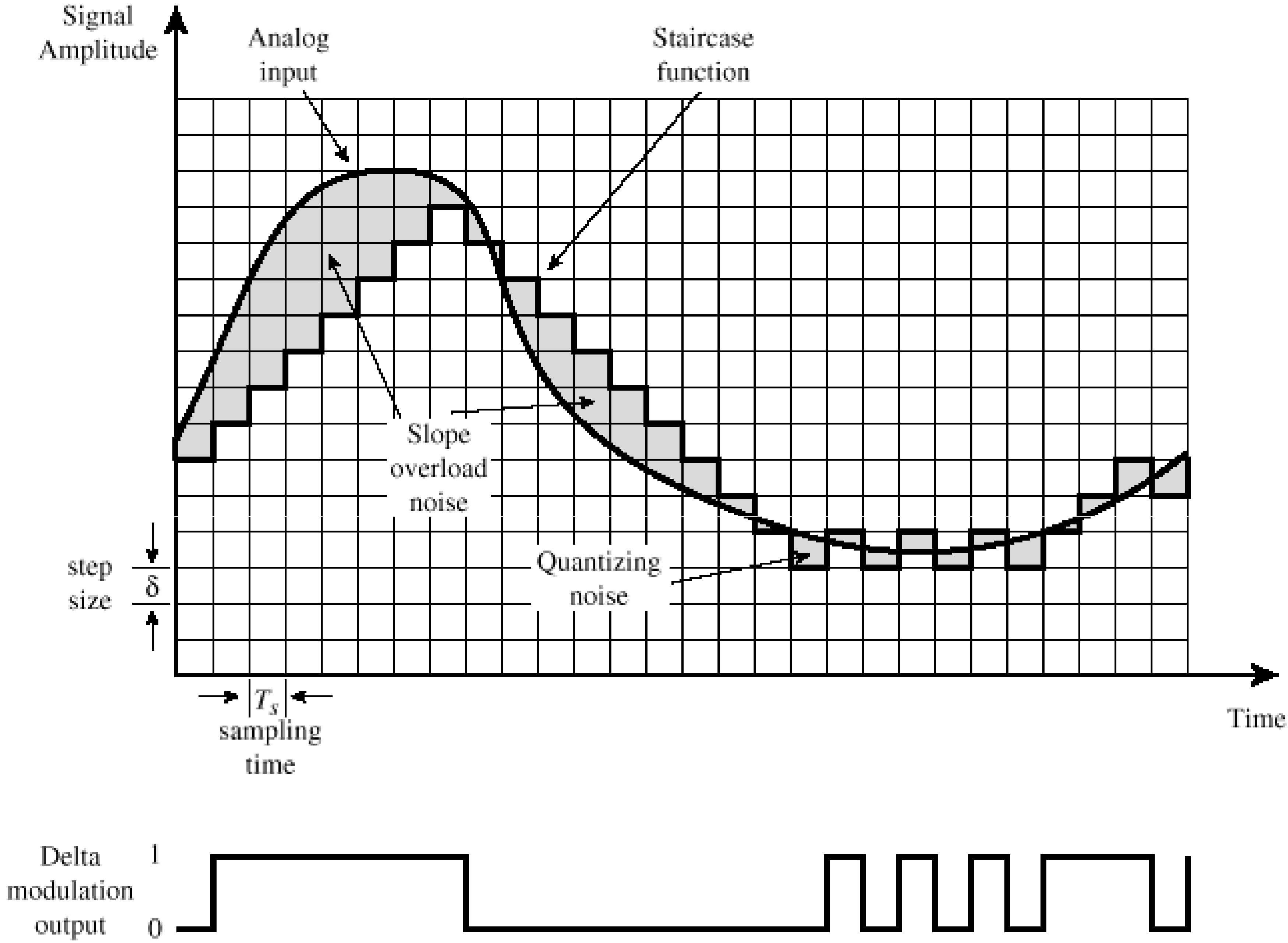


Figure 6.18 Example of Delta Modulation

Delta Modulation

- Two important parameters
  - Size of step assigned to each binary digit (δ)
  - Sampling rate
- Accuracy improved by increasing sampling rate
  - However, this increases the data rate
- Advantage of DM over PCM is the simplicity of its implementation