Chapter 7

Multiple Division Techniques

Outline

- **Introduction**
- **Concepts and Models for Multiple Divisions**
  - **Frequency Division Multiple Access (FDMA)**
  - **Time Division Multiple Access (TDMA)**
  - **Code Division Multiple Access (CDMA)**
  - **Orthogonal Frequency Division Multiplexing (OFDM)**
  - **Space Division Multiple Access (SDMA)**
  - **Comparison of FDMA, TDMA, and CDMA**
- **Modulation Techniques**
  - **Amplitude Modulation (AM)**
  - **Frequency Modulation (FM)**
  - **Frequency Shift Keying (FSK)**
  - **Phase Shift Keying (PSK)**
  - **Quadrature Phase Shift Keying (QPSK)**
  - **π/4QPSK**
  - **Quadrature Amplitude Modulation (QAM)**
  - **16QAM**

Concepts and Models for Multiple Divisions

- Multiple access techniques are based on orthogonalization of signals
- A radio signal is a function of frequency, time and code as;

$$s(f, t, c) = s(f, t)\, c(t)$$

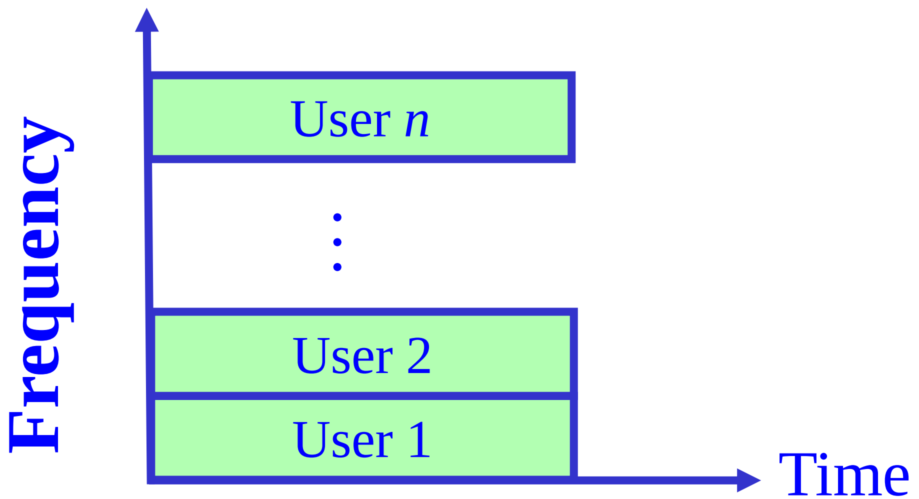
where $s(f, t)$ is the function of frequency and time and $c(t)$ is the function of code

  - Use of different frequencies to transmit a signal: FDMA
  - Distinct time slot: TDMA
  - Different codes CDMA
  - Multiple simultaneous channels: OFDM
  - Specially separable sectors: SDMA

Frequency Division Multiple Access (FDMA)

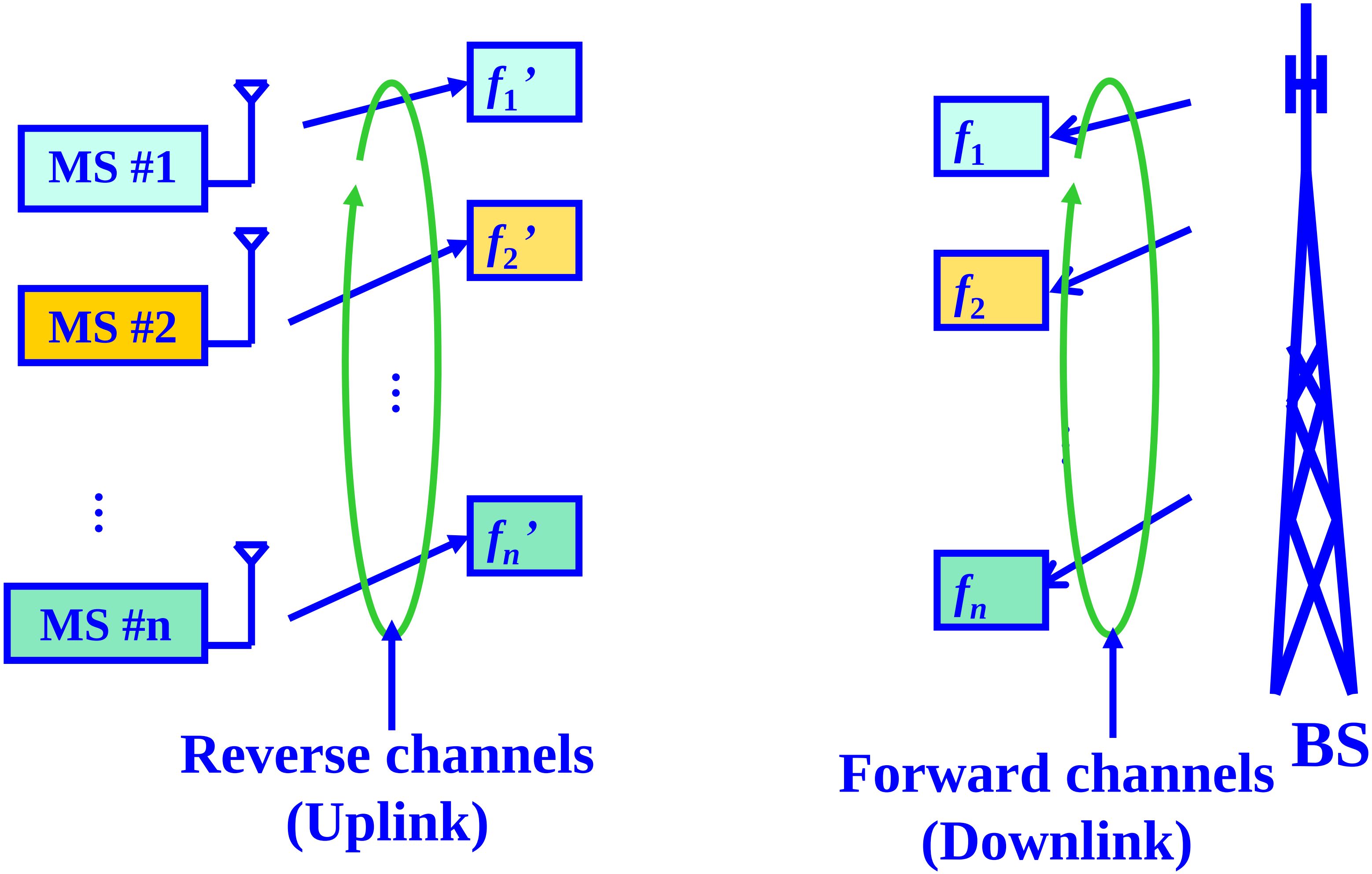
Orthogonality conditions of two signals in FDMA:

$$\int_F s_i(f,t)\, s_j(f,t)\,df = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}, \quad i, j = 1, 2, \ldots, k$$

