Wireless Networks

Text Book & Reference Book

- Text Book: Ad Hoc Wireless Networks Architectures and Protocols
- Authors: C. Siva Ram Murthy and B. S. Manoj
- Publisher: Prentice Hall
- 全華科技圖書代理
- Reference Book: Wireless Communications & Networks
- Author: William Stallings
- Publisher: Prentice Hall

Contents

- Fundamentals of Wireless Communications
- Wireless LANs and PANs
- Wireless WANs and MANs
- Wireless Internet (Mobile IP)
- Ad Hoc Wireless Networks
- MAC Protocols for Ad Hoc Wireless Networks
- Routing Protocols for Ad Hoc Wireless Networks
- Intelligent Transport Systems and Telematics

Chapter 1 Introduction

Fundamentals of Wireless Communication Technology

- Electromagnetic Spectrum
  - $c = \lambda f$, where c is the speed of light, f is the frequency of the wave in *Hz*, and λ is the wavelength in meters

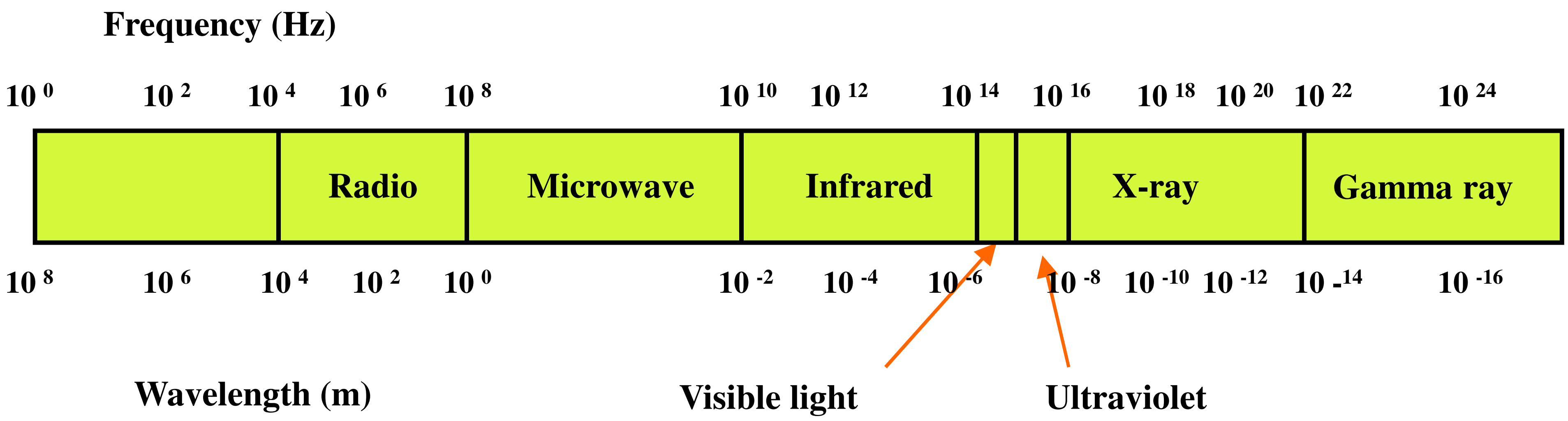


Figure 1.1. The electromagnetic spectrum

Table 1.1. Frequency bands and their common uses

Band Name	Frequency	Wavelength	Applications
Extremely low frequency (ELF)	30 to 300 Hz	10000 to 1000 Km	Powerline frequencies
Voice Frequency (VF)	300 to 3000 Hz	1000 to 100 Km	Telephone communications
Very low frequency (VLF)	3 to 30 KHz	100 to 10 Km	Marine communications
Low frequency (LF)	30 to 300 KHz	10 to 1 Km	Marine communications
Medium frequency (MF)	300 to 3000 KHz	100 to 100 m	AM broadcasting
High frequency (HF)	3 to 30 MHz	100 to 10 m	Long-distance aircraft / ship communications
Very high frequency (VHF)	30 to 300 MHz	10 to 1 m	FM broadcasting
Ultra high frequency (UHF)	300 to 3000 MHz	100 to 10 cm	Cellular telephone
Super high frequency (SHF)	3 to 30 GHz	10 to 1 cm	Satellite communications, microwave links
Extremely high frequency (EHF)	30 to 300 GHZ	10 to 1 mm	Wireless local loop
Infrared	300 GHz to 400 THz	1 mm to 400 nm	Consumer electronics
Visible light	400 THz to 900 THz	770 nm to 330 um	Optical communications

Radio Propagation Mechanisms

- 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

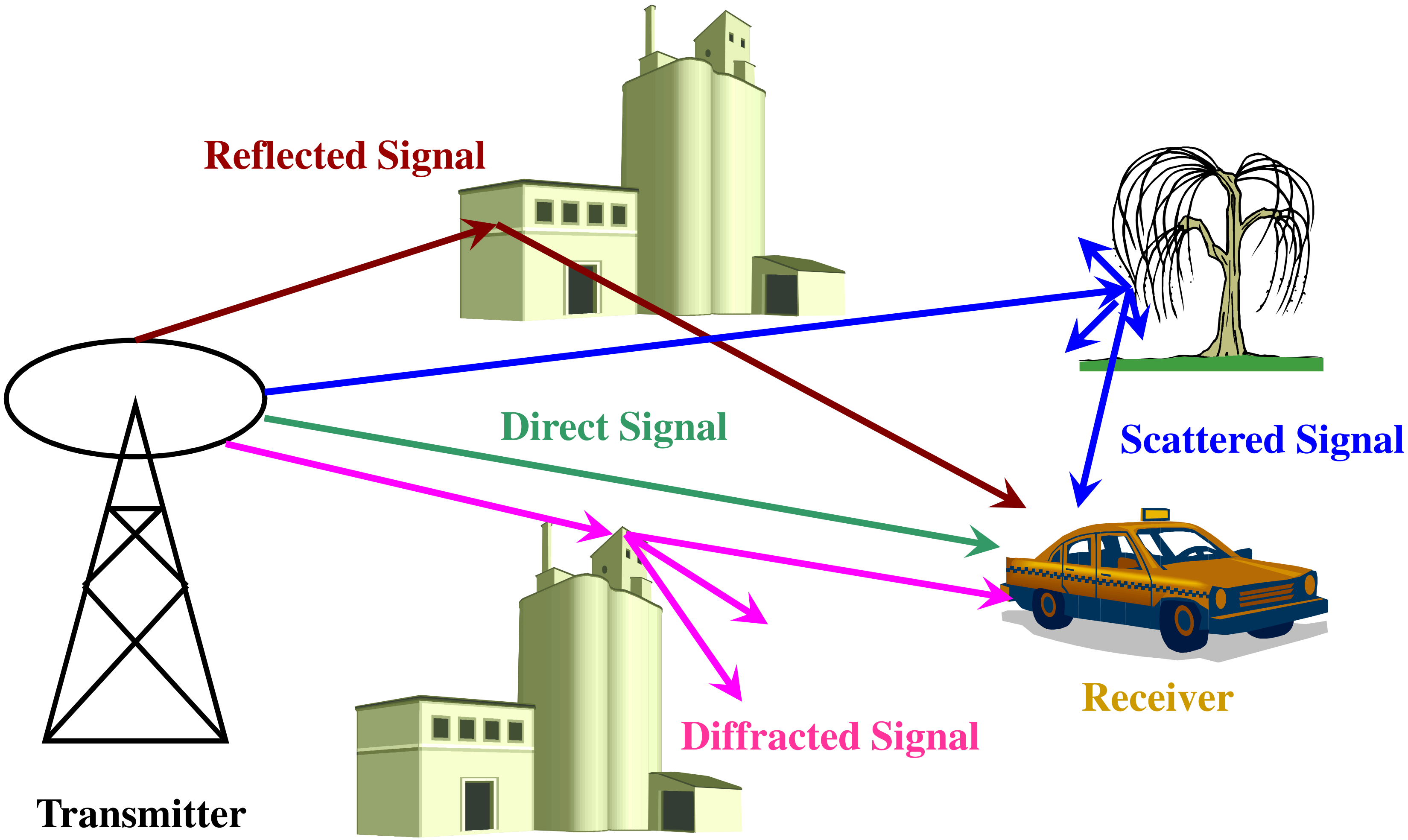


Figure 1.2. Propagation mechanisms

Characteristics of The Wireless Channel (1/2)

- Free space loss:

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

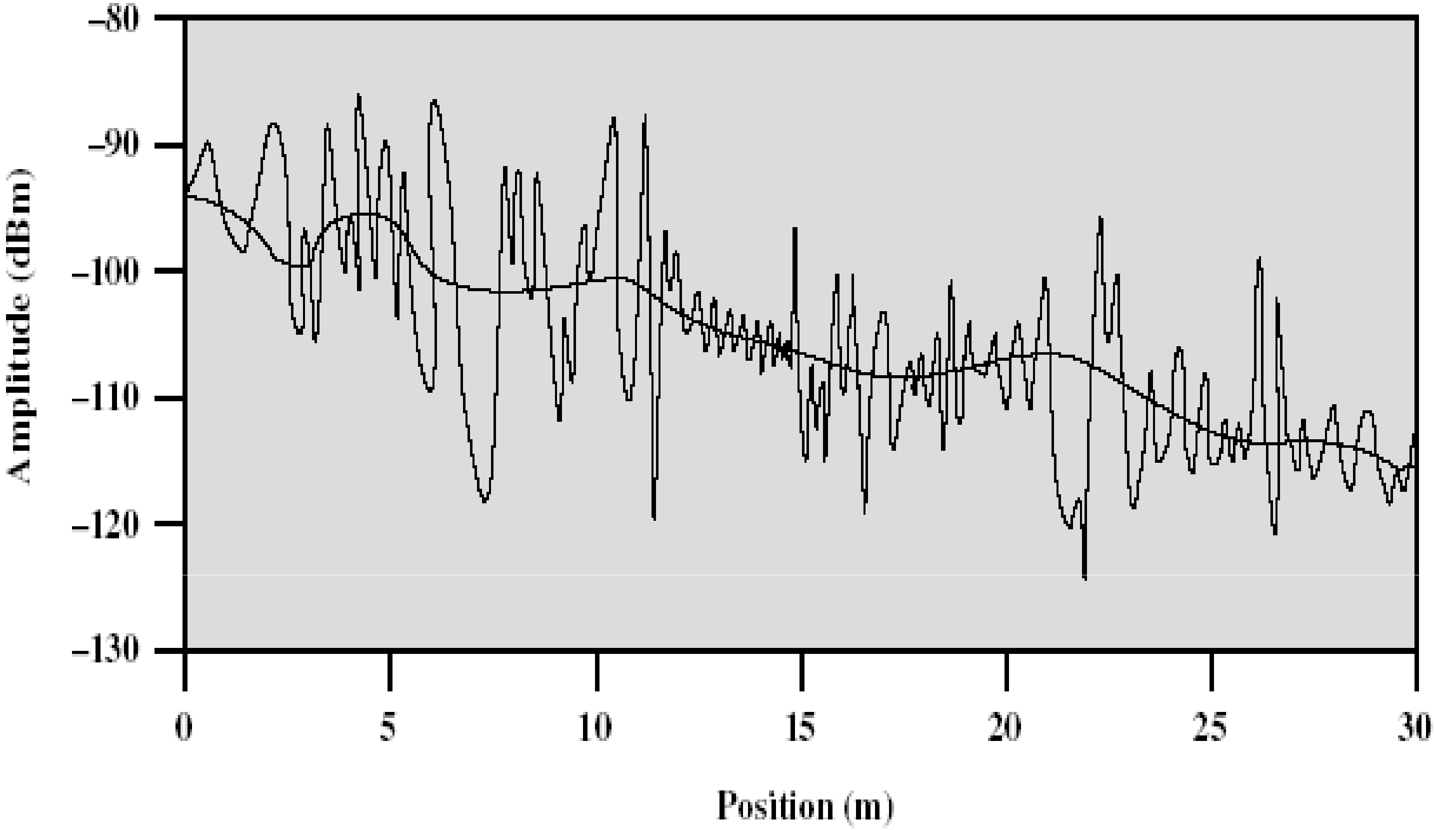
  - λ = carrier wavelength
  - d = distance between transmitter and receiver
  - G_t = gain of transmitting antenna
  - G_r = gain of receiving antenna
  - A_t = effective area of transmitting antenna
  - A_r = effective area of receiving antenna

Characteristics of The Wireless Channel (2/2)

- Two-path model: $$P_r = P_t G_r G_t \left(\frac{h_t h_r}{d^2}\right)^2$$
  - h_t and h_r are the height of the transmitter and receiver
- The general form: $$P_r = P_t G_r G_t \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{d^\gamma}$$
  - γ is the propagation coefficient that varies 2 ~ 5

Fading

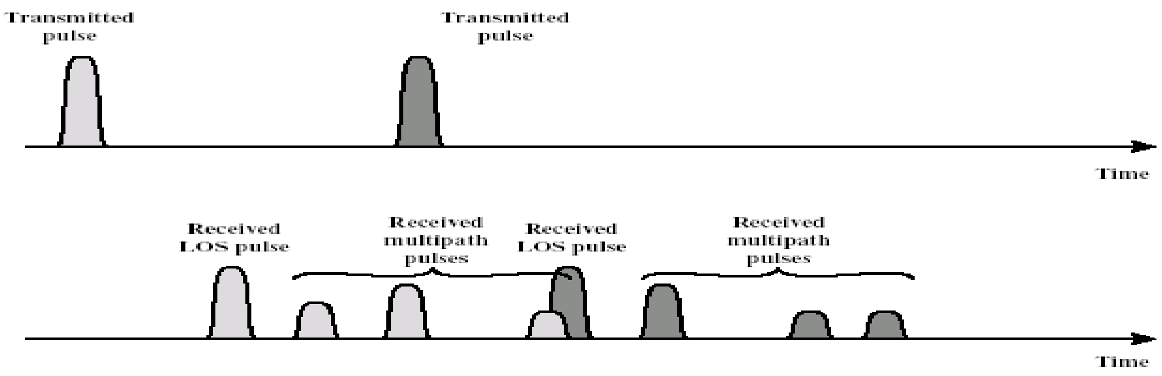
- Fading refers to fluctuations in signal strength when received at receiver
- Fast fading (short-term fading)
  - Observe the distance of about half a wavelength
  - Such as multipath propagation
- Slow fading (long-term fading)
  - Distance large enough to produce gross variations
  - Ex. temporarily shielded by a building , tree, cars, …



Typical Slow and Fast Fading in an Urban Mobile Environment

Interference

- Adjacent channel interference
- Co-channel interference
- Inter-symbol interference
  - Effect of multipath propagation
  - Can be solved by adaptive equalization mechanisms



Two Pulses in Time-Variant Multipath

Doppler Shift

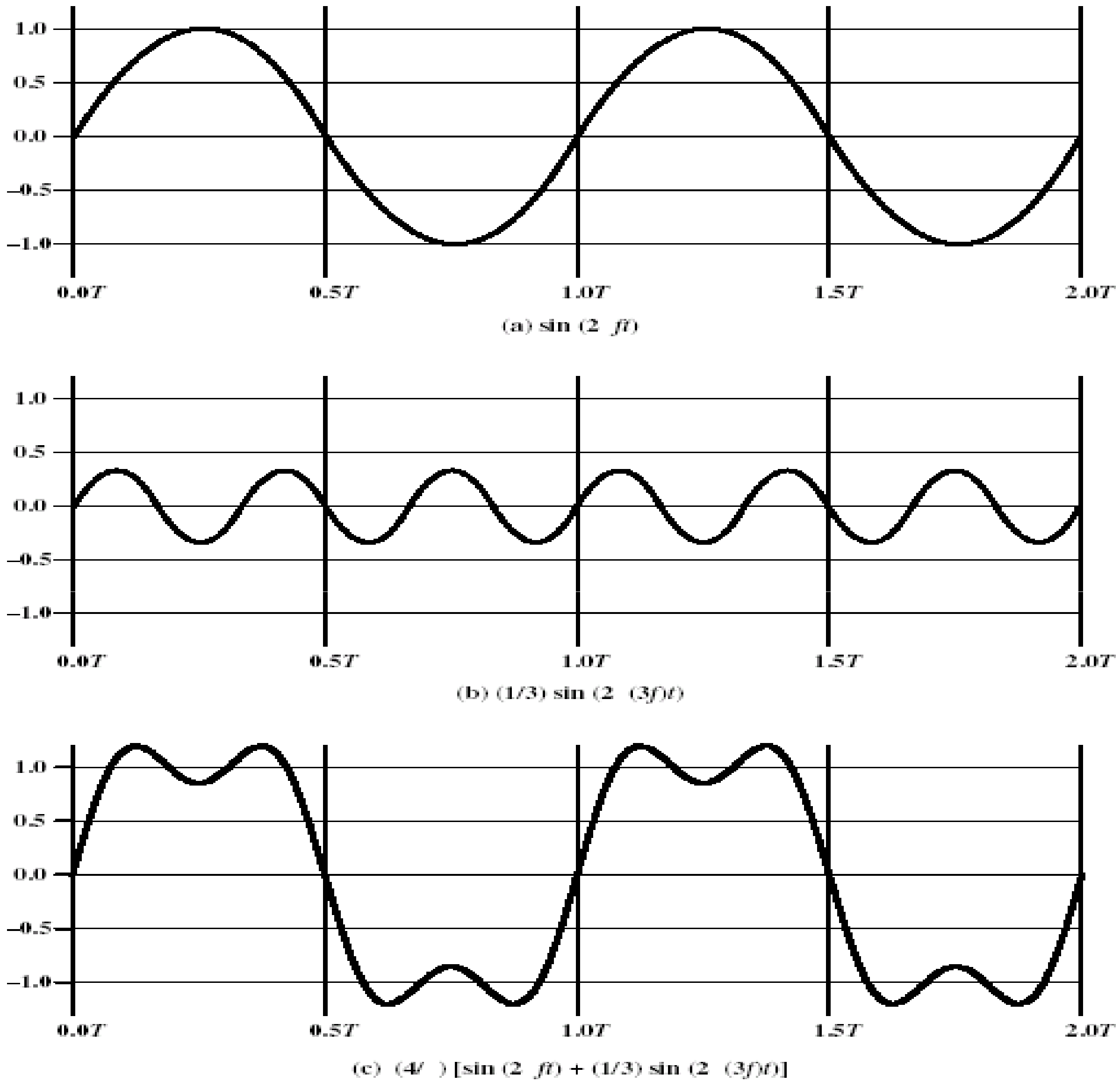
- Change/shift in the frequency of the received signal with the transmitter and receiver are mobile with respect to each other
  - the Doppler shift is: $$f_d = \frac{v}{\lambda}$$
  - Where v is the relative velocity between the transmitter and receiver, and λ is the wavelength of the signal