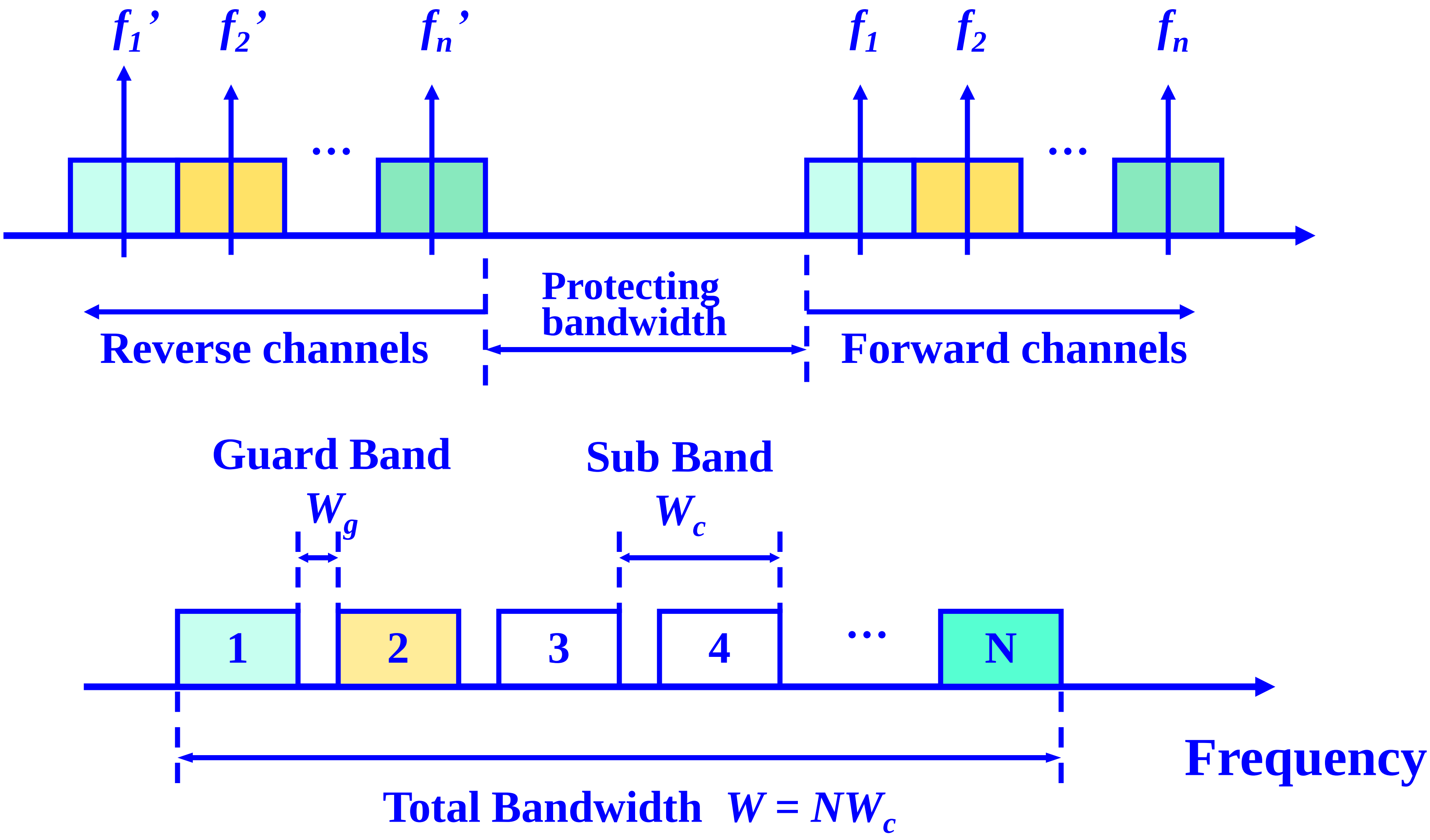


- Single channel per carrier
- All first generation systems use FDMA

Basic Structure of FDMA



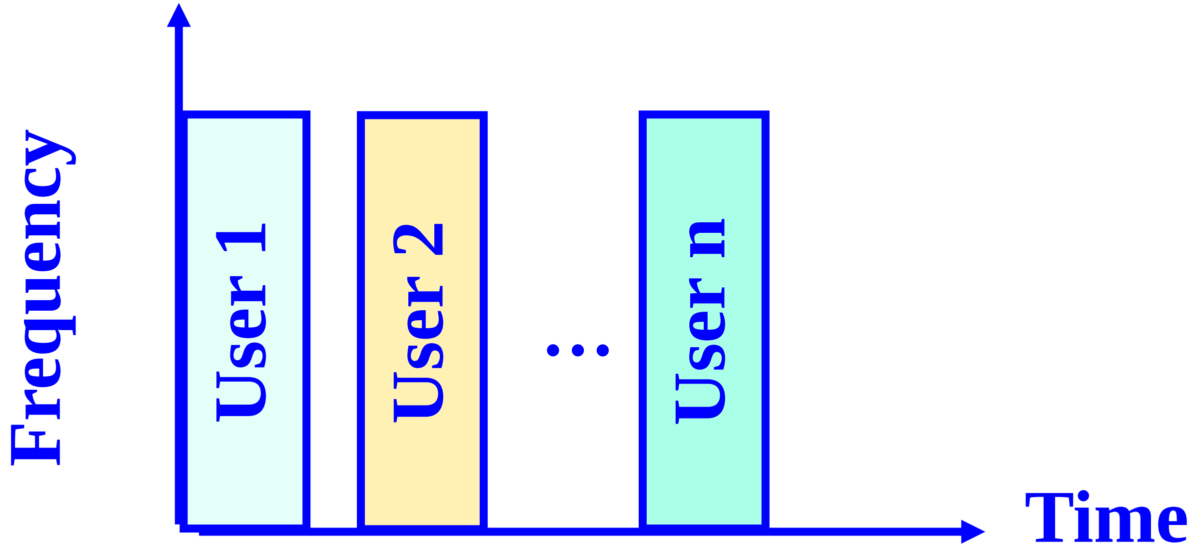
Forward and Reverse channels in FDMA and Guard Band



Time Division Multiple Access (TDMA)

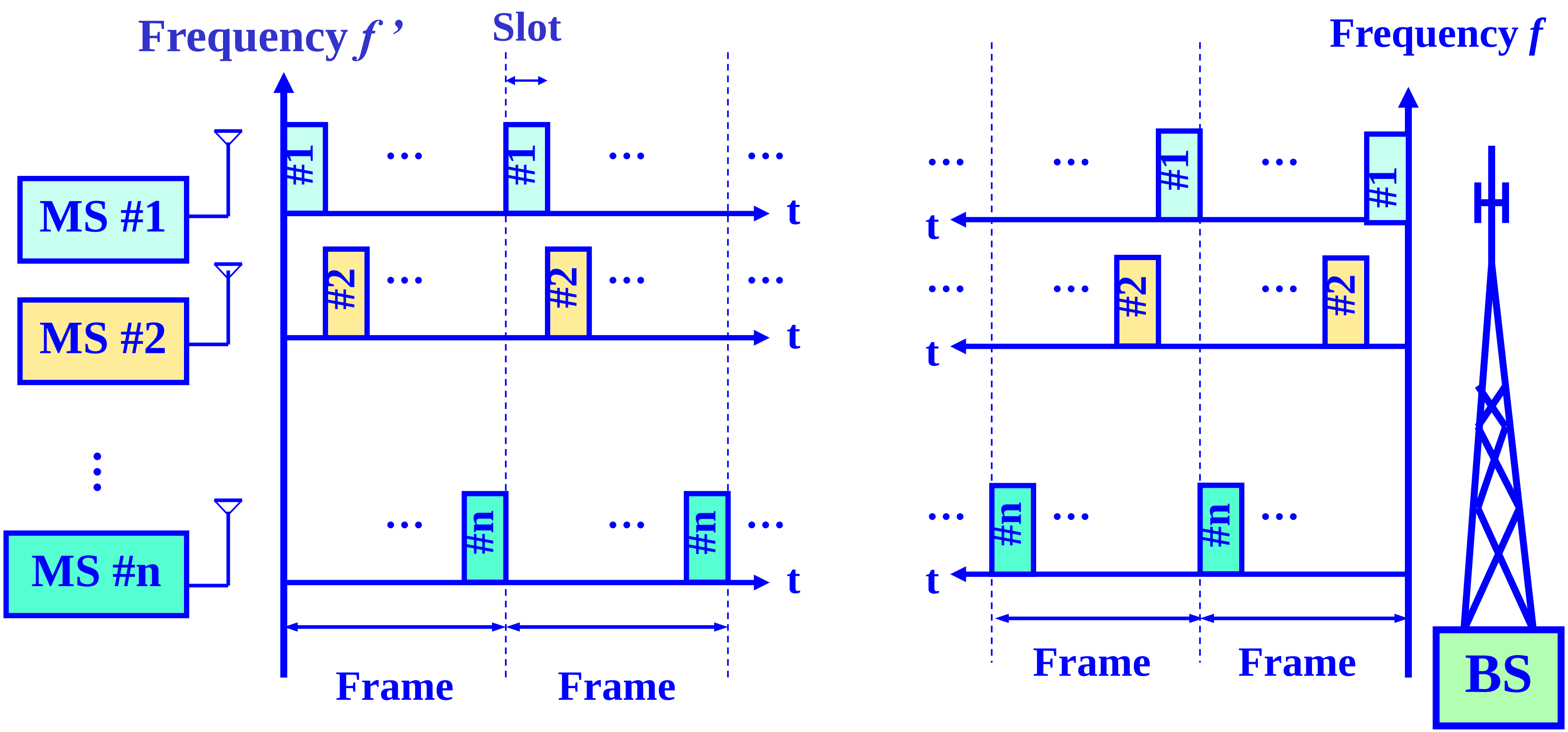
Orthogonality conditions of two signals in TDMA:

$$\int_T s_i(f,t)\, s_j(f,t)\,dt = \begin{cases} 1 & i=j \\ 0 & i \neq j \end{cases}, \quad i,j = 1,2,\ldots,k$$



- **Multiple channels per carrier**
- **Most of second generation systems use TDMA**

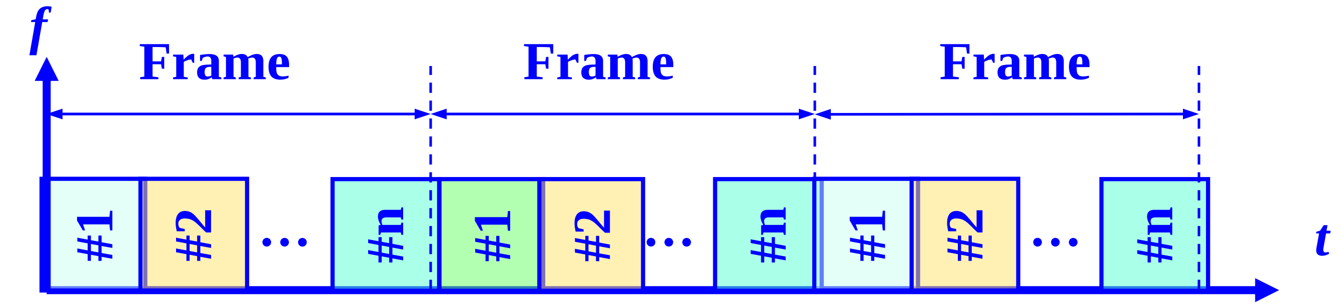
The Concept of TDMA



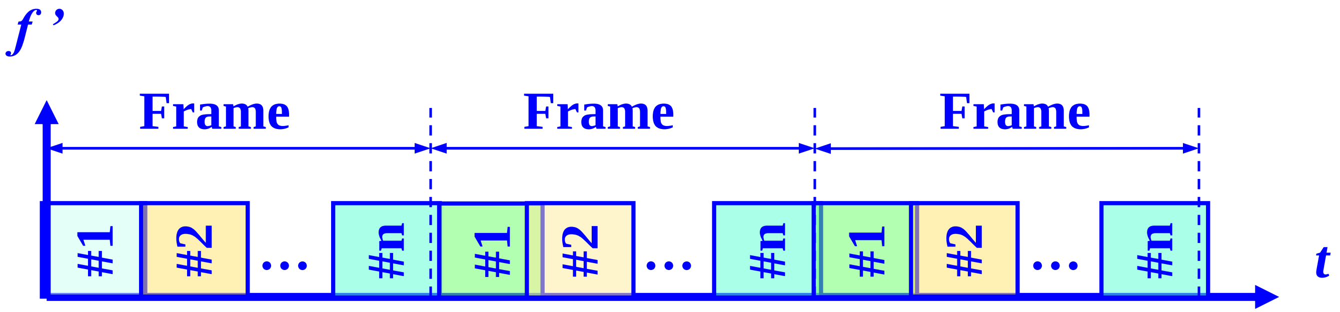
Reverse channels (Uplink)

Forward channels (Downlink)