Frequency-Domain Concepts

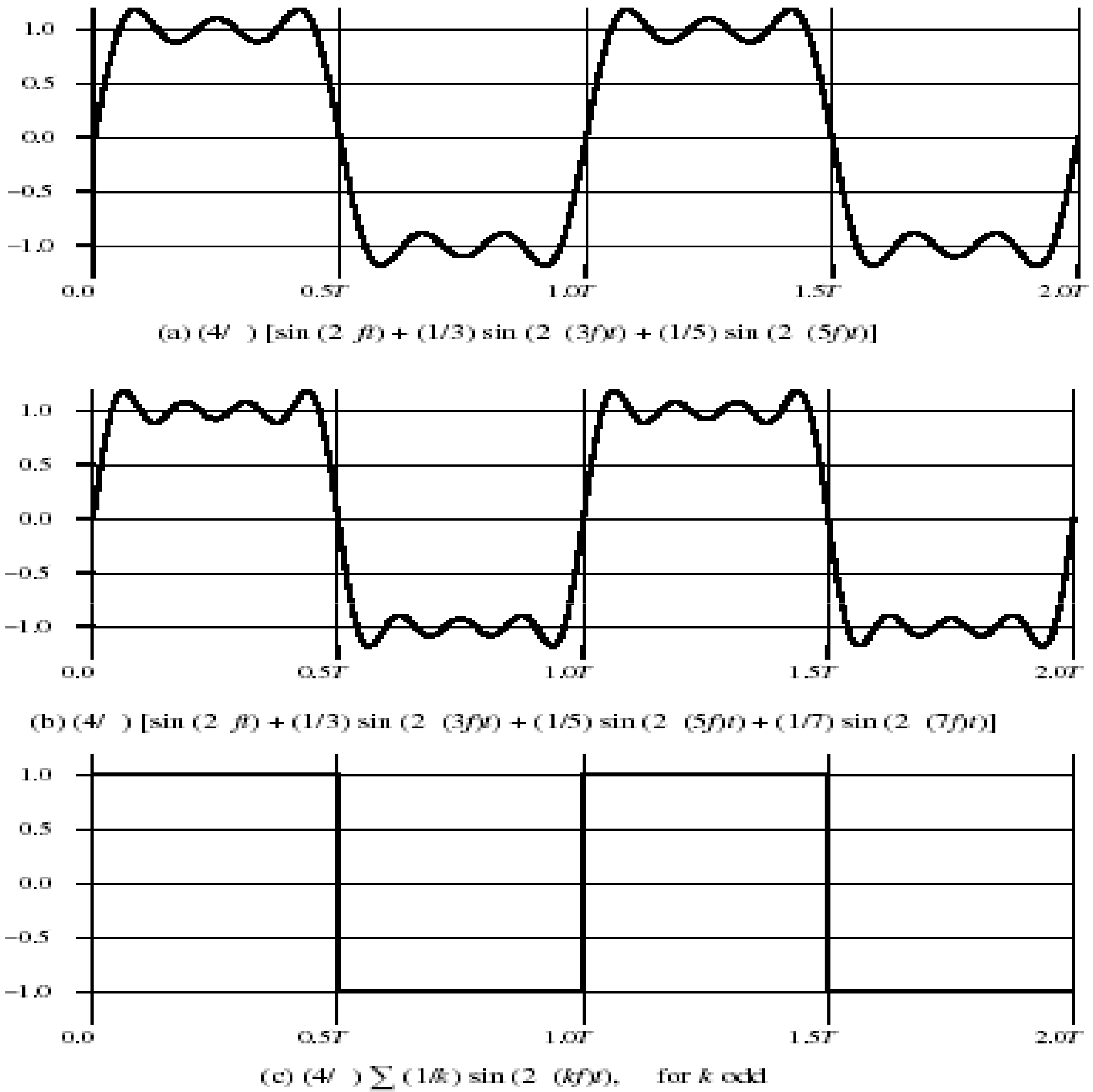
- Fundamental frequency - when all frequency components of a signal are integer multiples of one frequency, it's referred to as the fundamental frequency
- Spectrum - range of frequencies that a signal contains
- Absolute bandwidth - width of the spectrum of a signal
- Effective bandwidth (or just bandwidth) - narrow band of frequencies that most of the signal's energy is contained in

Concepts Related to Channel Capacity

- Data rate - rate at which data can be communicated (bps)
- Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise - average level of noise over the communications path
- Error rate - rate at which errors occur
  - Error = transmit 1 and receive 0; transmit 0 and receive 1



Addition of Frequency Components ($T = 1/f$)



Frequency Components of Square Wave ($T = 1/f$)

Transmission Rate Constraint

- Nyquist's Theorem
  - Given a BW B, the highest signal rate that can be carried is $2B$
  - With multilevel signaling $C = 2B \log_2 L,$ bit/sec where L = number of discrete signal or voltage levels
- Shannon's Theorem: theoretical maximum that can be achieved

$$C = B \log_2 (1 + \mathrm{S/N}) \quad \text{bit/sec}$$

  - Where S is the signal power and N is noise power

Modulation Techniques

- Analog Modulation: used for transmitting analog data
- Digital Modulation: used for transmitting digital data

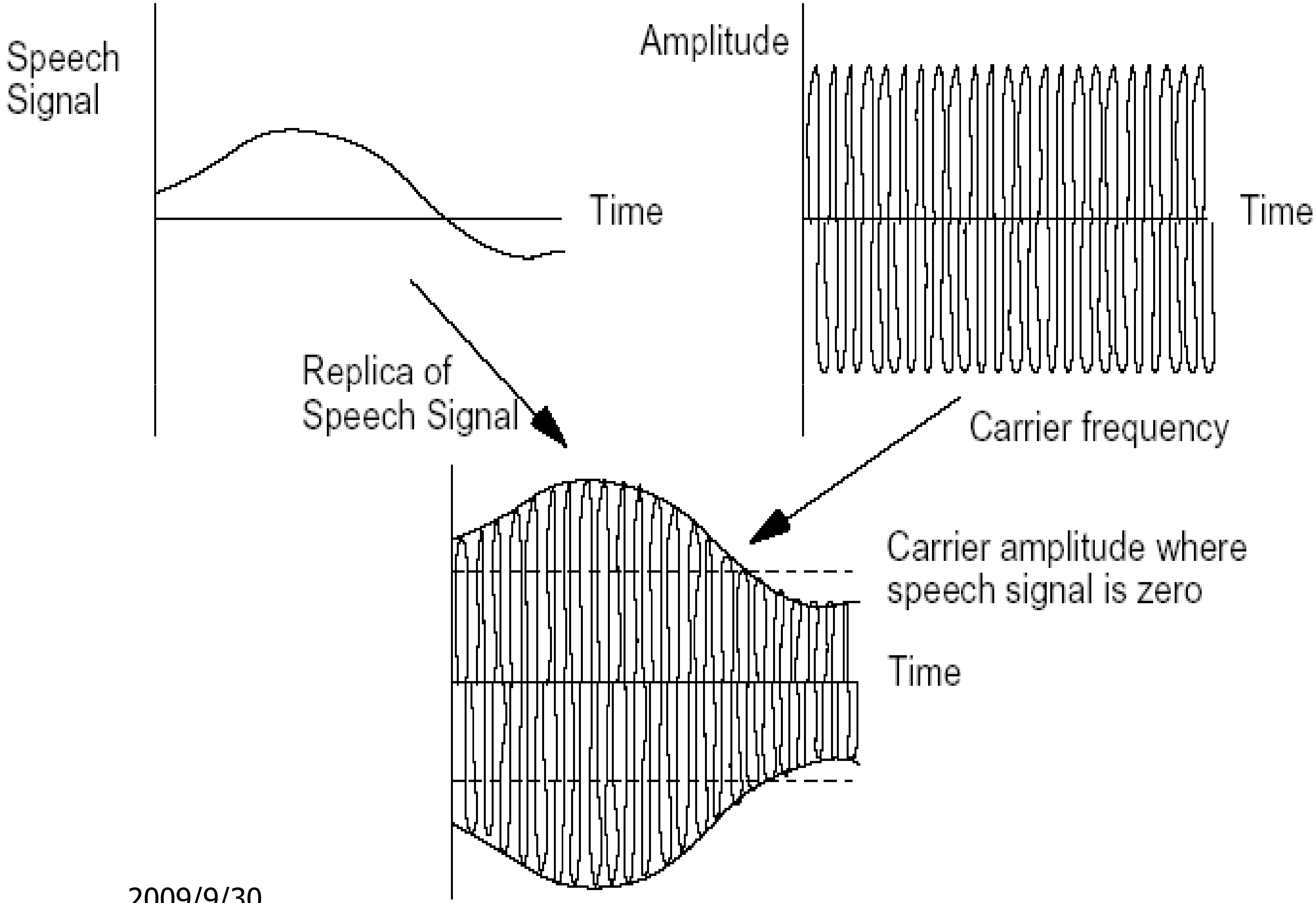
Amplitude Modulation

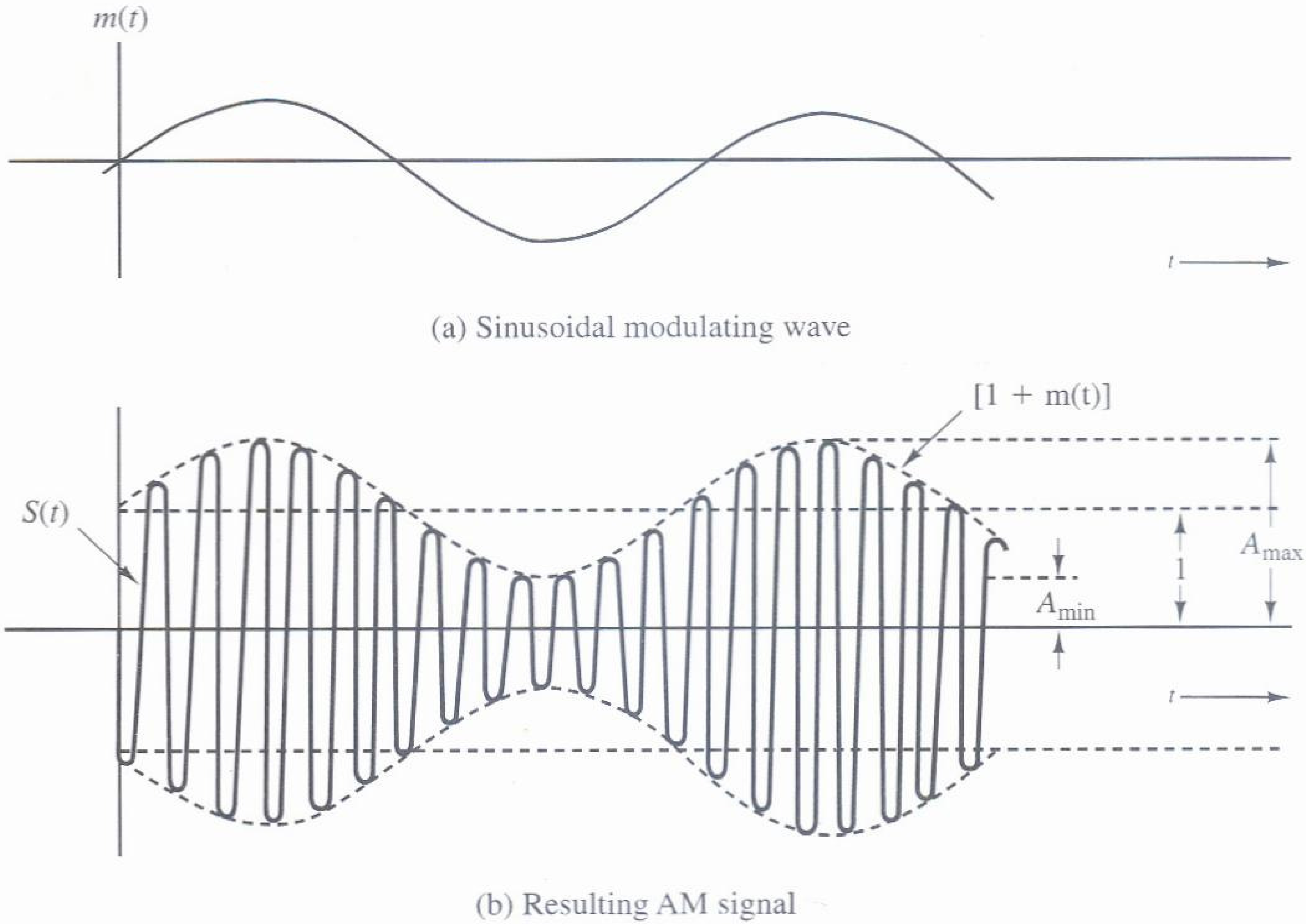
- Amplitude Modulation

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

  - $\cos 2\pi f_c t$ = carrier
  - $x(t)$ = input signal
  - n_a = modulation index <= 1
    - Ratio of amplitude of input signal to carrier

Amplitude Modulation (AM)





Amplitude Modulation

Angle Modulation (1/3)

- Frequency modulation (FM) and phase modulation (PM) are special cases of 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 (2/3)

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

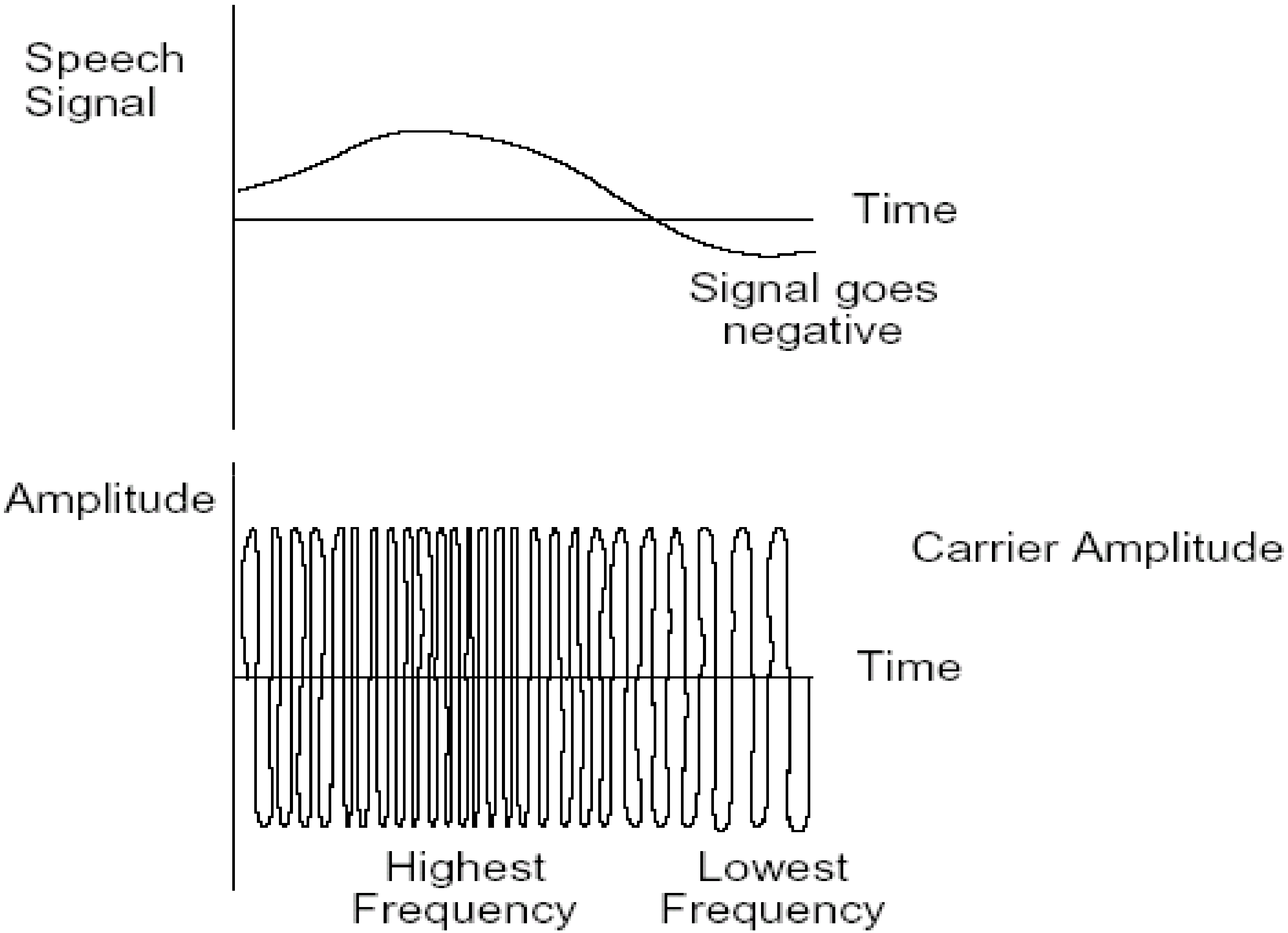
$$\phi'(t) = n_f m(t)$$

  - n_f = frequency modulation index

Angle Modulation (3/3)