TDMA: Channel Structure



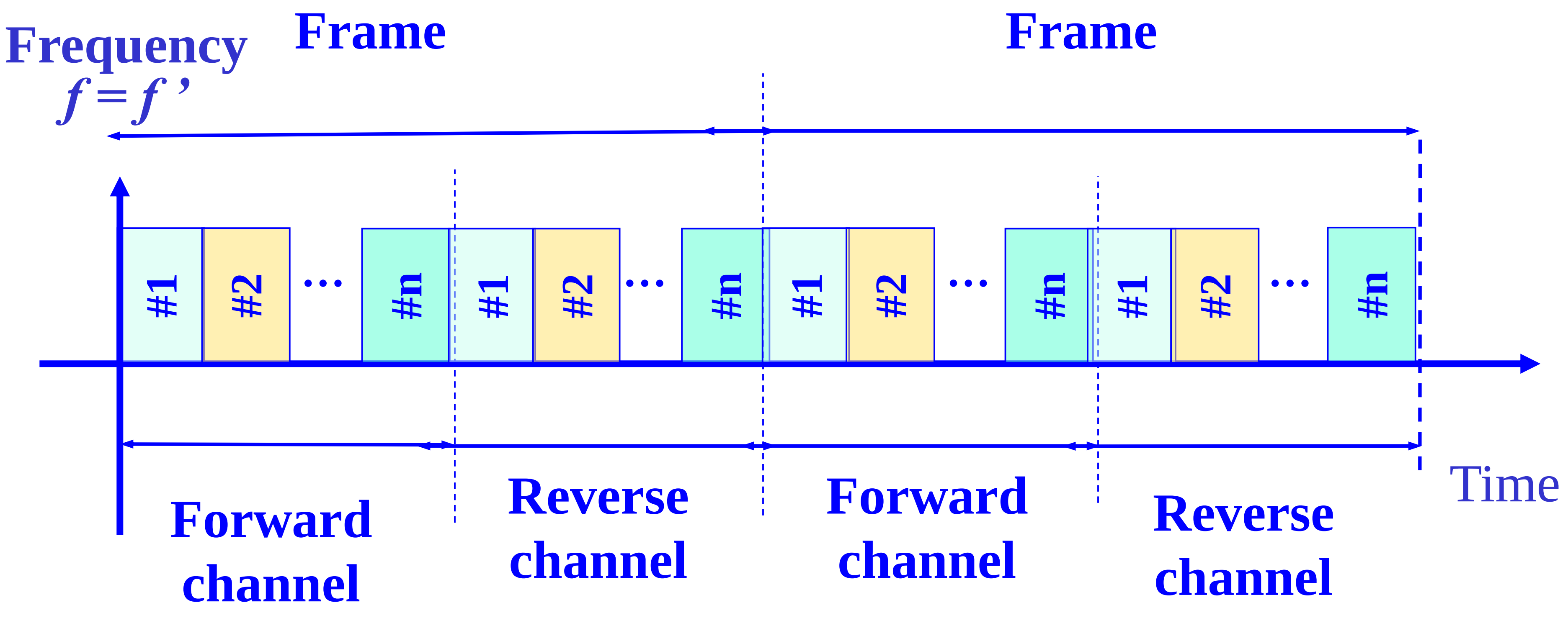
(a) Forward channel



(b) Reverse channel

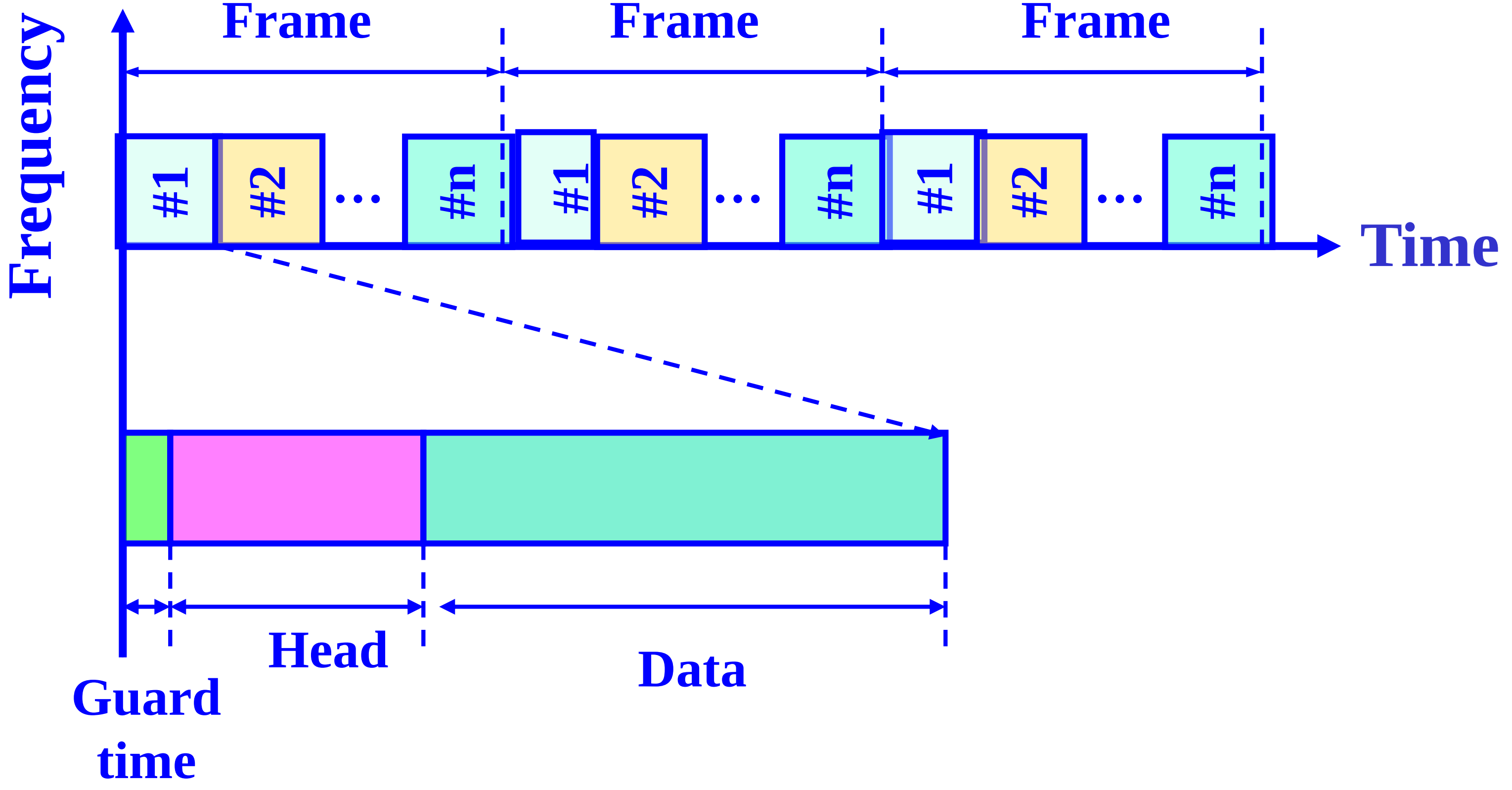
Channels in TDMA/FDD (Frequency Division Duplexing)

Forward and Reverse Channels in TDMA



Channels in TDMA/TDD

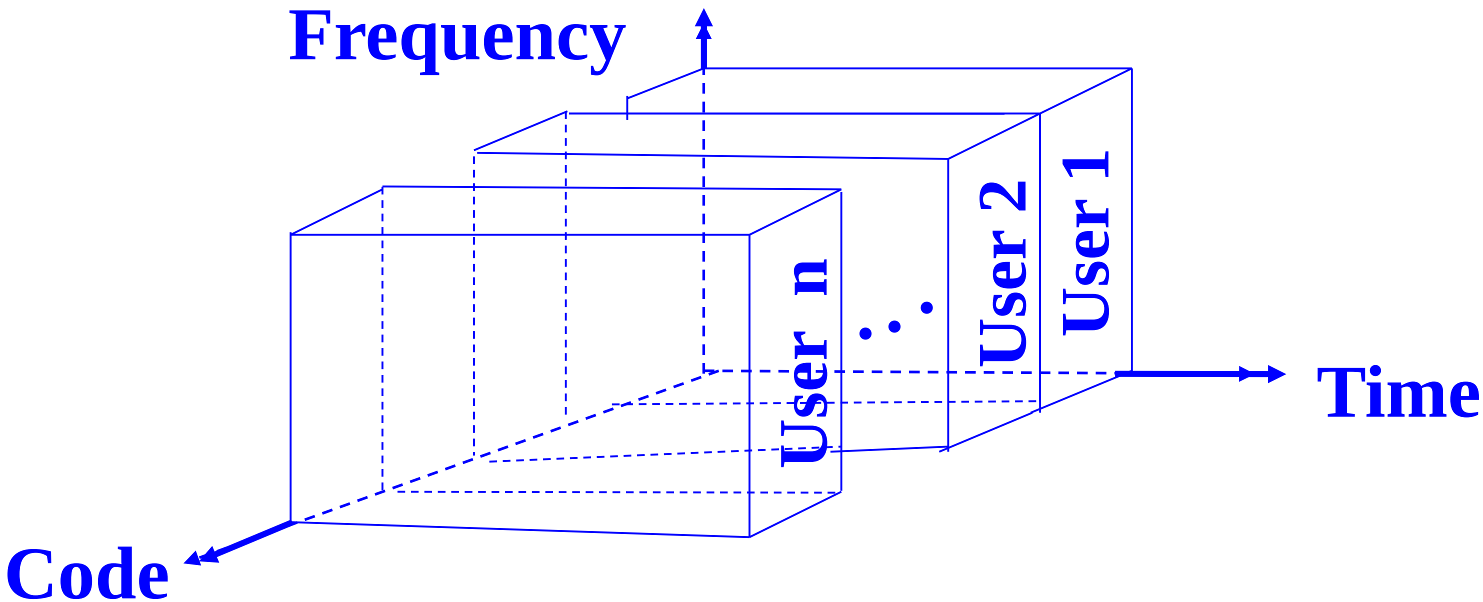
Frame Structure of TDMA



Code Division Multiple Access (CDMA)

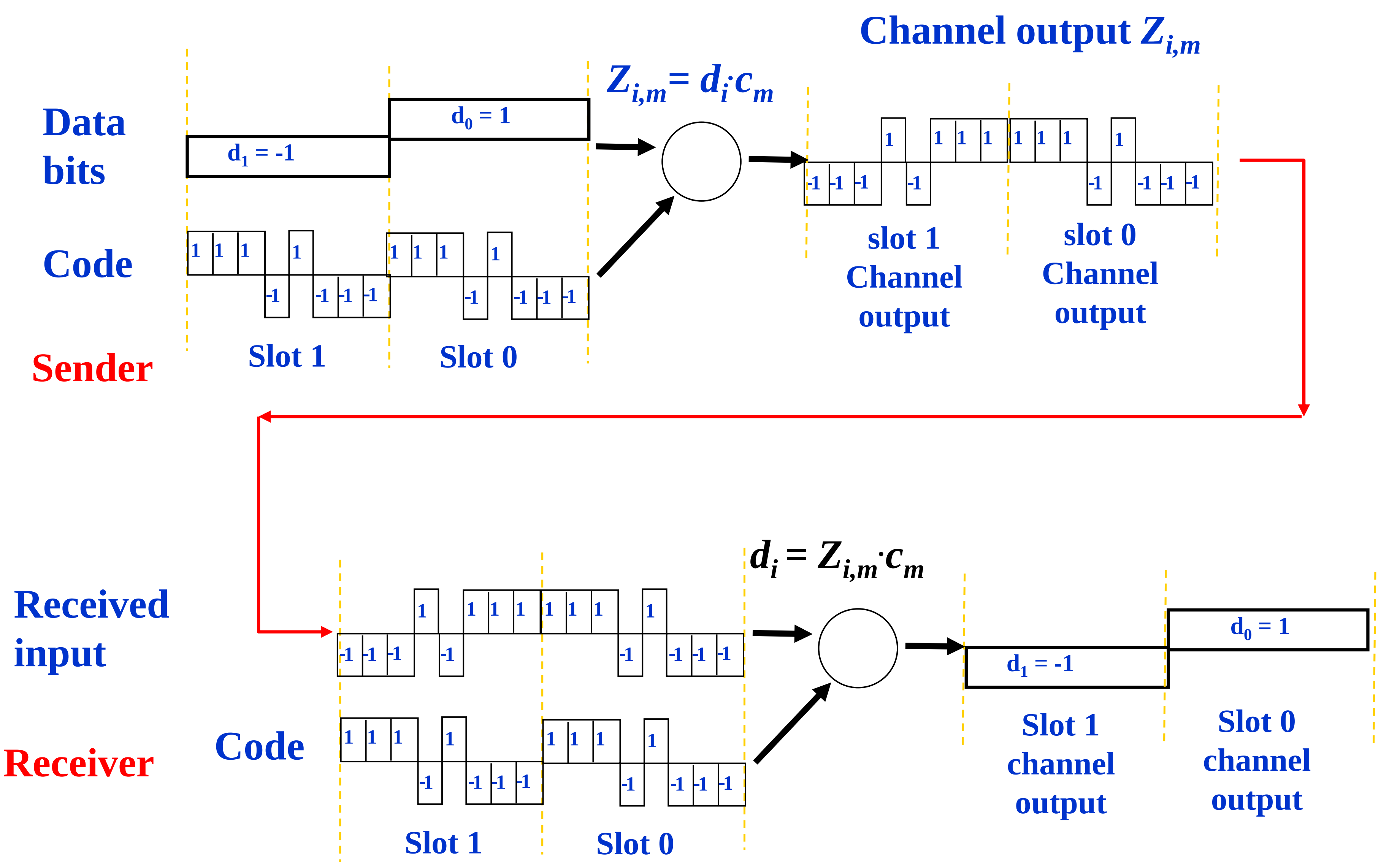
Orthogonality conditions of two signals in CDMA:

$$\int_C s_i(t)\, s_j(t)\,dt = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}, \qquad i, j = 1, 2, \ldots, k$$