- 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
    - Angle modulation includes cos($\varnothing$ (t)) which produces a wide range of frequencies
- Thus, FM and PM require greater bandwidth than AM

Frequency Modulation (FM)



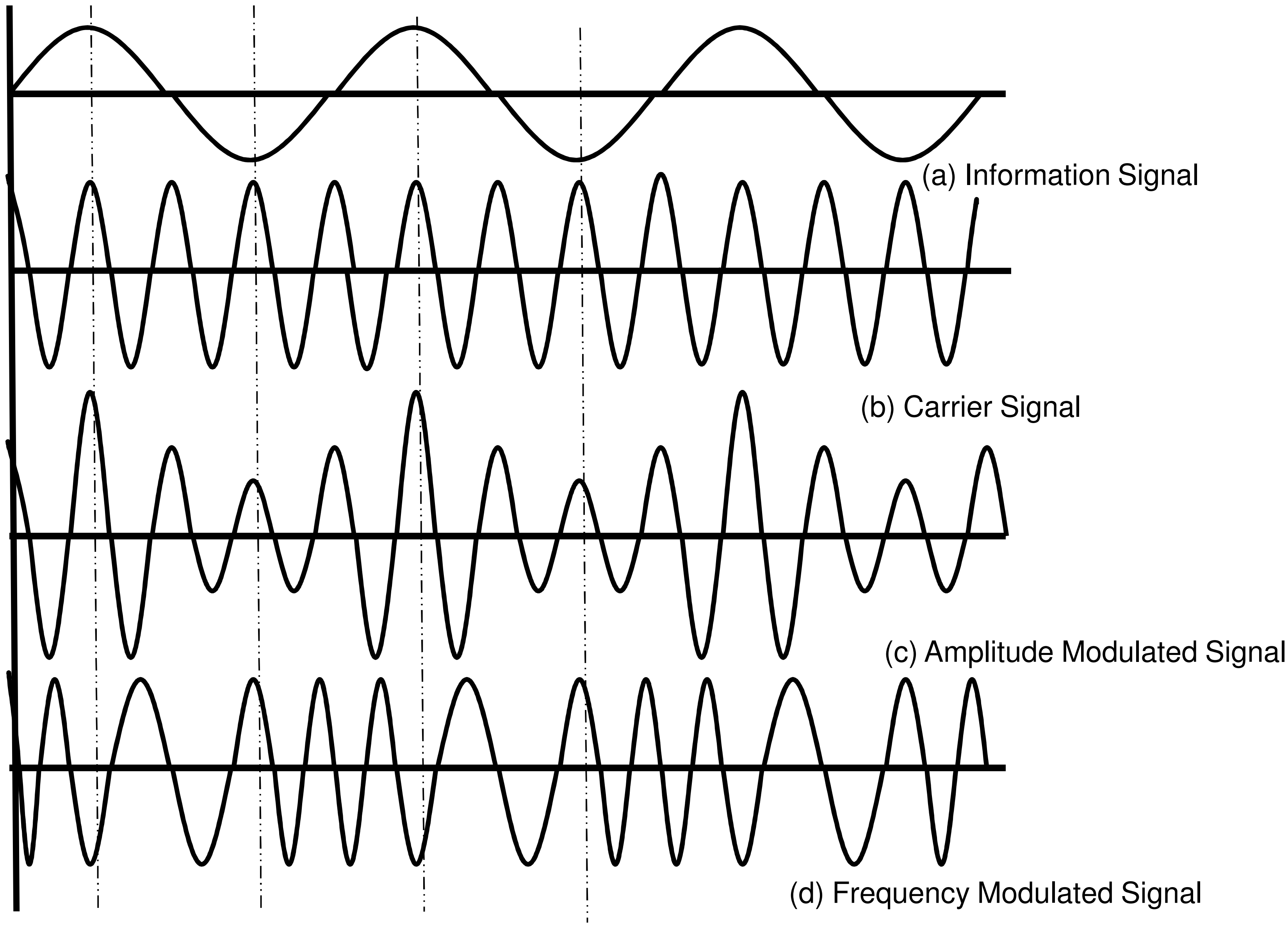
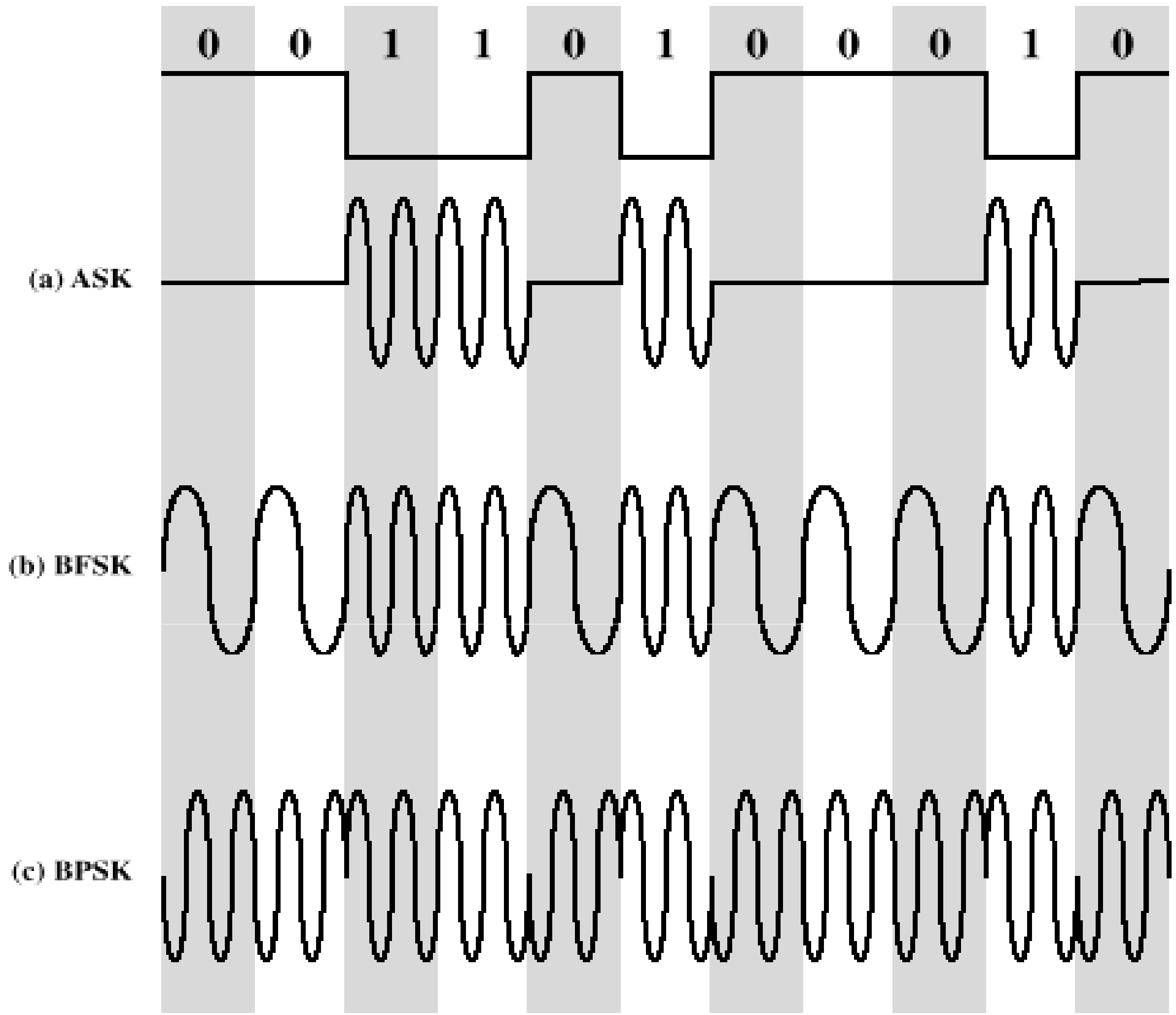


Figure1.3. Analog modulation schemes.

Digital Modulation

- Basic Encoding Techniques
- Digital data to analog signal
  - 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



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

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

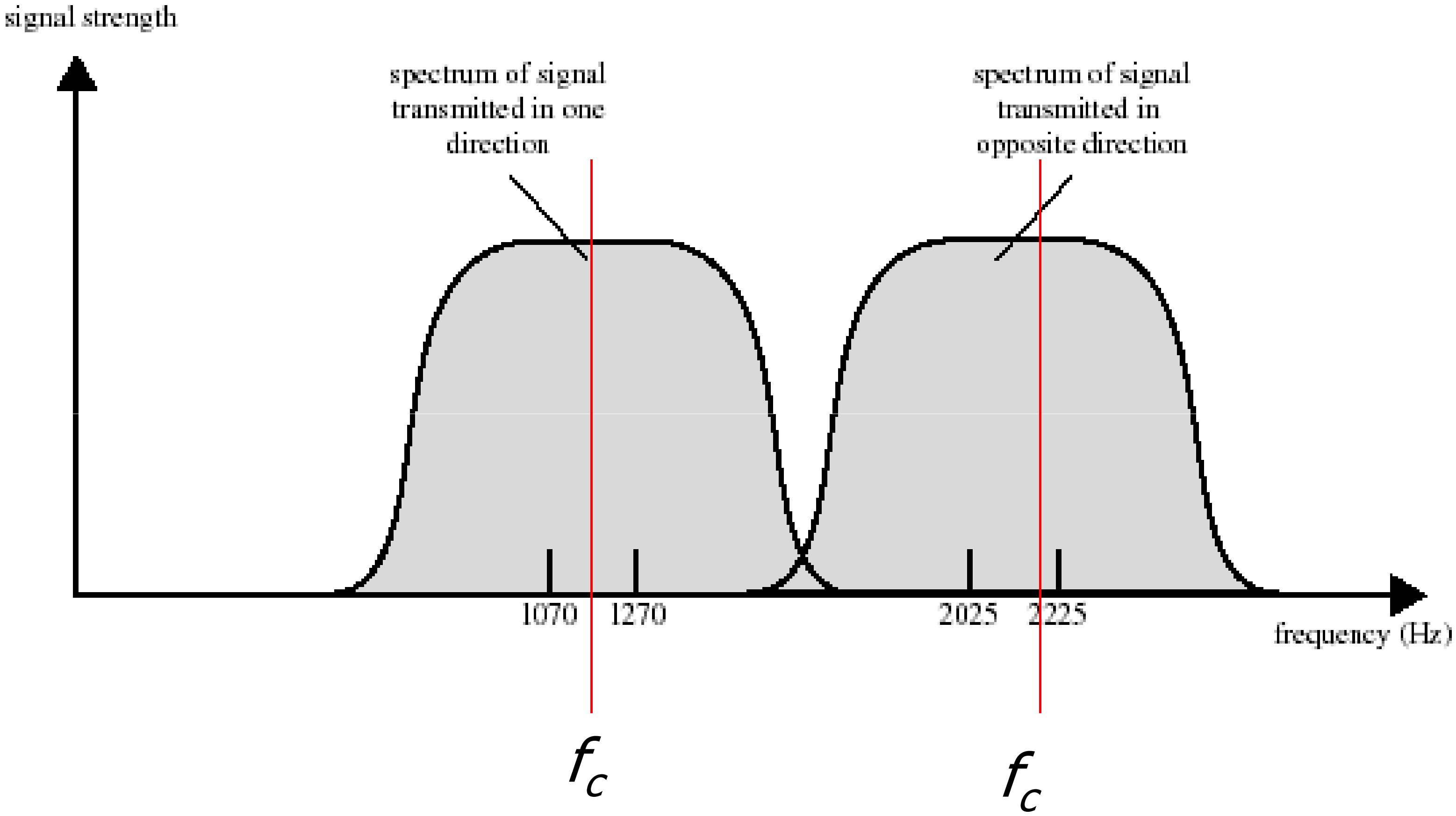
  - where the carrier signal is $A\cos(2\pi f_c t)$

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



Full-Duplex FSK Transmission on a Voice-Grade Line

Phase-Shift Keying (PSK) (1/3)

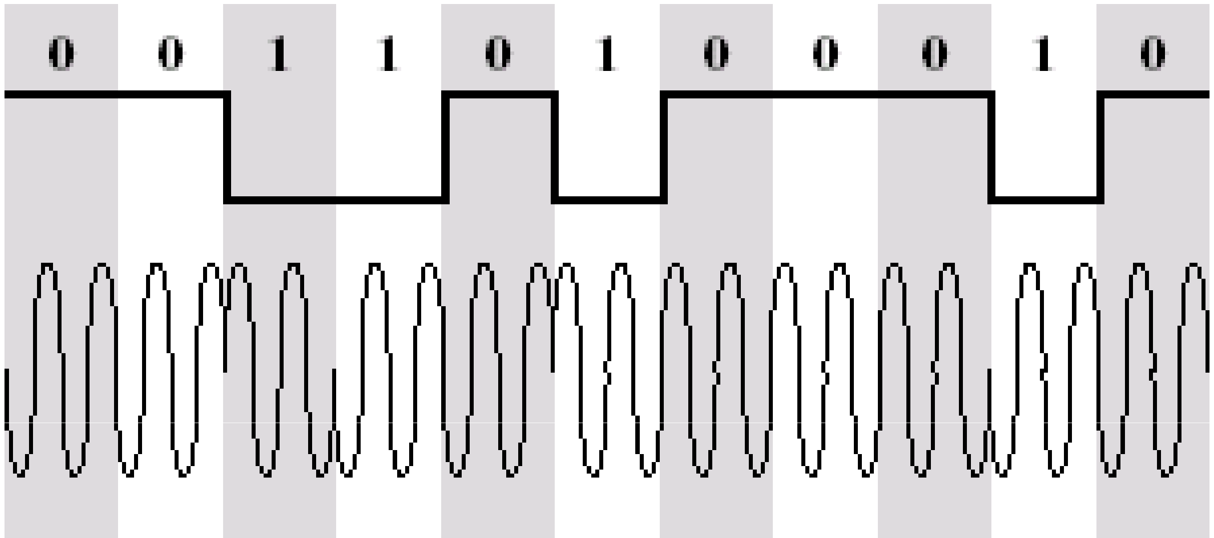
- Two-level PSK (BPSK)
  - Uses two phases to represent binary digits

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

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

Phase-Shift Keying (PSK) (2/3)

- 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



Differential Phase-Shift Keying (DPSK)

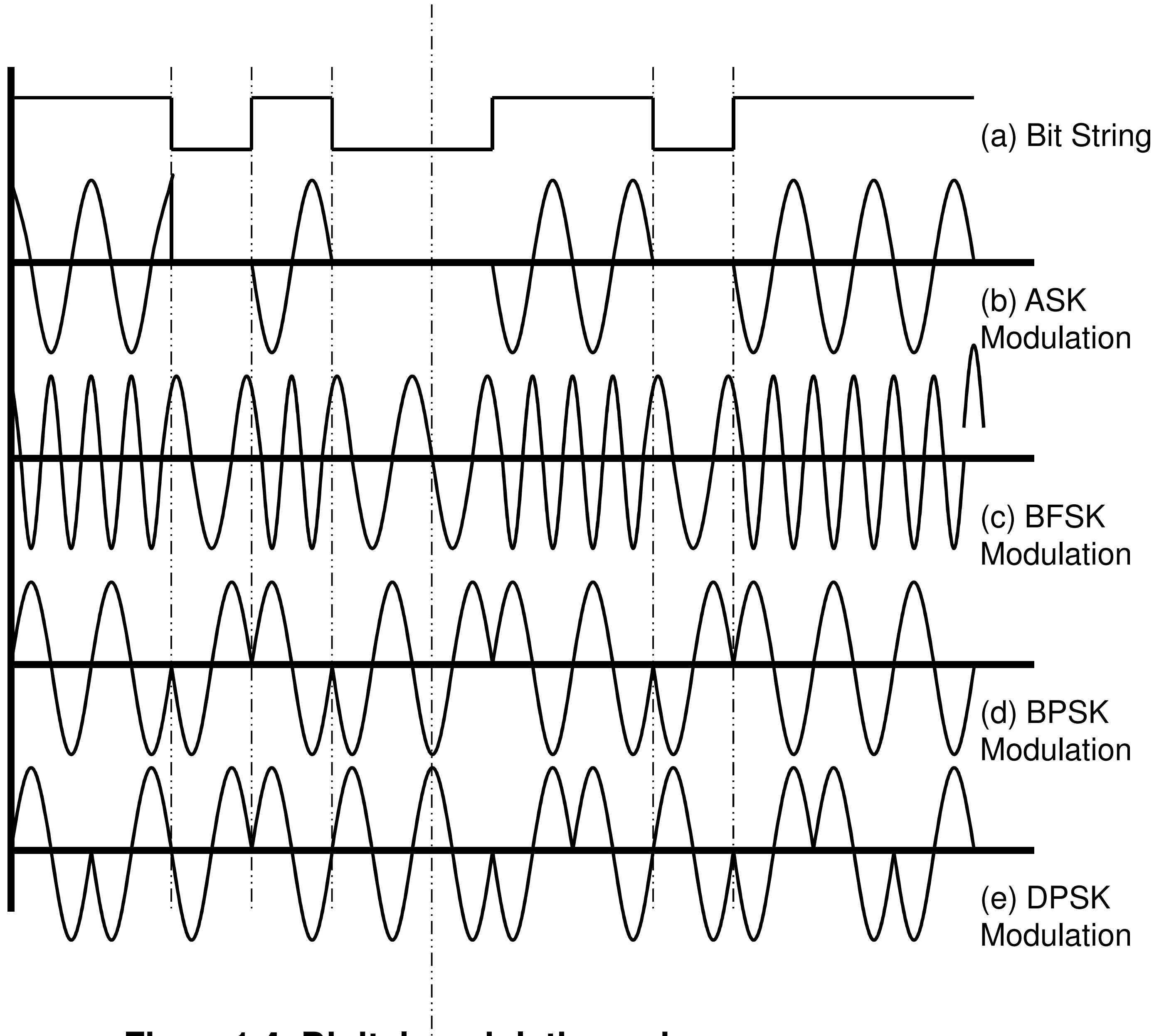


Figure1.4. Digital modulation schemes.