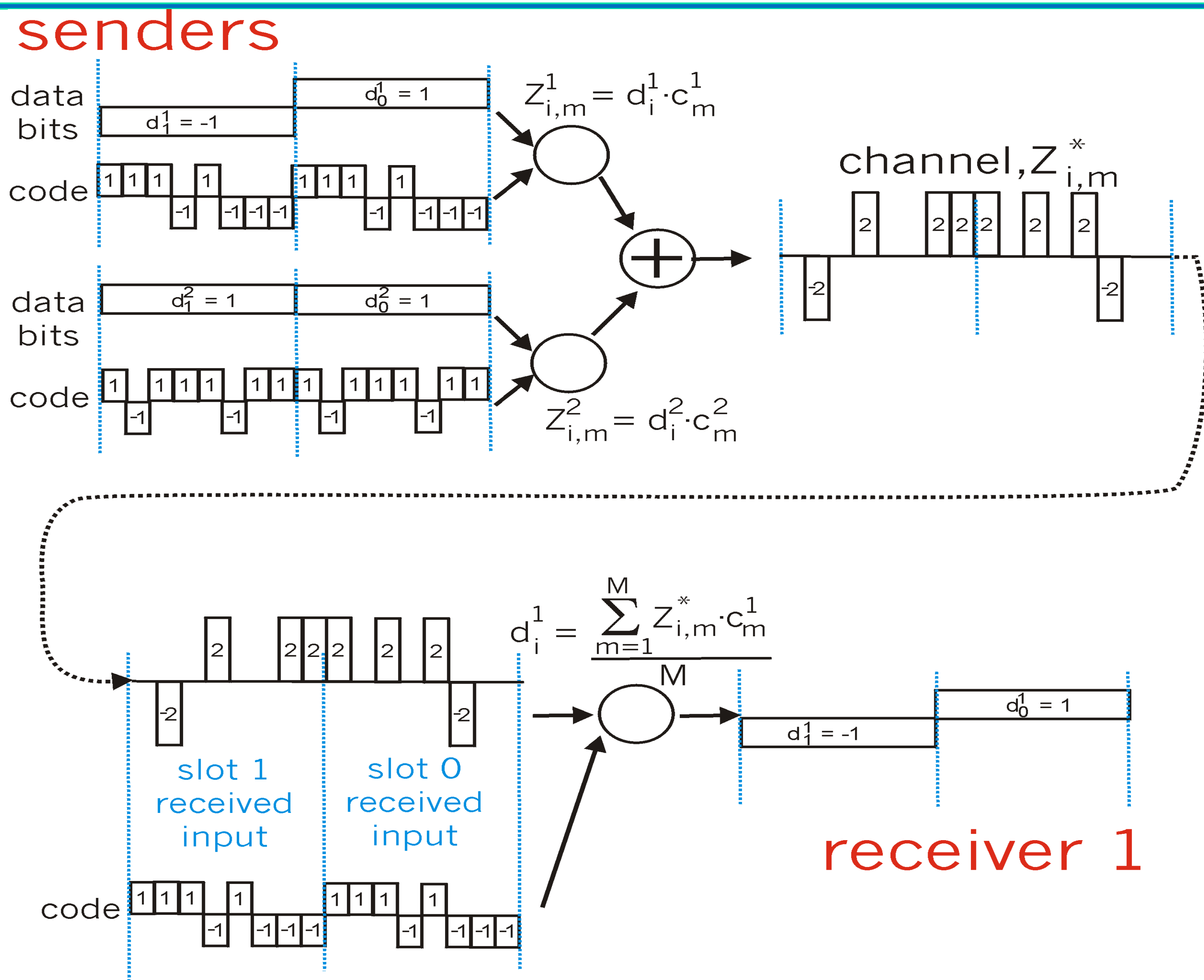


- Users share bandwidth by using code sequences that are orthogonal to each other
- Some second generation systems use CDMA
- Most of third generation systems use CDMA

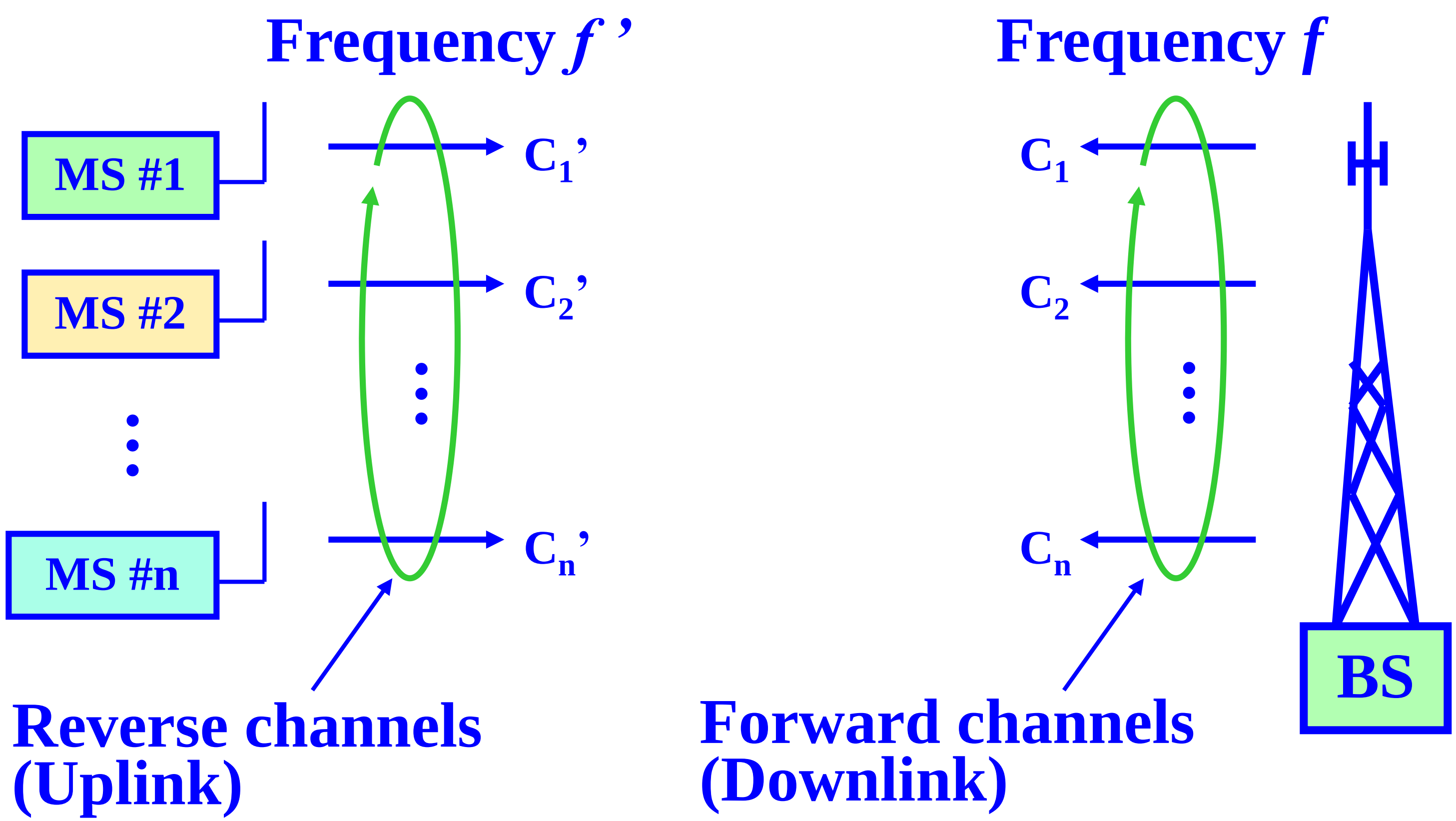
CDMA Encode/Decode



CDMA: Two-Sender Interference



Structure of a CDMA System



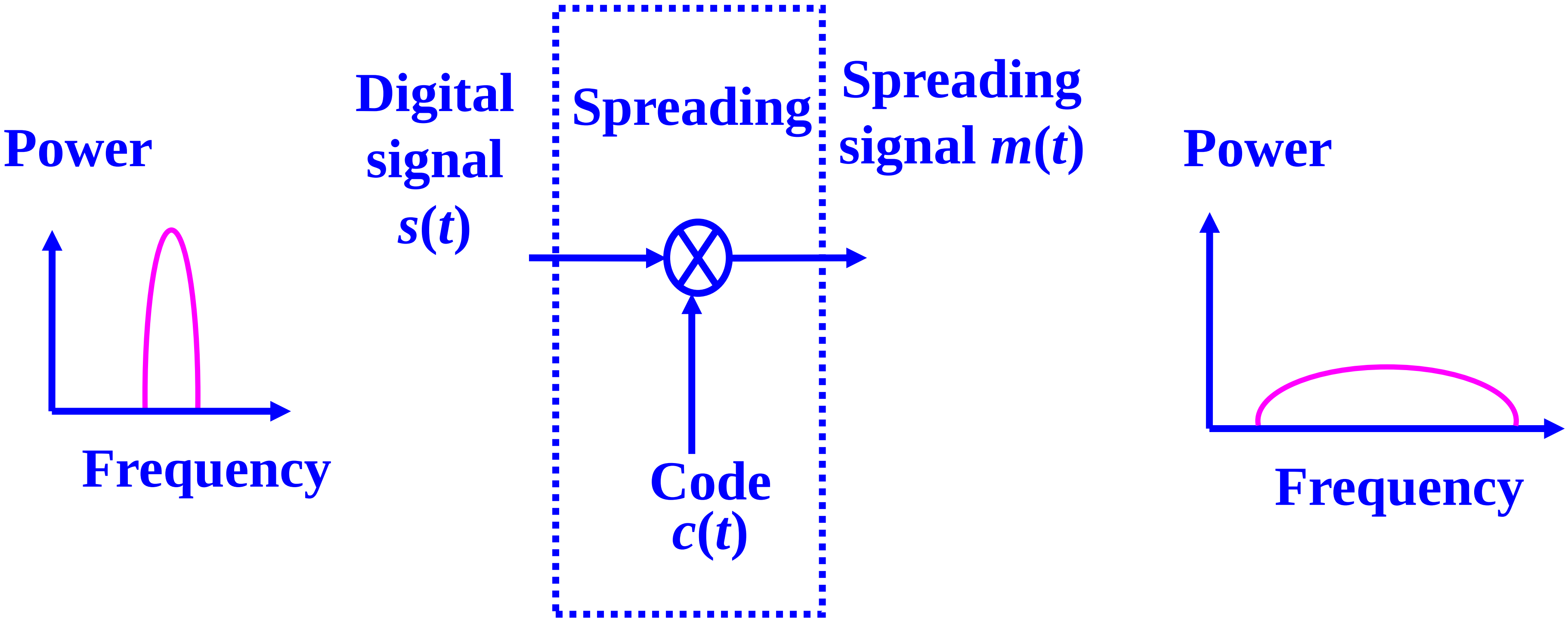
$C_i' \times C_j' = 0$, i.e., C_i' and C_j' are orthogonal codes,

$C_i \times C_j = 0$, i.e., C_i and C_j are orthogonal codes

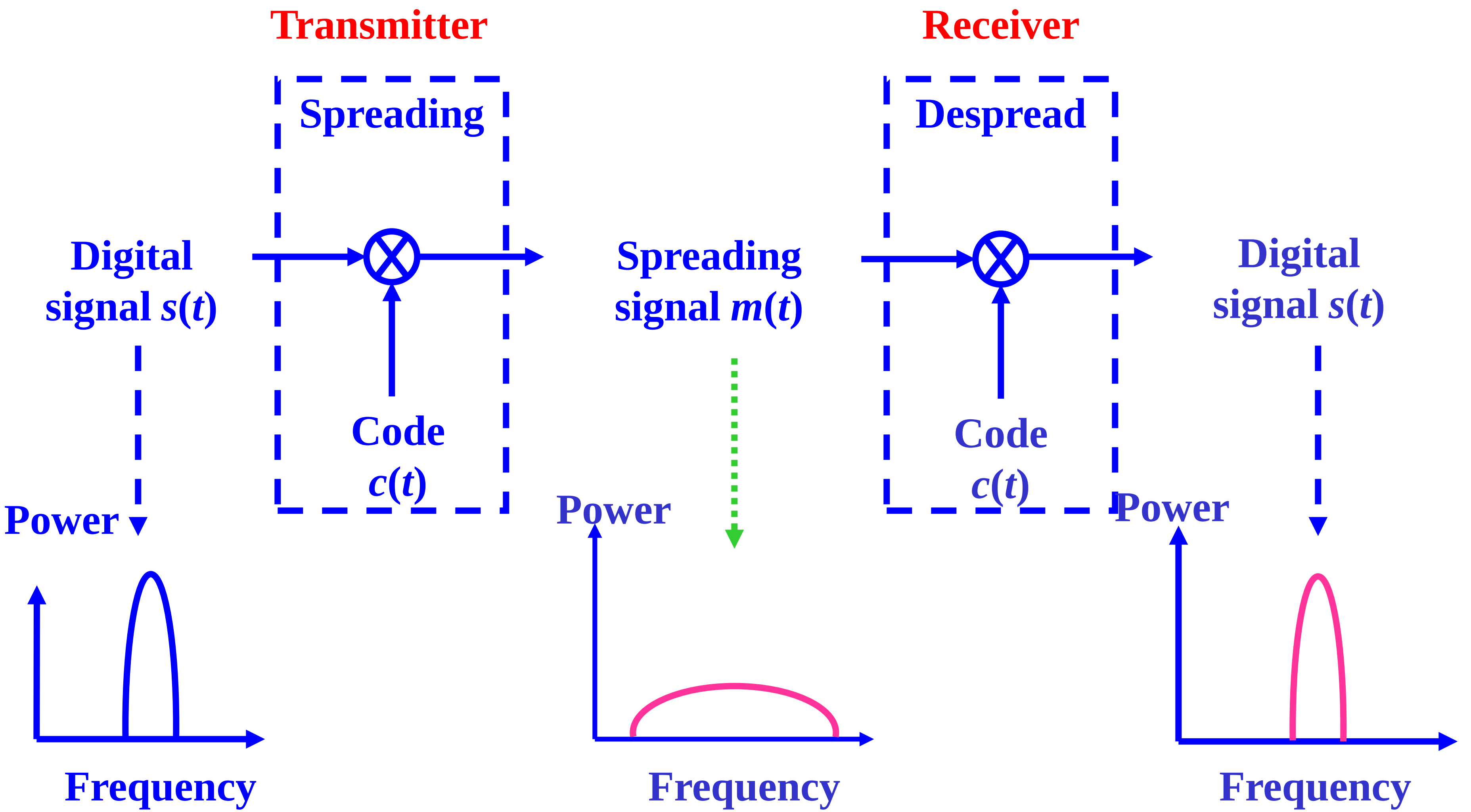
Spread Spectrum

Spreading of data signal *s*(*t*) by the code signal *c*(*t*) to result in message signal *m(t)* as:

$$m(t) = s(t) \otimes c(t)$$



Direct Sequence Spread Spectrum (DSSS)



Using Pseudorandom code or orthogonal code

Orthogonal Codes

- Orthogonal codes
  - All pairwise cross correlations are zero
  - Fixed- and variable-length codes used in CDMA systems
  - For CDMA application, each mobile user uses one sequence in the set as a spreading code
    - Provides zero cross correlation among all users
- Types
  - Walsh codes
  - Variable-length Orthogonal codes

Walsh Codes

- Set of Walsh codes of length *n* consists of the *n* rows of an *n* x *n* Walsh matrix:
  - $W_1 = (0)$

$$W_{2n} = \begin{pmatrix} W_n & W_n \\ W_n & \overline{W_n} \end{pmatrix}$$

  where *n* = dimension of the matrix.
  - Every row is orthogonal to every other row
  - Requires tight synchronization
    - Cross correlation between different shifts of Walsh sequences is not zero