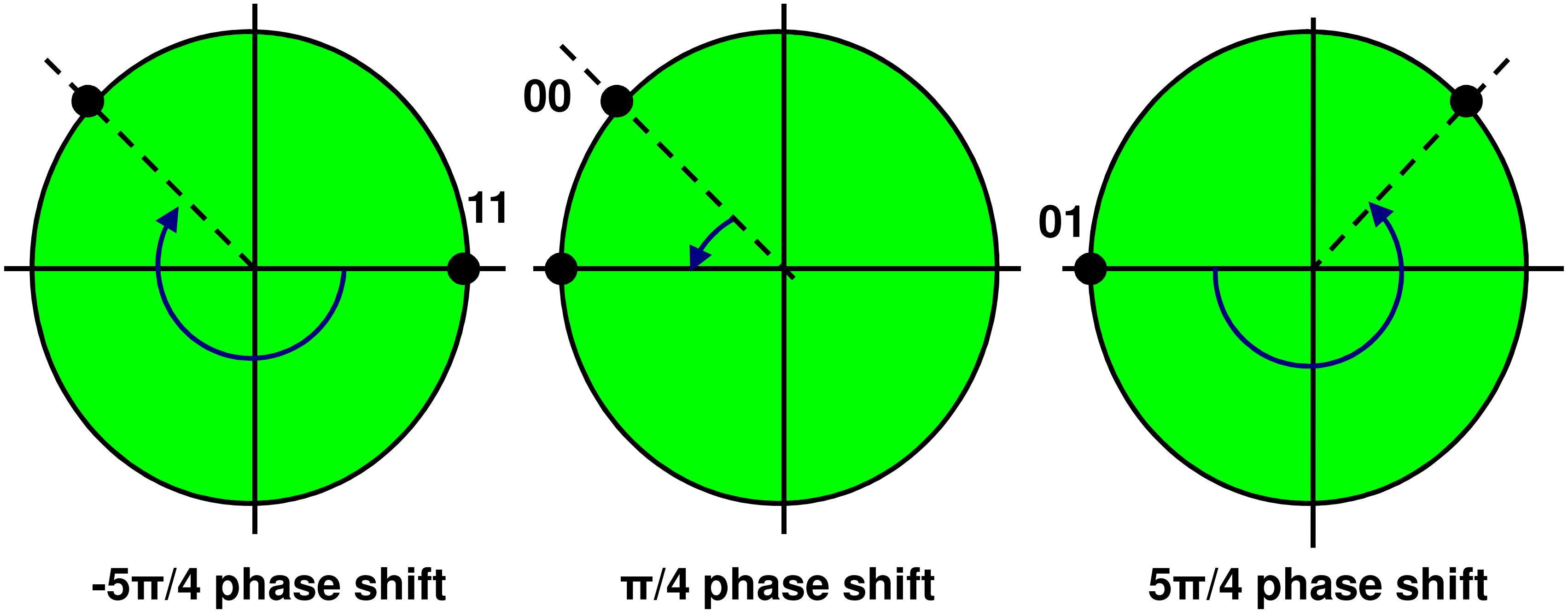
Phase-Shift Keying (PSK)

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

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

Table 1.2. phase change used in π/4 shifted PSK

Pair of Bits	Phase Change
00	$\pi/4$
01	$5\pi/4$
10	$-\pi/4$
11	$-5\pi/4$



Transmission of bit string 110001

Figure1.5. Operation of π/4 shifted PSK.

Quadrature Amplitude Modulation (QAM)

- Both amplitude and phase are varied in QAM in order to present bits
- If two amplitude values combine with QPSK, it would obtain eight different combinations
- N-QAM can encode $\log_2 N$ bits
- The main drawback of QAM is more susceptible to errors caused due to noise and distortion

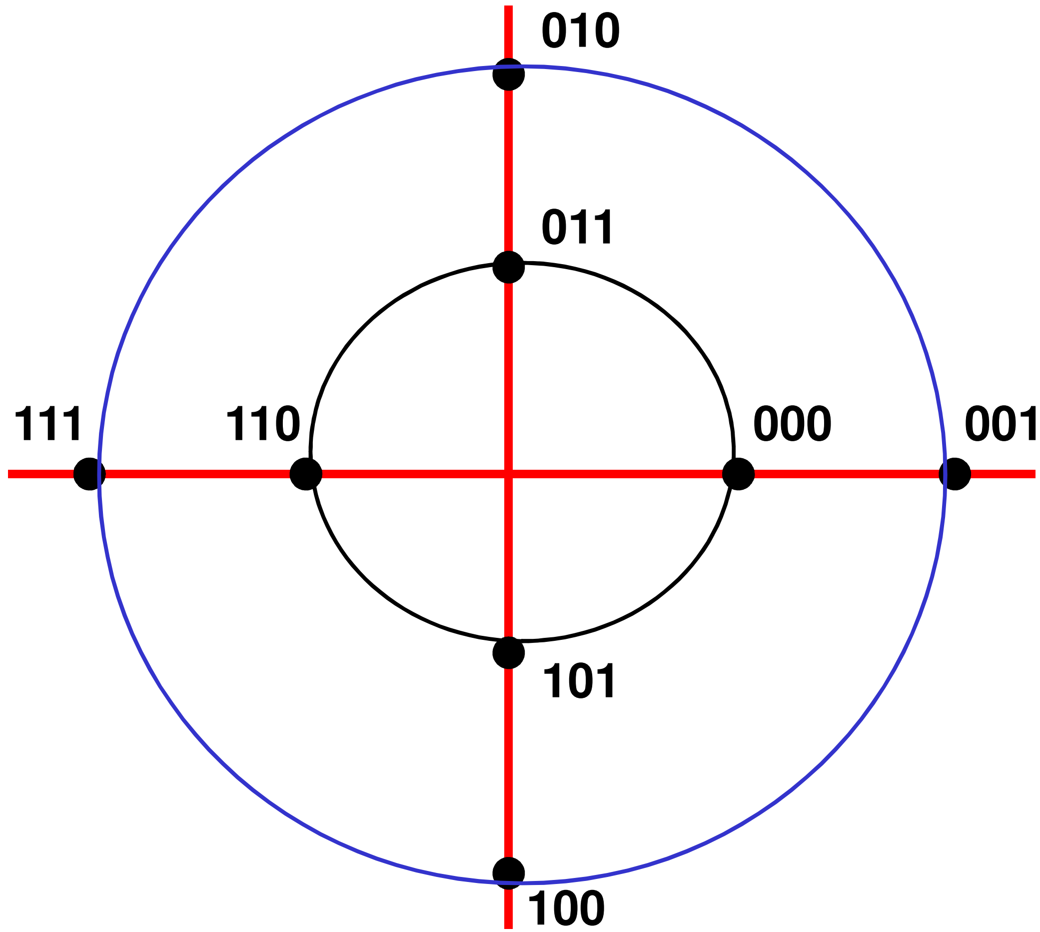
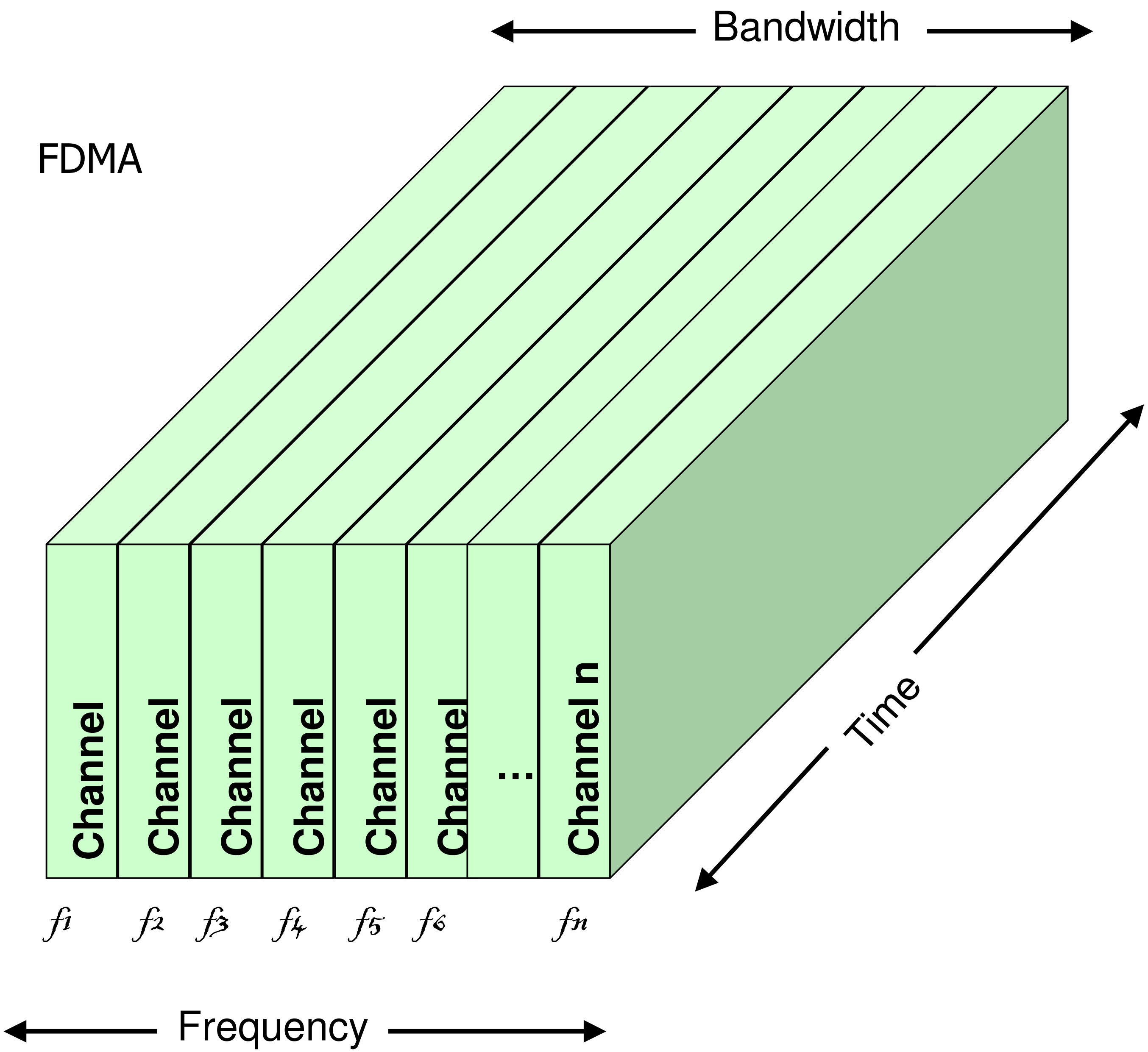


Figure1.6. Constellation pattern in 8-QAM.

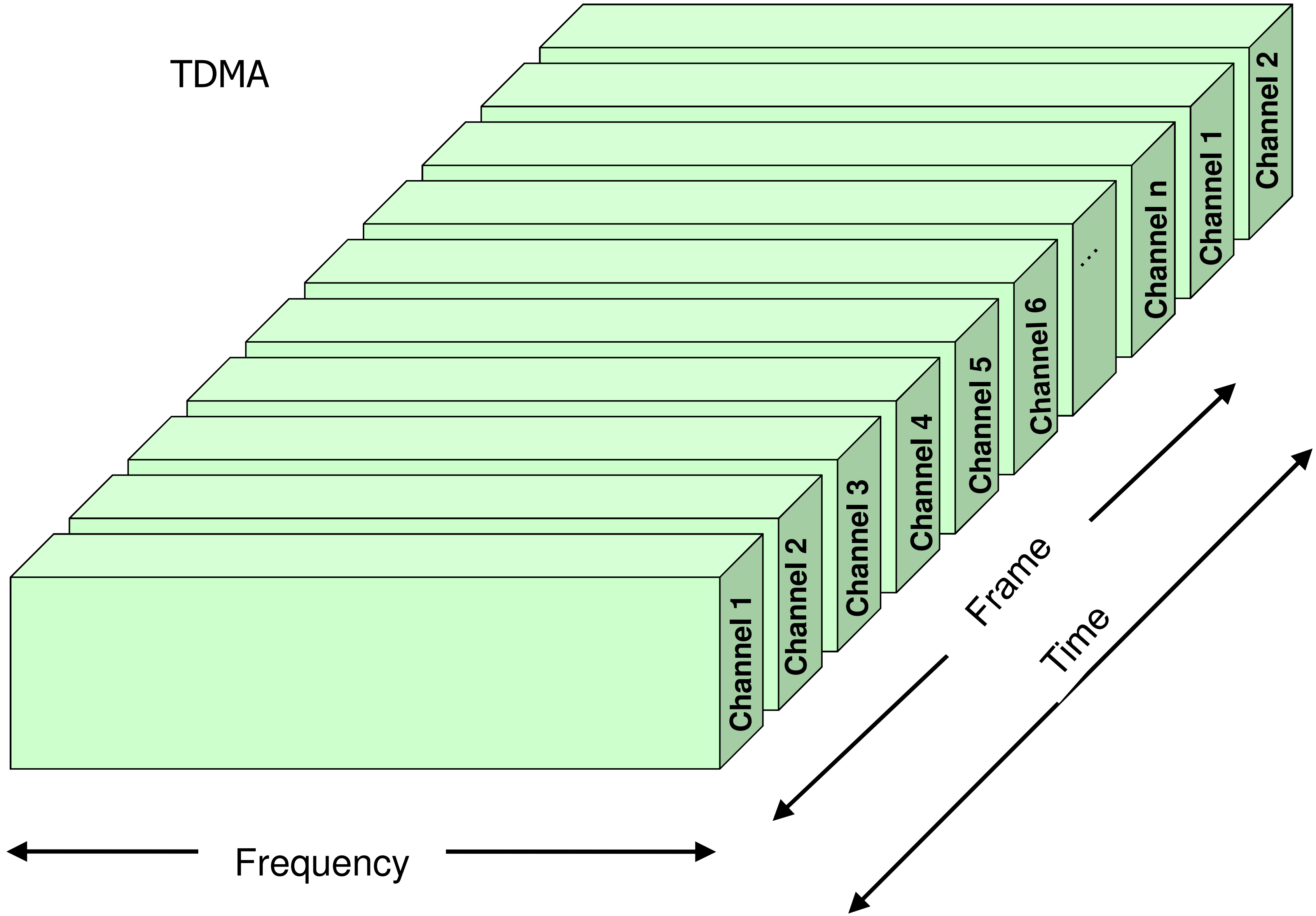
Multiple Access Techniques

- Frequency Division Multiple Access (FDMA)
  - Takes advantage of the fact that the useful bandwidth of the medium exceeds the required bandwidth of a given signal
- Time Division Multiple Access (TDMA)
  - Takes advantage of the fact that the achievable bit rate of the medium exceeds the required data rate of a digital signal
- Code Division Multiple Access (CDMA)
  - A multiplexing technique used with spread spectrum
- Space Division Multiple Access (SDMA)
- Orthogonal Frequency Division Multiple Access (OFDM)
  - Splitting the carrier into multiple orthogonal smaller sub-carriers and then broadcasting the sub-carriers simultaneously reduce the signal distortion due to multipath propagation

FDMA


Bandwidth
Channel
Channel
Channel
Channel
Channel
Channel
…
Channel n
Time
f1
f2
f3
f4
f5
f6
fn
Frequency

TDMA


Channel 1
Channel 2
Channel 3
Channel 4
Channel 5
Channel 6
...
Channel n
Channel 1
Channel 2
Frame
Time
Frequency

Spread Spectrum (1/5)

- Developed initially for military and intelligence requirements
- Spread the information signal over a wider BW to make jamming and interception more difficult
- Both of frequency hoping and direct sequence are used in various wireless communication standards and products

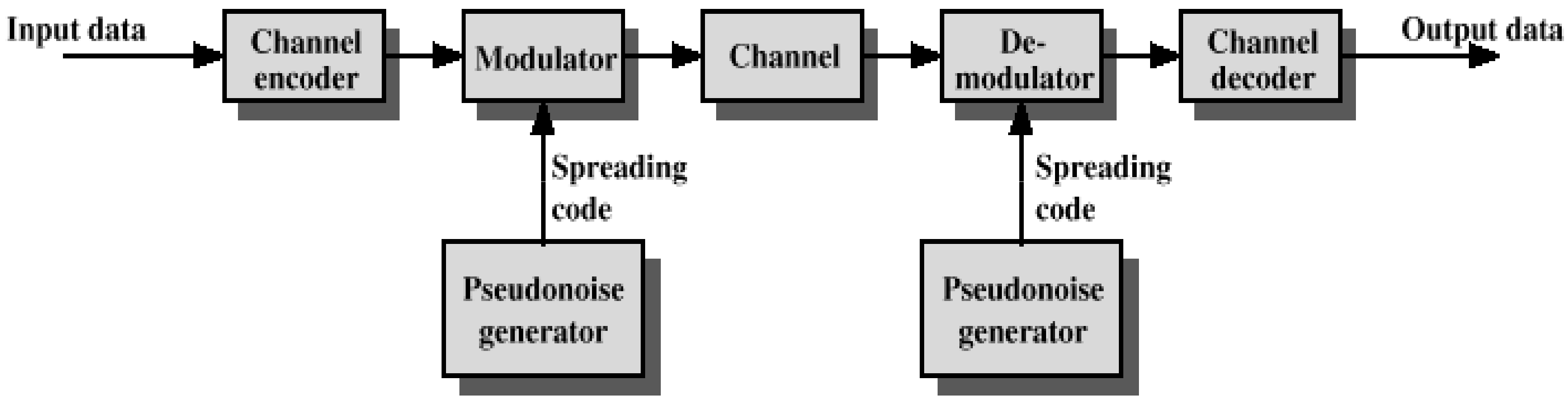
Spread Spectrum (2/5)

- Input is fed into a channel encoder
  - Produces analog signal with narrow bandwidth
- Signal is further modulated using sequence of digits
  - Spreading code or spreading sequence
  - Generated by pseud-onoise, or pseudo-random number generator

Spread Spectrum (3/5)

- Effect of modulation is to increase bandwidth of signal to be transmitted
- On receiving end, digit sequence is used to demodulate the spread spectrum signal
- Signal is fed into a channel decoder to recover data

Spread Spectrum (4/5)



General Model of Spread Spectrum Digital Communication System

Spread Spectrum (5/5)

- What can be gained from apparent waste of spectrum?
  - Immunity from various kinds of noise and multipath distortion
  - Can be used for hiding and encrypting signals
  - Several users can independently use the same higher bandwidth with very little interference
    - Eg. Code division multiple access (CDMA)

Frequency Hoping Spread Spectrum (FHSS) (1/2)

- Signal is broadcast over seemingly random series of radio frequencies
  - A number of channels are allocated for the FH signal
  - Width of each channel corresponds to bandwidth of input signal
- Signal hops from frequency to frequency at fixed intervals
  - Transmitter operates in one channel at a time
  - Bits are transmitted using some encoding scheme
  - At each successive interval, a new carrier frequency is selected

Frequency Hoping Spread Spectrum (FHSS) (2/2)

- Channel sequence dictated by spreading code
- Receiver, hopping between frequencies in synchronization with transmitter, picks up message
- Advantages
  - Eavesdroppers hear only unintelligible blips
  - Attempts to jam signal on one frequency succeed only at knocking out a few bits

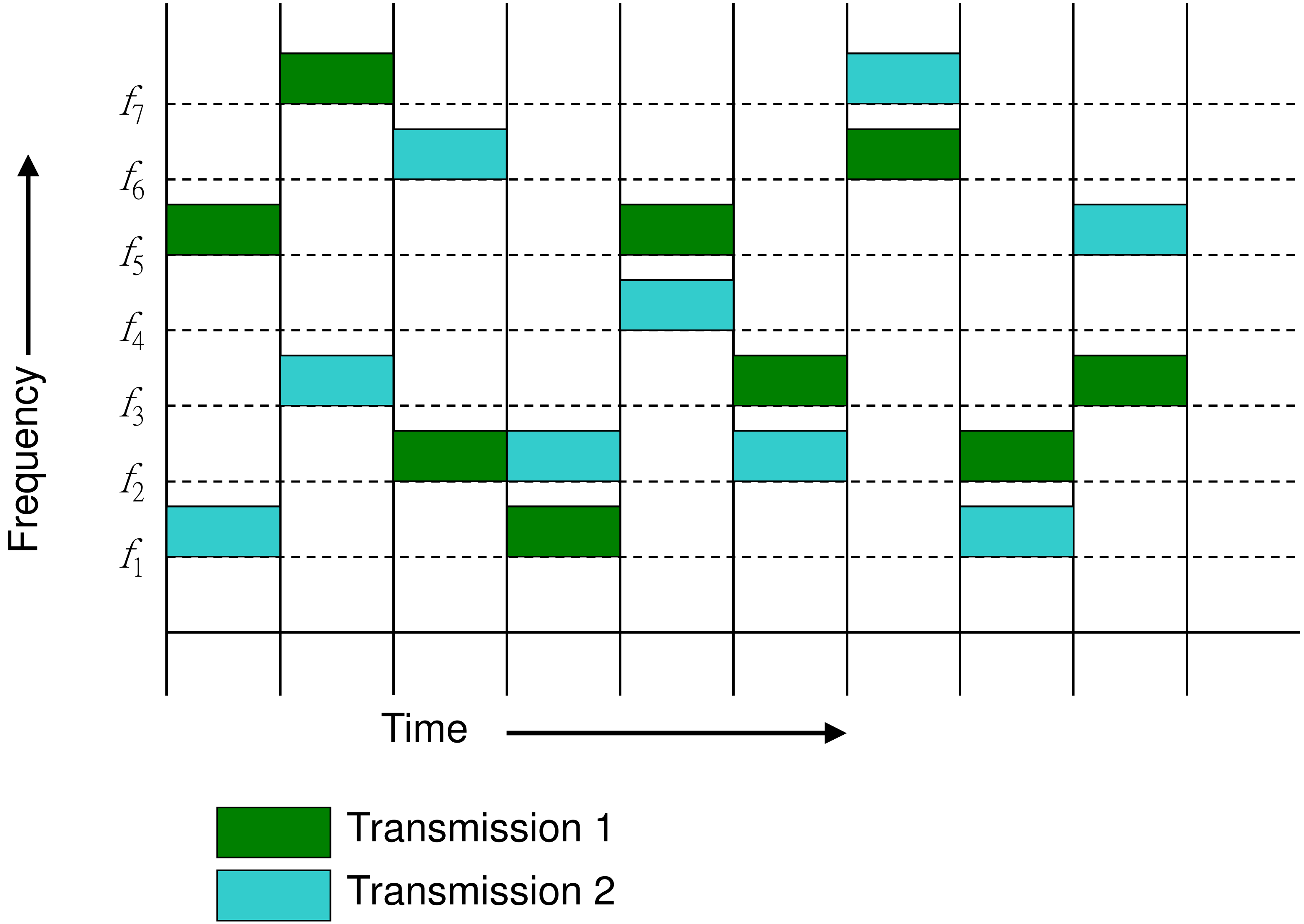
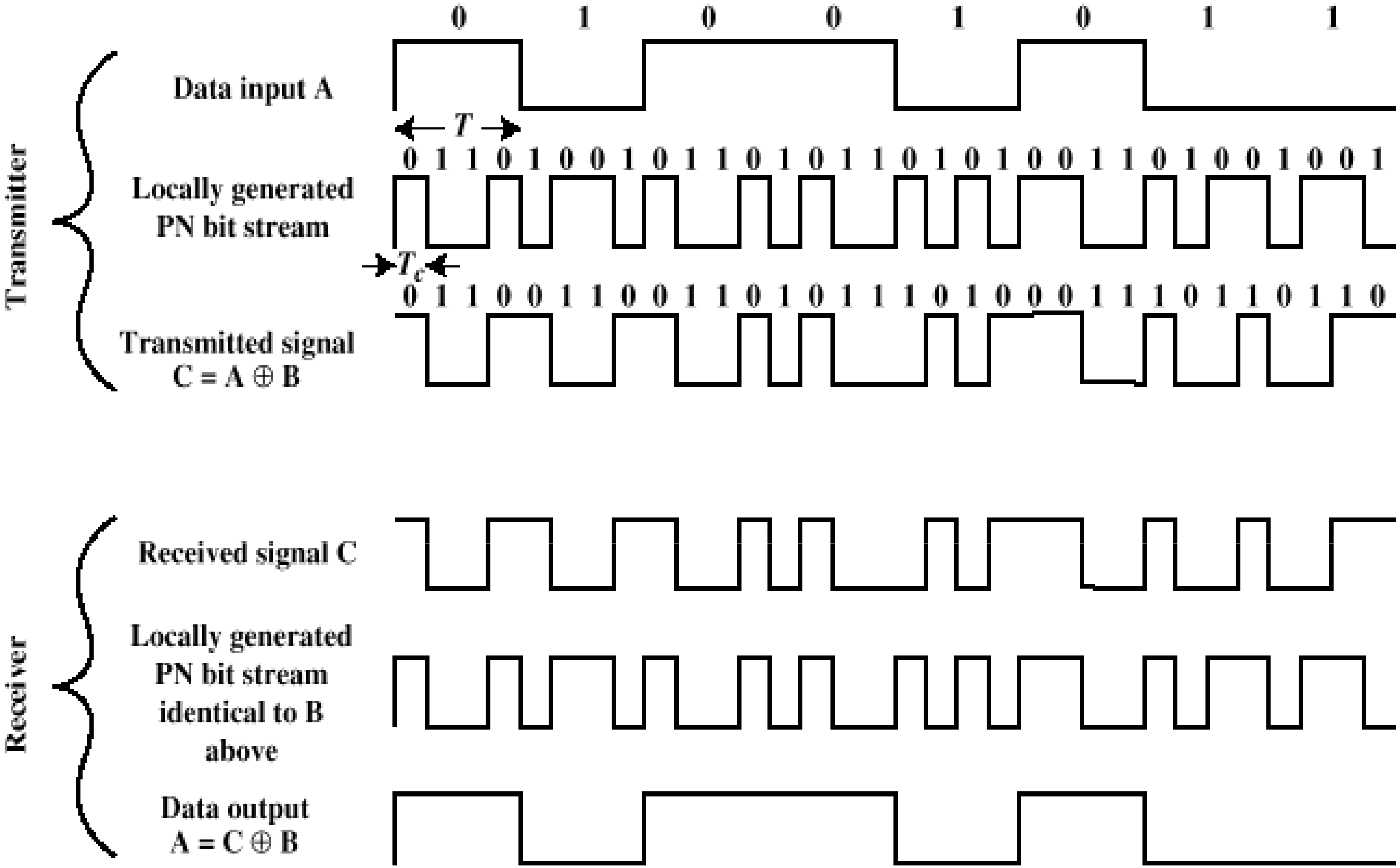


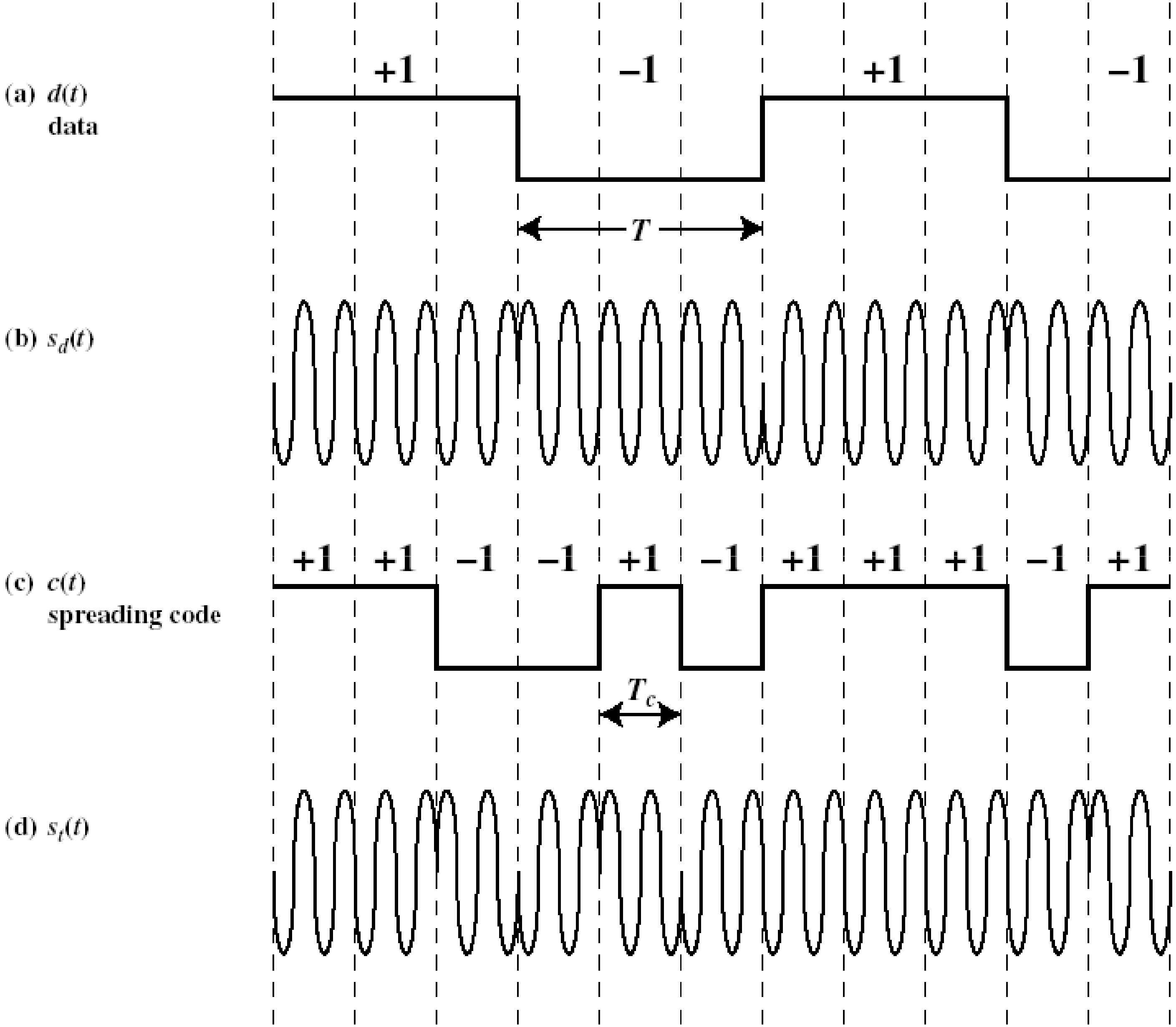
Figure 1.9 Illustration of FHSS.

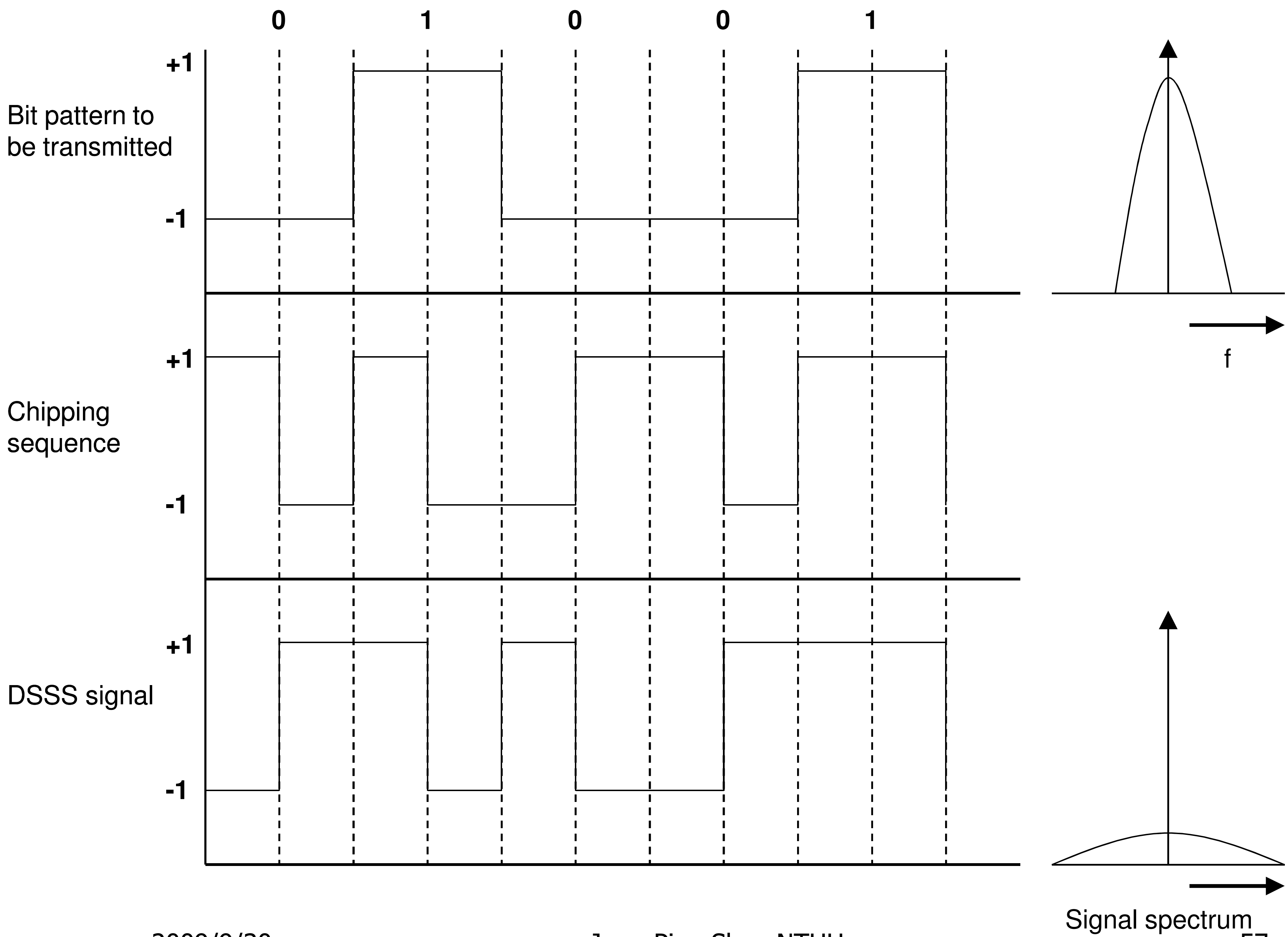
Direct Sequence Spread Spectrum (DSSS)

- Each bit in original signal is represented by multiple bits in the transmitted signal
- Spreading code spreads signal across a wider frequency band
  - Spread is in direct proportion to number of bits used
- One technique combines digital information stream with the spreading code bit stream using exclusive-OR



Example of Direct Sequence Spread Spectrum


(a) d(t)
data
+1
−1
+1
−1
T
(b) s_d(t)
(c) c(t)
spreading code
+1
+1
−1
−1
+1
−1
+1
+1
+1
−1
+1
T_c
(d) s_t(t)


0
1
0
0
1
+1
-1
Bit pattern to be transmitted
Chipping sequence
DSSS signal
f
Signal spectrum

Code-Division Multiple Access (CDMA)

- Basic Principles of CDMA
  - *D* = rate of data signal
  - Break each bit into *k chips*
    - Chips are a user-specific fixed pattern
  - Chip data rate of new channel = *kD*

CDMA Example (1/3)

- If $k = 6$ and code is a sequence of 1s and -1s
  - For a '1' bit, A sends code as chip pattern
    - <c1, c2, c3, c4, c5, c6>
  - For a '0' bit, A sends complement of code
    - <-c1, -c2, -c3, -c4, -c5, -c6>
- Receiver knows sender's code and performs electronic decode function

$$S_u(d) = d1 \times c1 + d2 \times c2 + d3 \times c3 + d4 \times c4 + d5 \times c5 + d6 \times c6$$

  - <d1, d2, d3, d4, d5, d6> = received chip pattern
  - <c1, c2, c3, c4, c5, c6> = sender's code

CDMA Example (2/3)

- Each station has its own unique chip sequence (CS)
- All CSs are pairwise orthogonal
- For example :(codes A, B, C and D are pair-wise orthogonal)
  - A: 00011011 => (-1-1-1+1+1-1+1+1)
  - B: 00101110 => (-1-1+1-1+1+1+1-1)
  - C: 01011100 => (-1+1-1+1+1+1-1-1)
  - D: 01000010 => (-1+1-1 - 1-1-1+1-1)

CDMA Example (3/3)

- $A \cdot B = (1+1-1-1+1-1+1-1) = 0$
- $B \cdot C = (1-1-1-1+1+1-1+1) = 0$
- Ex: If station C transmits 1 to station E, station B transmits 0 and station A transmits 1 simultaneously then the signal received by station E will become
  - $S_E = (-1+1-1+1+1+1-1-1) + (+1+1-1+1-1-1-1+1) + (-1-1-1+1+1-1+1+1) = (-1+1-3+3-1-1-1+1)$
  - E can convert the signal S_E to $S_E C = S_E(-1+1-1+1+1+1-1-1) = (1+1+3+3+1-1+1-1)/8 = 1$

Categories of Spreading Sequences

- Spreading Sequence Categories
  - PN sequences
  - Orthogonal codes
- For FHSS systems
  - PN sequences most common
- For DSSS systems not employing CDMA
  - PN sequences most common
- For DSSS CDMA systems
  - PN sequences
  - Orthogonal codes

Space Division Multiple Access (SDMA)

- SDMA uses directional antennas to cover regular regions; thus different areas can be served using the same frequency channel

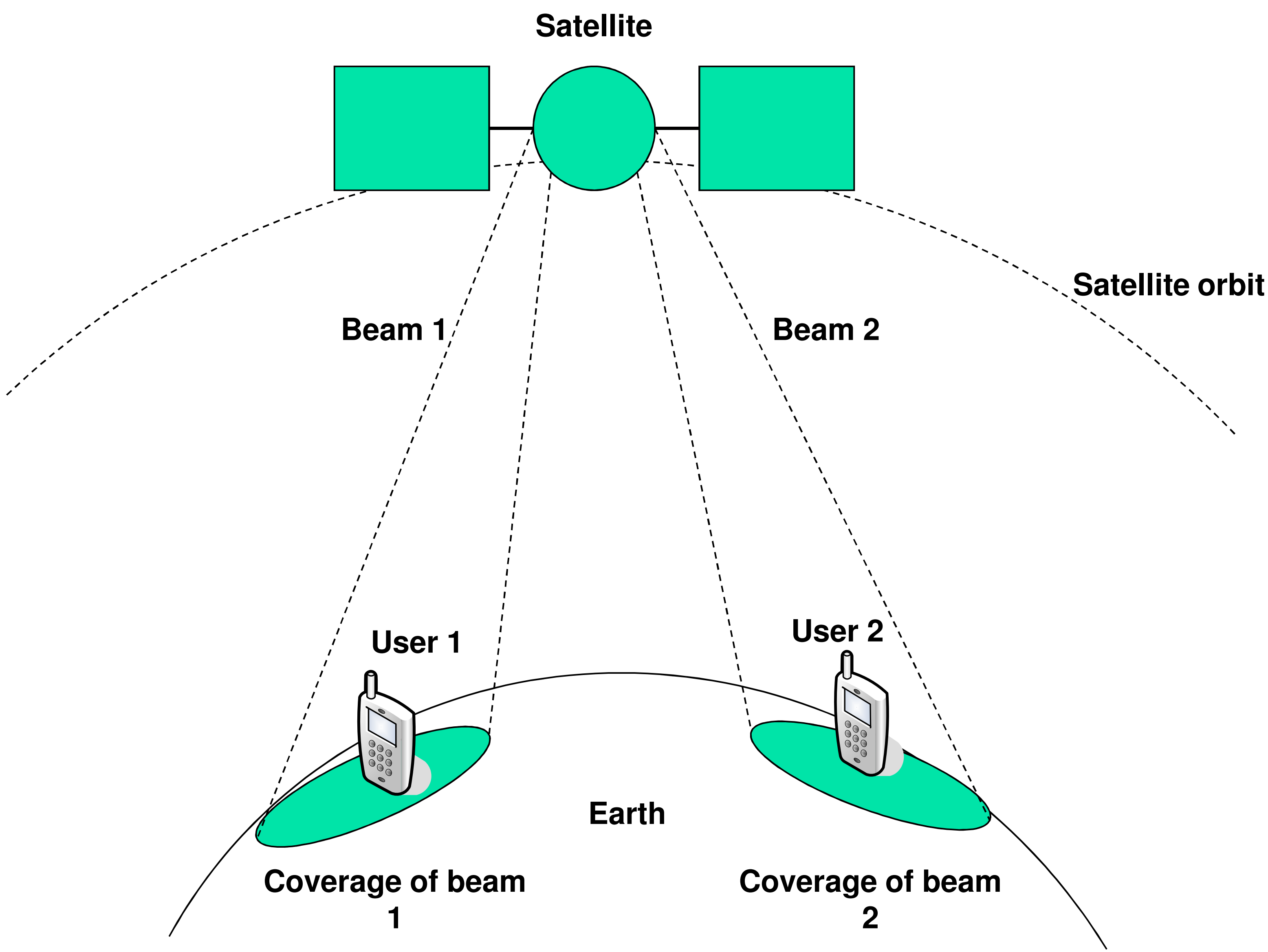


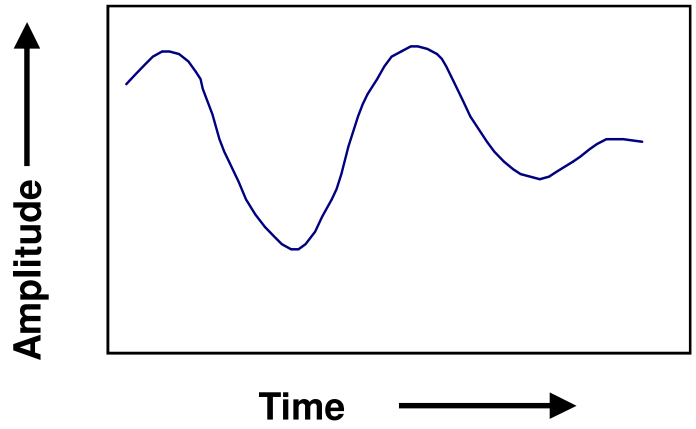
Figure Illustration of SDMA.

Voice Coding

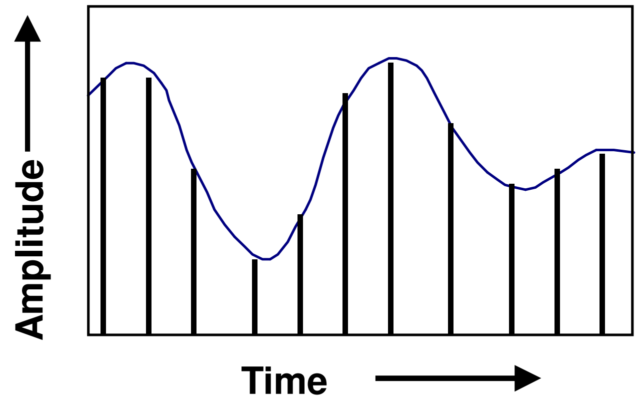
- The voice coding process converts the analog signal into its equivalent digital representation
- Codec performs analog to digital conversion and the reverse digital to analog
- The main goal of codec is to convert the voice signal into a digital bit stream that has the lowest possible bit rate, while maintaining an acceptable level of quality

Pulse Code Modulation

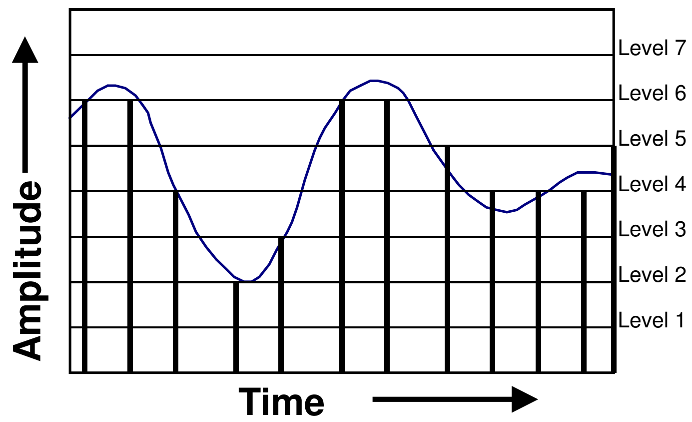
- Based on the sampling theorem
  - If a signal $f(t)$ is sampled at a rate higher than twice the highest signal frequency, then the samples contain all the information of the original signal
- Each analog sample is assigned a binary code
  - Analog samples are referred to as pulse amplitude modulation (PAM) samples
- The digital signal consists of block of n bits, where each n-bit number is the amplitude of a PCM pulse



(a) Analog Signal Input



(b) PAM Pulses



(c) Quantization Output

Figure 1.12 Pulse code modulation.

Error Control

- Three approaches are common use:
- Error detection codes
  - Detects the presence of an error
- Automatic repeat request (ARQ) protocols
  - Block of data with error is discarded
  - Transmitter retransmits that block of data
- Error correction codes, or forward correction codes (FEC)
  - Designed to detect and correct errors

Parity Check

- Parity bit appended to a block of data
- Even parity
  - Added bit ensures an even number of 1s
- Odd parity
  - Added bit ensures an odd number of 1s
- Example, 7-bit character [1110001]
  - Even parity [11100010]
  - Odd parity [11100011]

Cyclic Redundancy Check (CRC)

- Transmitter
  - For a *k*-bit block, transmitter generates an (*n*-*k*)-bit frame check sequence (FCS)
  - Resulting frame of *n* bits is exactly divisible by predetermined number
- Receiver
  - Divides incoming frame by predetermined number
  - If no remainder, assumes no error

Hamming Code

- Hamming codes are designed to correct single bit errors
- Family of (n, k) block error-correcting codes with parameters:
  - Block length: $n = 2^m - 1$
  - Number of data bits: $k = 2^m - m - 1$
  - Number of check bits: $n - k = m$
  - Minimum distance: $d_{min} = 3$
- Single-error-correcting (SEC) code
  - SEC double-error-detecting (SEC-DED) code

Hamming Code Principle

- Hamming distance- for 2 *n*-bit binary sequences, the number of different bits
  - E.g., v_1=011011; v_2=110001; $d(v_1, v_2) = 3$
  - Example:

Data block	Codeword
00	00000
01	00111
10	11001
11	11110

  - We can correct 1-bit error or detect 2-bit error

Hamming Code Process

- Encoding: k data bits + (n - k) check bits
- Decoding: compares received (n -k) bits with calculated (n - k) bits using XOR
  - Resulting (n - k) bits called *syndrome word*
  - Syndrome range is between 0 and $2^{(n-k)} - 1$
  - Each bit of syndrome indicates a match (0) or conflict (1) in that bit position and hence

    $2^{(n-k)} - 1 >= k + (n - k) = n$

Hamming Code Characteristics

- We would like to generate a syndrome with the following characteristics:
  - If the syndrome contains all 0s, no error has been detected
  - If the syndrome contains only one bit set to 1, then an error has occurred in one of the check bits
  - If the syndrome contains more than one bit set to 1, then the numerical value of the syndrome indicates the position of the data bit in error

Hamming Code Generation

- Hamming check bits are inserted at the position of power of 2 i.e., positions 1, 2, 4, …, $2^{(n-k)}$
- The remaining bits are data bits
- Each data position which has a value 1 is presented by a binary value equal to its position; thus if the 9^{th} bit is 1 the corresponding value is 1001
- All of the position values are then XORed together to produce the bits of the Hamming code
  - Example: The 8-bit data block is 00111001

Table 8.2 Layout of Data Bits and Check Bits (page 1 of 2)

(a) Transmitted block

Bit Position	12	11	10	9	8	7	6	5	4	3	2	1
Position Number	1100	1011	1010	1001	1000	0111	0110	0101	0100	0011	0010	0001
Data Bit	D8	D7	D6	D5		D4	D3	D2		D1		
Check Bit					C8				C4		C2	C1
Transmitted Block	0	0	1	1	0	1	0	0	1	1	1	1
Codes			1010	1001		0111				0011		

(b) Check bit calculation prior to transmission

Position	**Code**
10	1010
9	1001
7	0111
3	0011
XOR = C8 C4 C2 C1	0111

Table 8.2 Layout of Data Bits and Check Bits (page 2 of 2)

(c) Received block

Bit Position	12	11	10	9	8	7	6	5	4	3	2	1
Position Number	1100	1011	1010	1001	1000	0111	0110	0101	0100	0011	0010	0001
Data Bit	D8	D7	D6	D5		D4	D3	D2		D1		
Check Bit					C8				C4		C2	C1
Transmitted Block	0	0	1	1	0	1	1	0	1	1	1	1
Codes			1010	1001		0111	0110			0011		

(d) Check bit calculation after reception

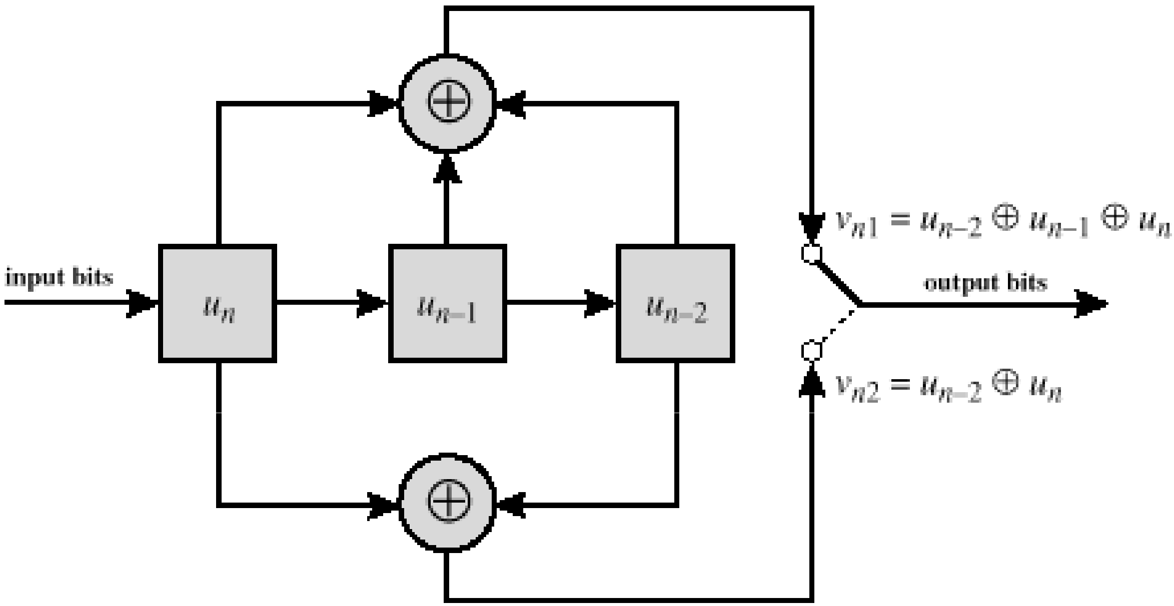
Position	Code
Hamming	0111
10	1010
9	1001
7	0111
6	0110
3	0011
XOR = syndrome	0110

Table 8.1 Hamming Code Requirements

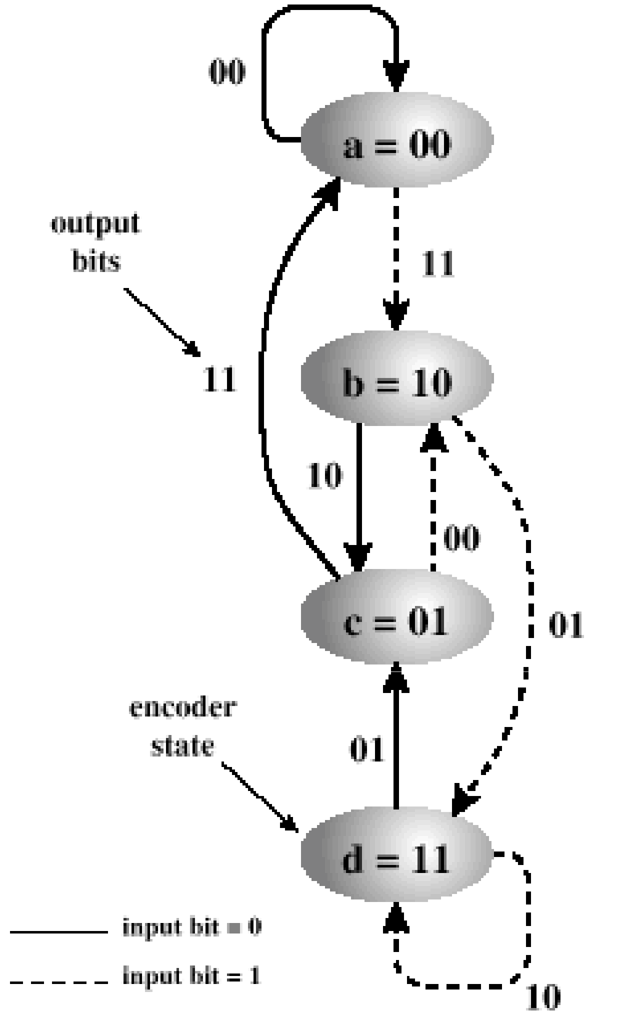
	Single-Error Correction		Single-Error Correction/ Double-Error Detection	
Data Bits	Check Bits	% Increase	Check Bits	% Increase
8	4	50	5	62.5
16	5	31.25	6	37.5
32	6	18.75	7	21.875
64	7	10.94	8	12.5
128	8	6.25	9	7.03
256	9	3.52	10	3.91

Convolutional Codes

- Generates redundant bits continuously
- Error checking and correcting carried out continuously
  - (n, k, K) code
    - Input processes k bits at a time
    - Output produces n bits for every k input bits
    - K = constraint factor
    - k and n generally very small
  - n-bit output of (n, k, K) code depends on:
    - Current block of k input bits
    - Previous K-1 blocks of k input bits



(a) Encoder shift register



Ex: input 1011 generates output 11100001

(b) Encoder state diagram

Figure 8.9 Convolutional Encoder with $(n, k, K) = (2, 1, 3)$

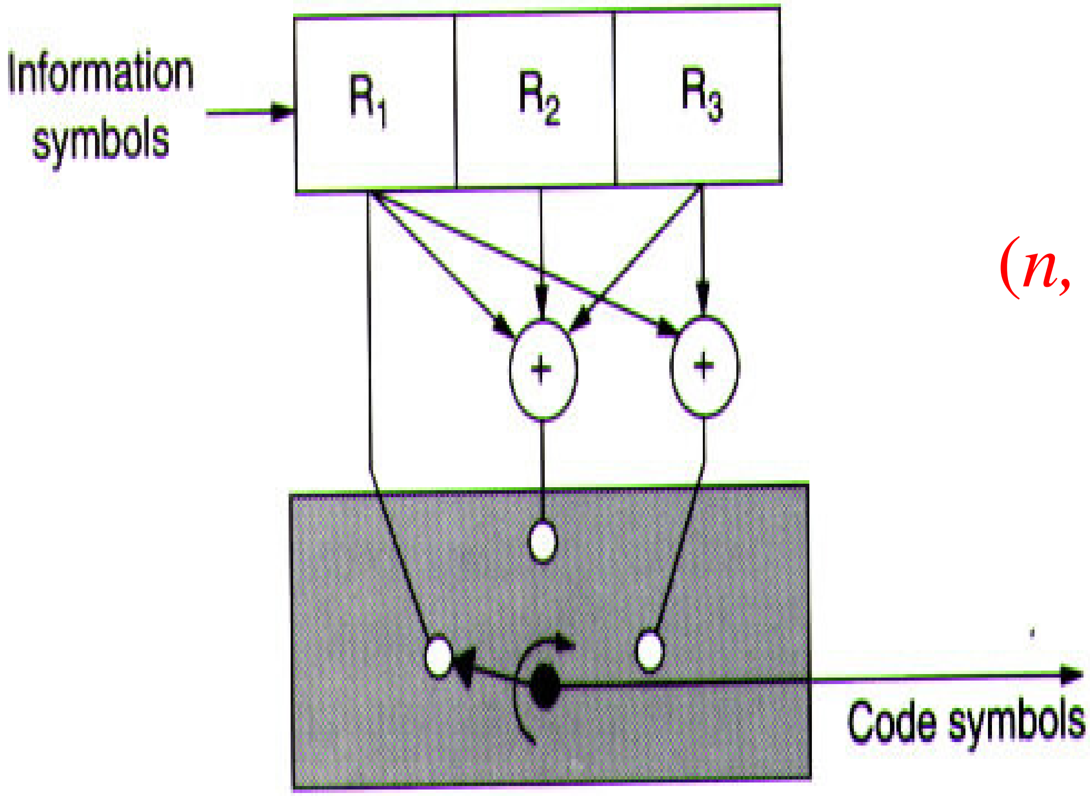
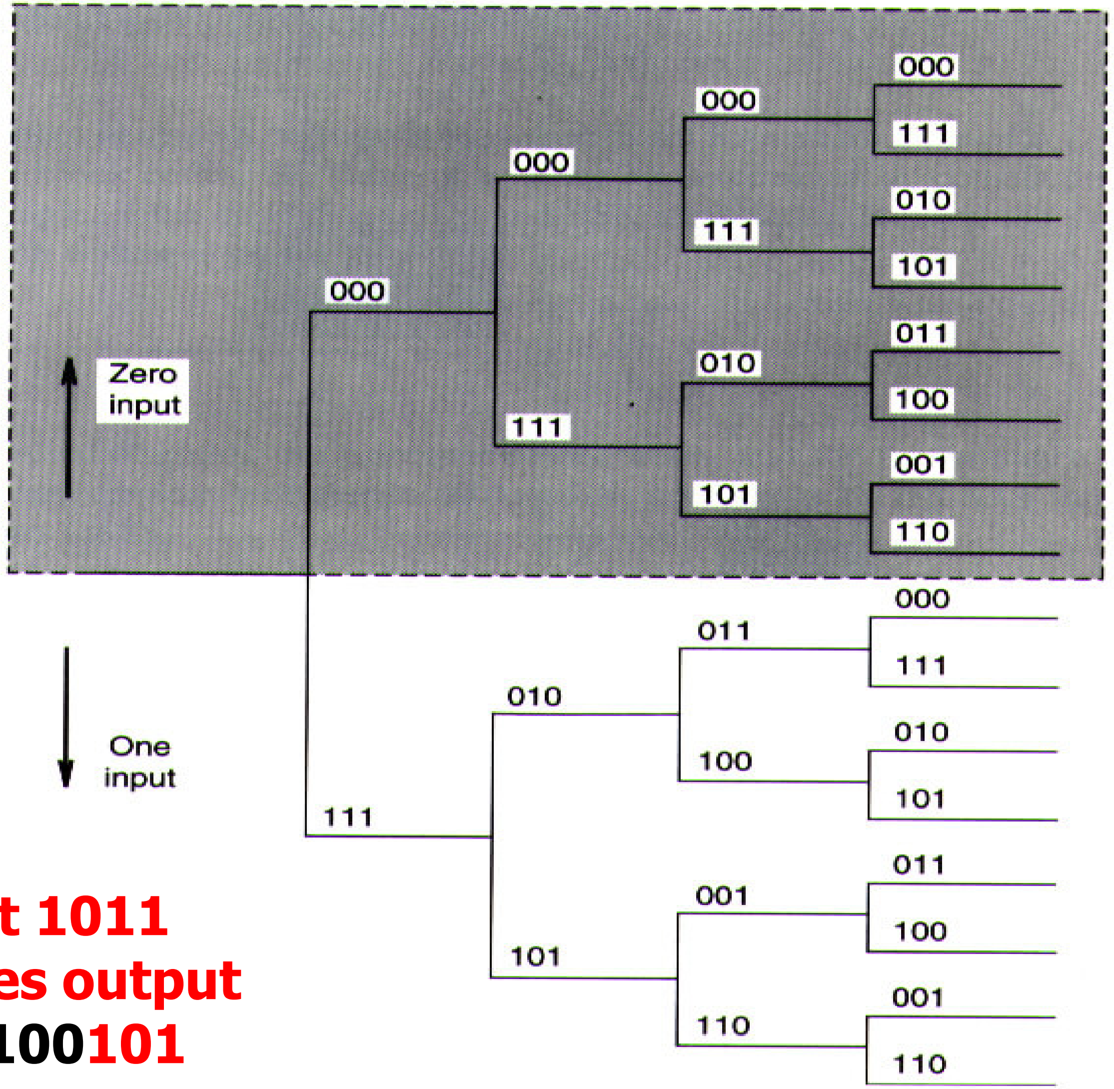


Figure 5.4.2 Example of a systematic rate $\frac{1}{3}$ convolutional encoder.

$(n, k, K) = (3, 1, 3)$

$$V_1 = R_1$$
$$V_2 = R_1 \oplus R_2 \oplus R_3$$
$$V_3 = R_1 \oplus R_3$$



Ex: input 1011 generates output 111010100101

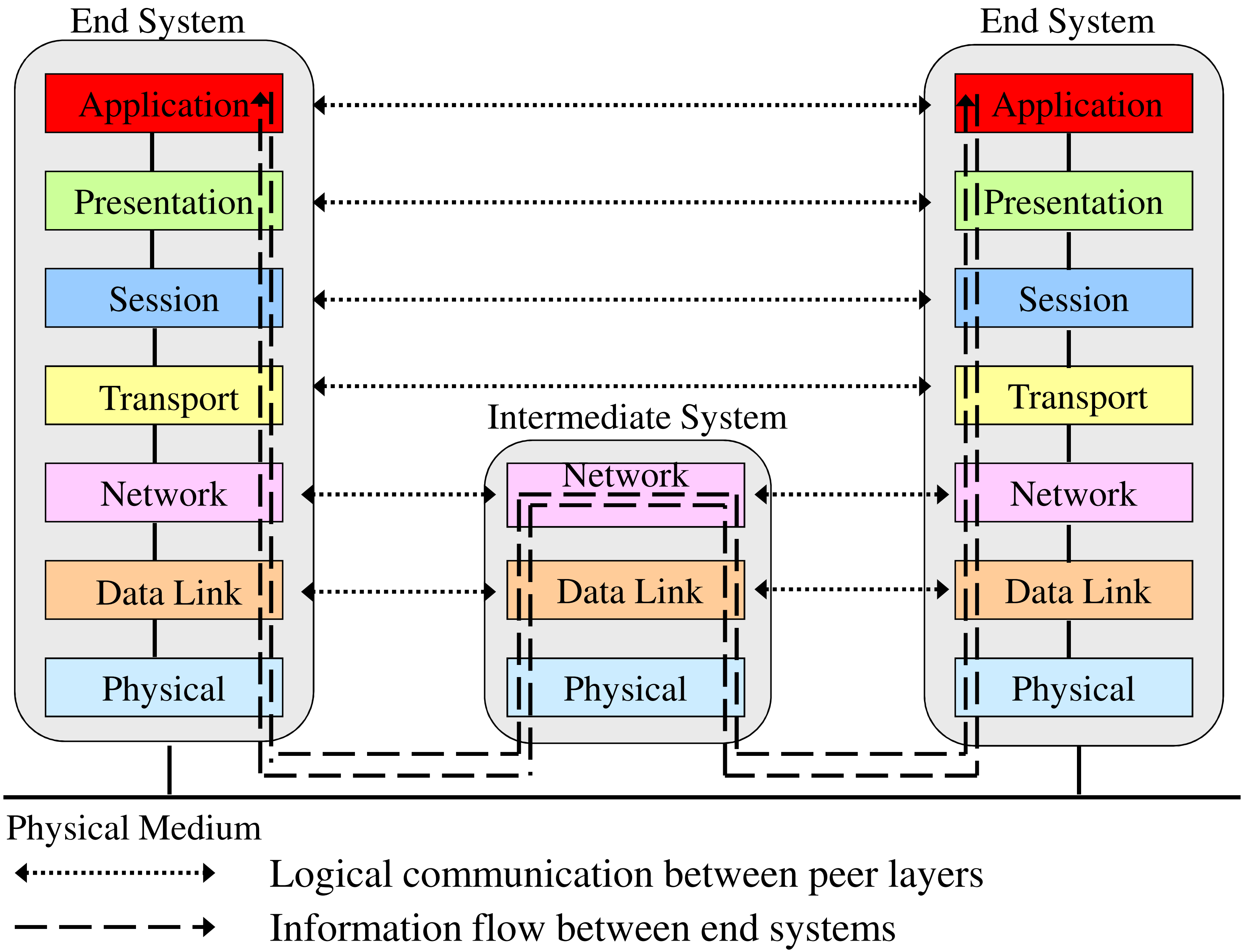
Figure 5.4.3 Code tree for encoder shown in Figure 5.4.2. (From J.A. Heller and I.M. Jacobs, "Viterbi decoding for satellite and space communication," *Proceedings of the IEEE*, (© 1971 IEEE).

Computer Network Architecture

- Open System Interconnection (OSI) proposed by International Organization for Standardization (ISO)
- TCP/IP reference model: adapted by most network applications
- Asynchronous Transfer Mode: designed for QoS sevices

The OSI Reference Model

- Shortcomings
  - The session and presentation layers were not required for most applications
  - Several layers in the model were performing redundant operations
- The OSI model was never implemented due its complexity


End System
Application
Presentation
Session
Transport
Network
Data Link
Physical
Intermediate System
Network
Data Link
Physical
End System
Application
Presentation
Session
Transport
Network
Data Link
Physical
Physical Medium
Logical communication between peer layers
Information flow between end systems

The TCP/IP Reference Model

- Shortcomings
  - Too specific to the TCP/IP stack
  - Difficult to design new networks with new technologies using the TCP/IP reference model
  - Lack of data control layer to perform error control, link-level flow control, and MAC
- However, it is the most successful model and even forms the backbone of today's Internet

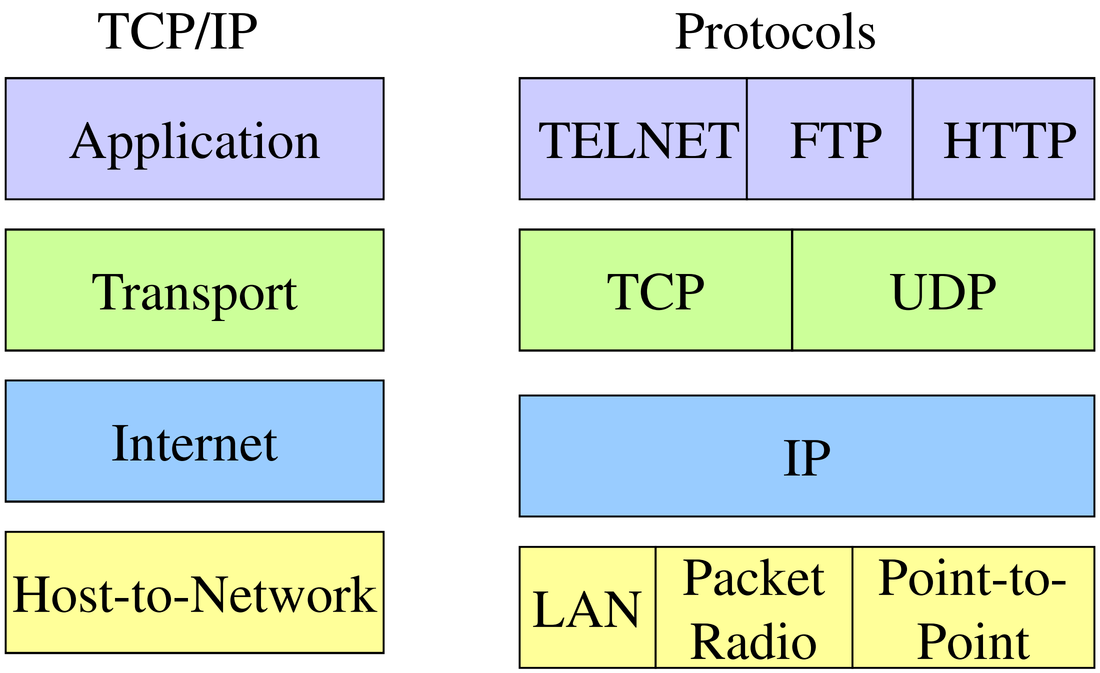


Figure 1.18. TCP / IP reference model.

The ATM Reference Model

- Shortcomings
  - High packet header control overhead (around 10%)
  - Complex mechanism for ensuring fairness and providing QoS
  - Complex packet scheduling algorithm
  - High cost and complexity of devices, and lack of scalability
- Not widely in use today

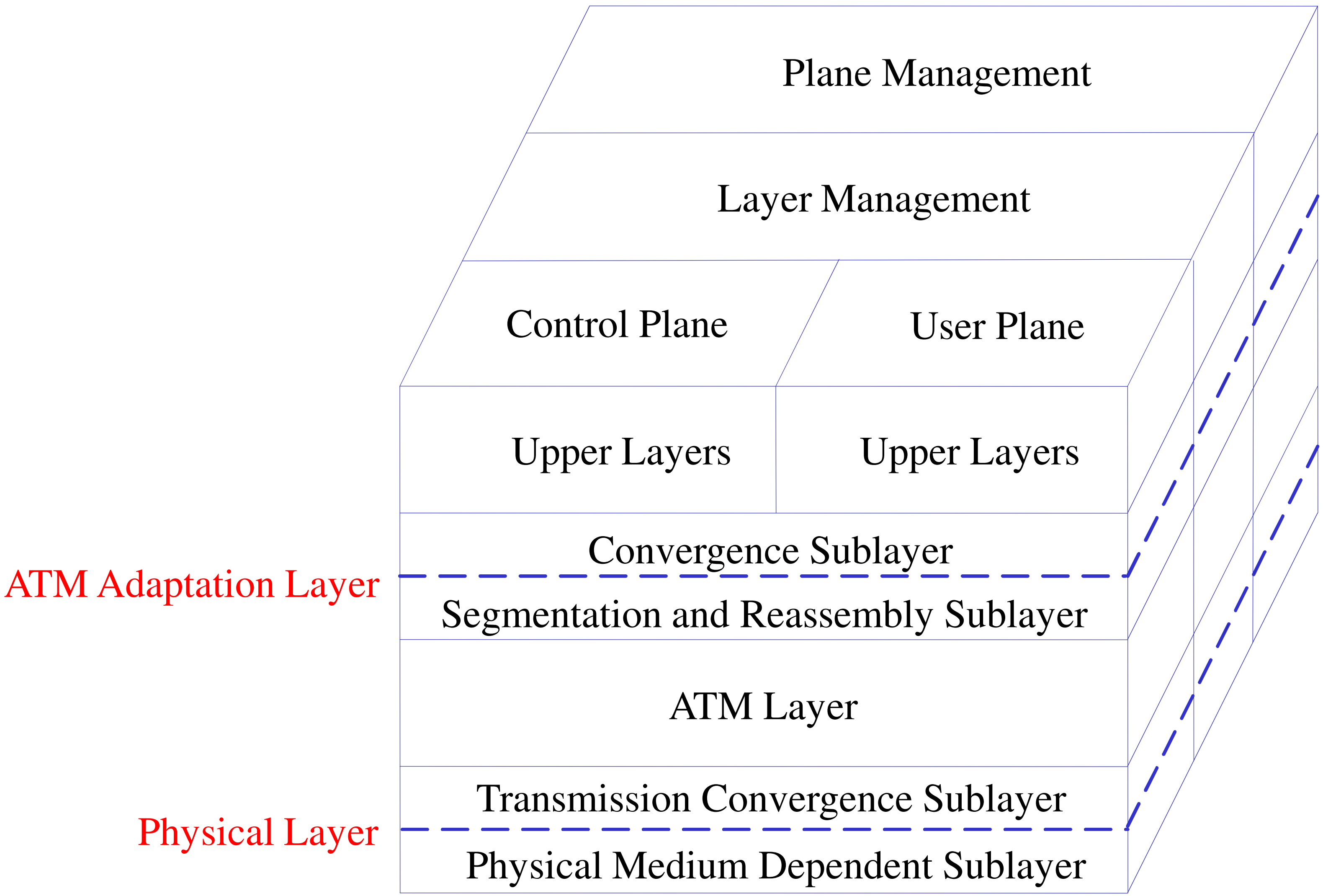


Figure 1.19. ATM reference model.

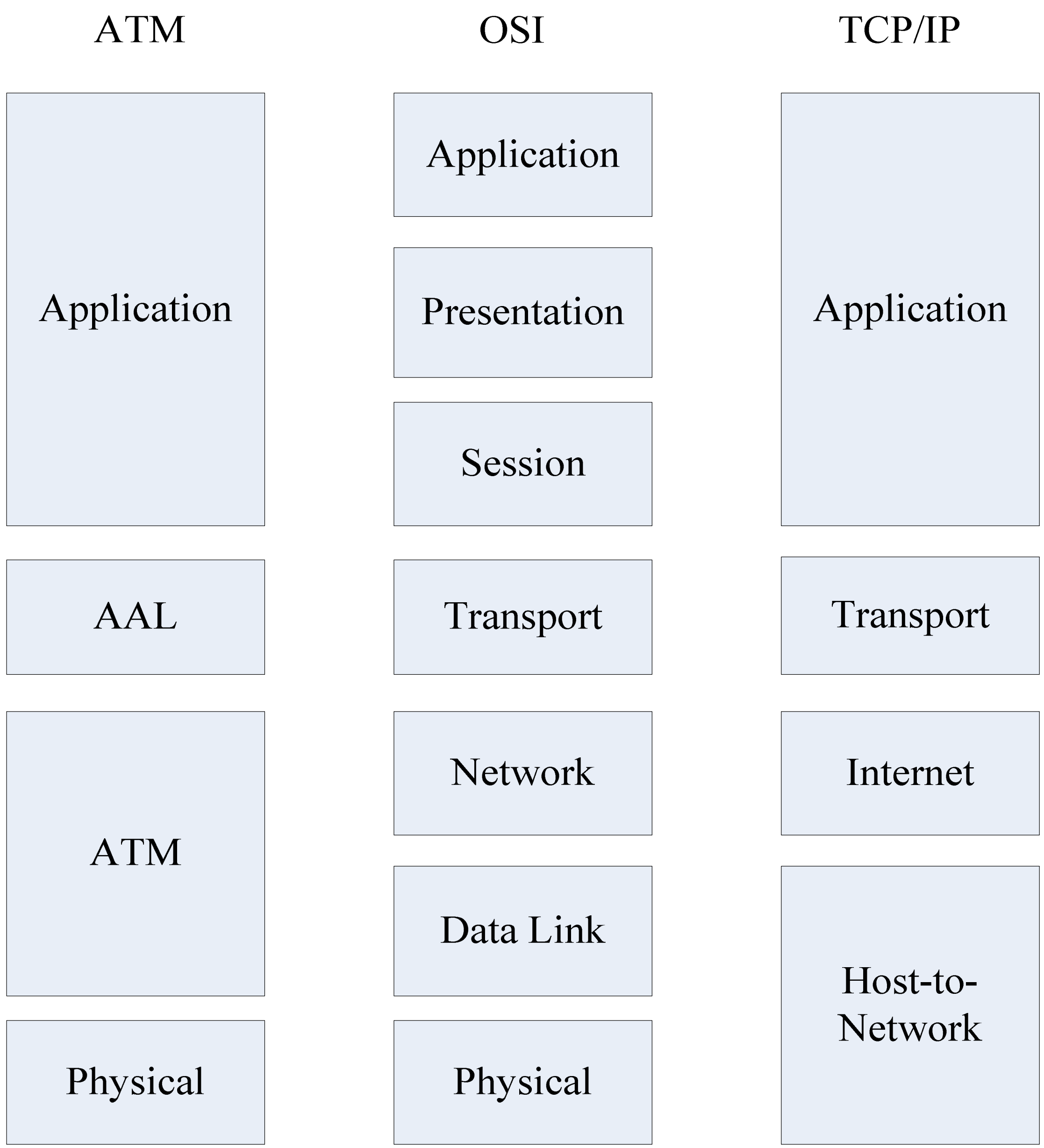


Figure 1.20. Comparison among ATM, OSI, and TCP/IP reference models.

IEEE 802 Networking Standard (1/2)

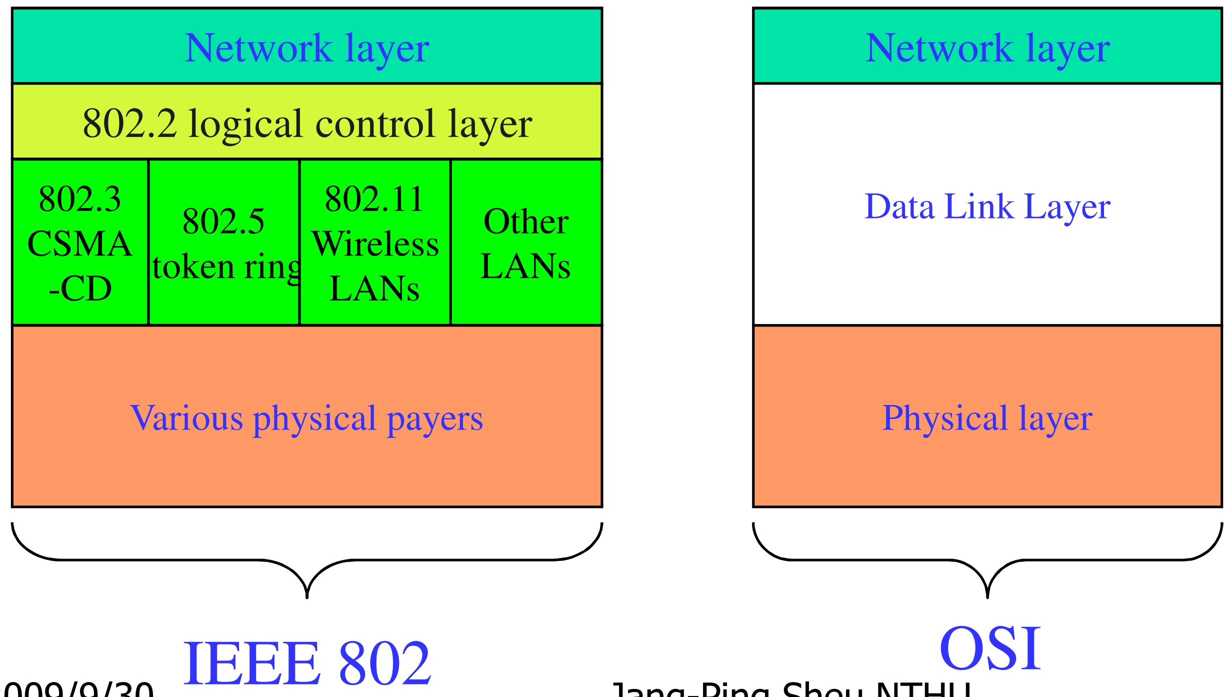
- 802.1: Internetworking
- 802.2: Logical link control
- 802.3: Ethernet or CSMA/CD
- 802.4: Token bus LANs
- 802.5: Token ring LANs
- 802.6: MANs
- 802.7: Broadband LANs
- 802.8: Fiber optic LANs and MANs

IEEE 802 Networking Standard (2/2)

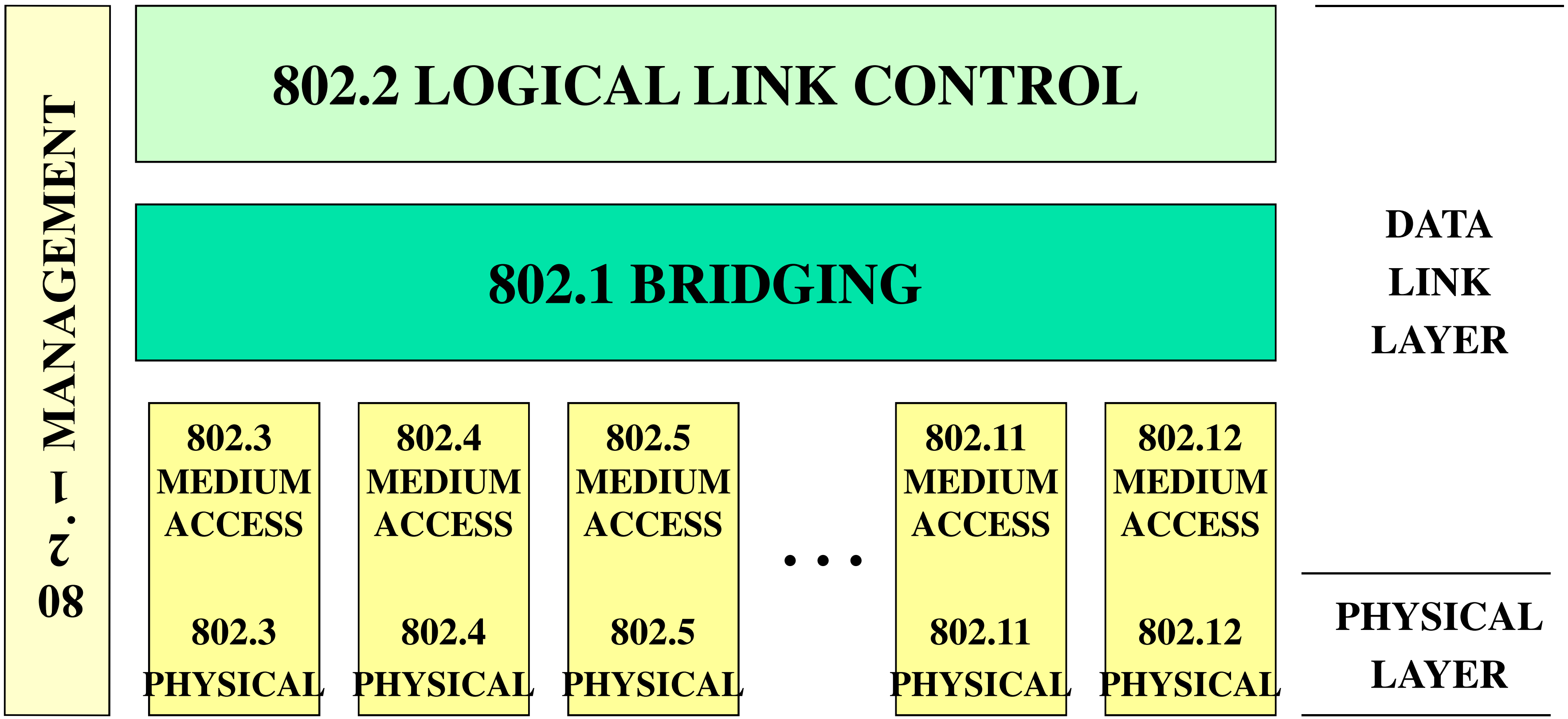
- 802.9: Integrated (voice/data) services LANs and MANs
- 802.10: Security in LANs and MANs
- 802.11: Wireless LANs
- 802.12: Demand priority access LANs
- 802.15: Wireless PANs
- 802.16: Broadband wireless MANs

The Protocol Stacks

- MAC sublayer and OSI (Open Systems Interconnection) reference model



The Protocol Stacks



IEEE 802.11 Standards

- WLAN standard: IEEE 802.11-1997
- Direct-sequence spread spectrum
  - Operating in 2.4 GHz ISM band
  - Data rates of 1 and 2 Mbps
- Frequency-hopping spread spectrum
  - Operating in 2.4 GHz ISM band
  - Data rates of 1 and 2 Mbps
- Infrared
  - 1 and 2 Mbps
  - Wavelength between 850 and 950 nm

IEEE 802.11a and IEEE 802.11b

- IEEE 802.11a- 1999
  - Makes use of 5-GHz band
  - Provides rates of 6, 9 , 12, 18, 24, 36, 48, 54 Mbps
  - Uses orthogonal frequency division multiplexing (OFDM)
  - Subcarrier modulated using BPSK, QPSK, 16-QAM or 64-QAM
- IEEE 802.11b- 1999
  - Provides data rates of 5.5 and 11 Mbps
  - Complementary code keying (CCK) modulation scheme

Other 802.11 Task Groups

- 802.11c (1998): bridges and access points
- 802.11e: QoS
- 802.11f (2003): interoperability between devices made by different vendors
- 802.11g(2003): 802.11 to support 54 Mbps in 5 G Hz and backward compatible
- 802.11i : enhance security
- 802.11n: enhance throughputs up to 100 Mbps

Decibel- dB

- Decibel is the unit used to express relative differences in signal strength
- It is expressed as the base 10 logarithm of the ratio of the **powers** of two signals:
  - $dB = 10 \log (P1/P2)$
- Logarithms are useful as the unit of measurement
  - signal power tends to span several orders of magnitude
  - signal attenuation losses and gains can be expressed in terms of subtraction and addition

Example

- Suppose that a signal passes through two channels is first attenuated in the ratio of 20 and 7 on the second. The total signal degradation is the ratio of 140 to 1. Expressed in dB, this become $10 \log 20 + 10 \log 7 = 13.01 + 8.45 = 21.46$ dB

The Order of dB

- The following table helps to indicate the order of magnitude associated with dB:
  - **1 dB attenuation means that 0.79 of the input power survives.**
  - **3 dB attenuation means that 0.5 of the input power survives.**
  - **10 dB attenuation means that 0.1 of the input power survives.**
  - **20 dB attenuation means that 0.01 of the input power survives.**
  - **30 dB attenuation means that 0.001 of the input power survives.**
  - **40 dB attenuation means that 0.0001 of the input power survives.**

Exercises

- 2, 4, 6, 7, 11, 15