Example:

$$W_2 = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

(a) 2×2

$$W_4 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

(b) 4×4

$$W_8 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{pmatrix}$$

(c) 8×8

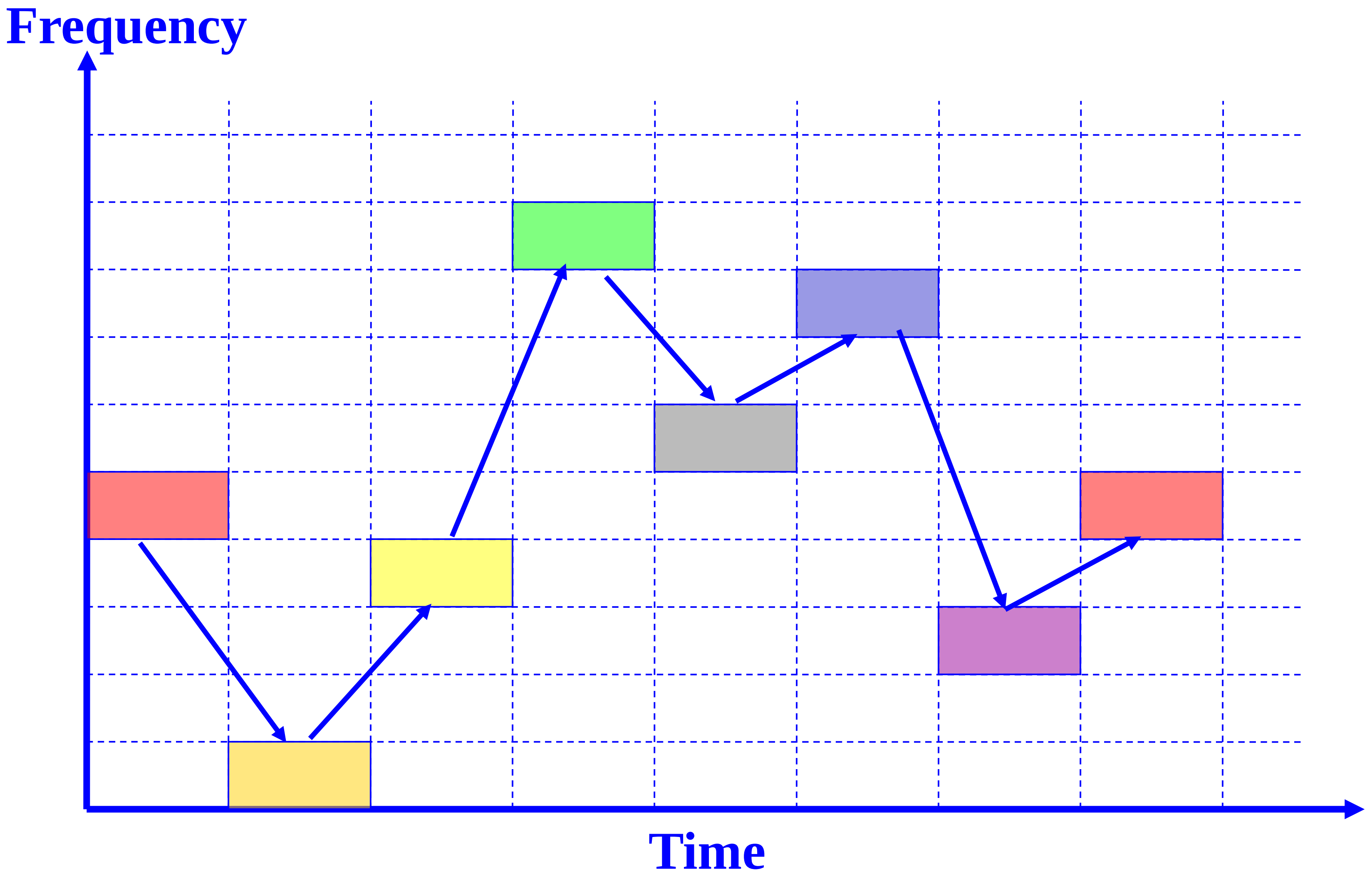
Frequency Hoping Spread Spectrum (FHSS)

- 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
- At each successive interval, a new carrier frequency is selected

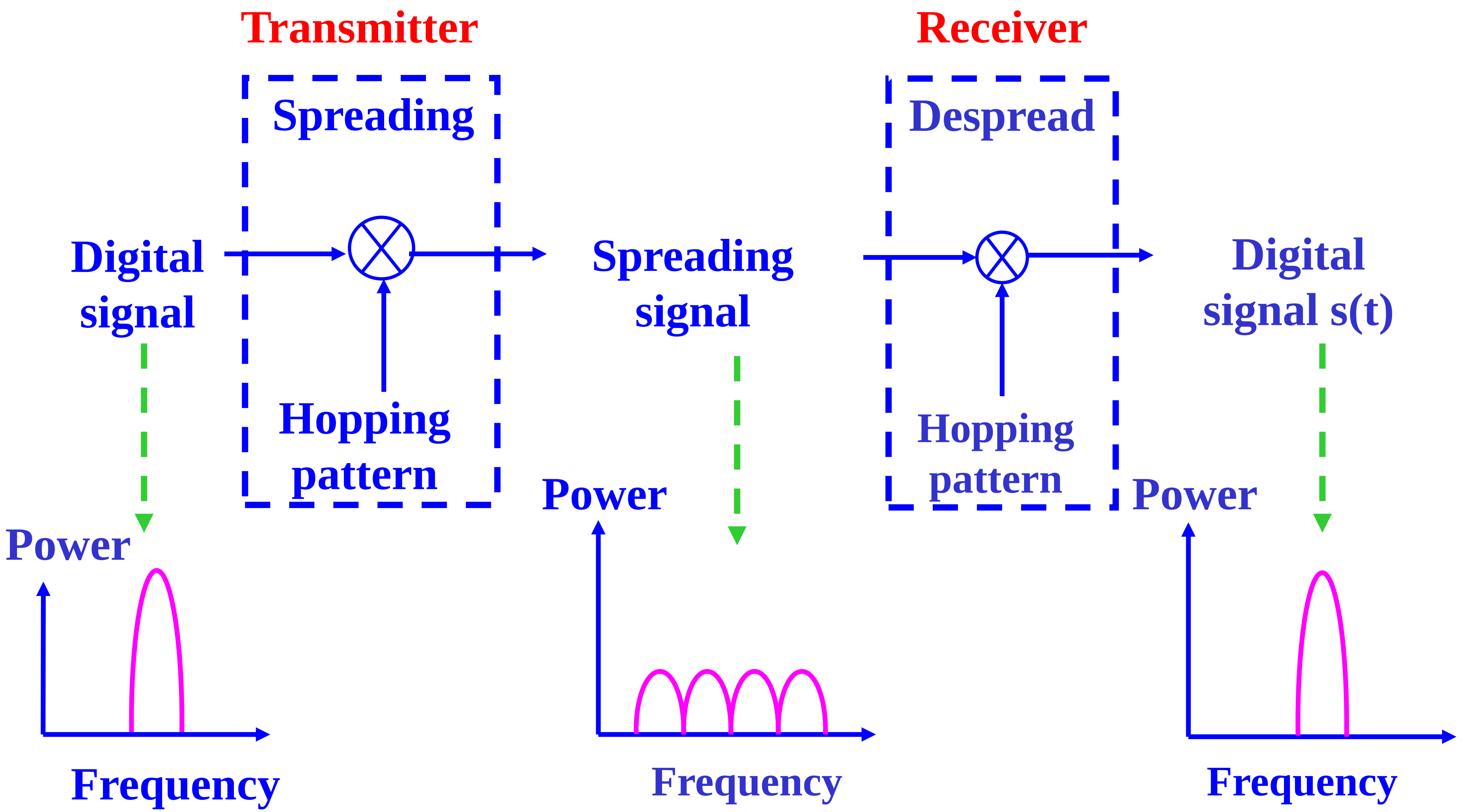
Frequency Hoping Spread Spectrum

- 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

An Example of Frequency Hopping Pattern

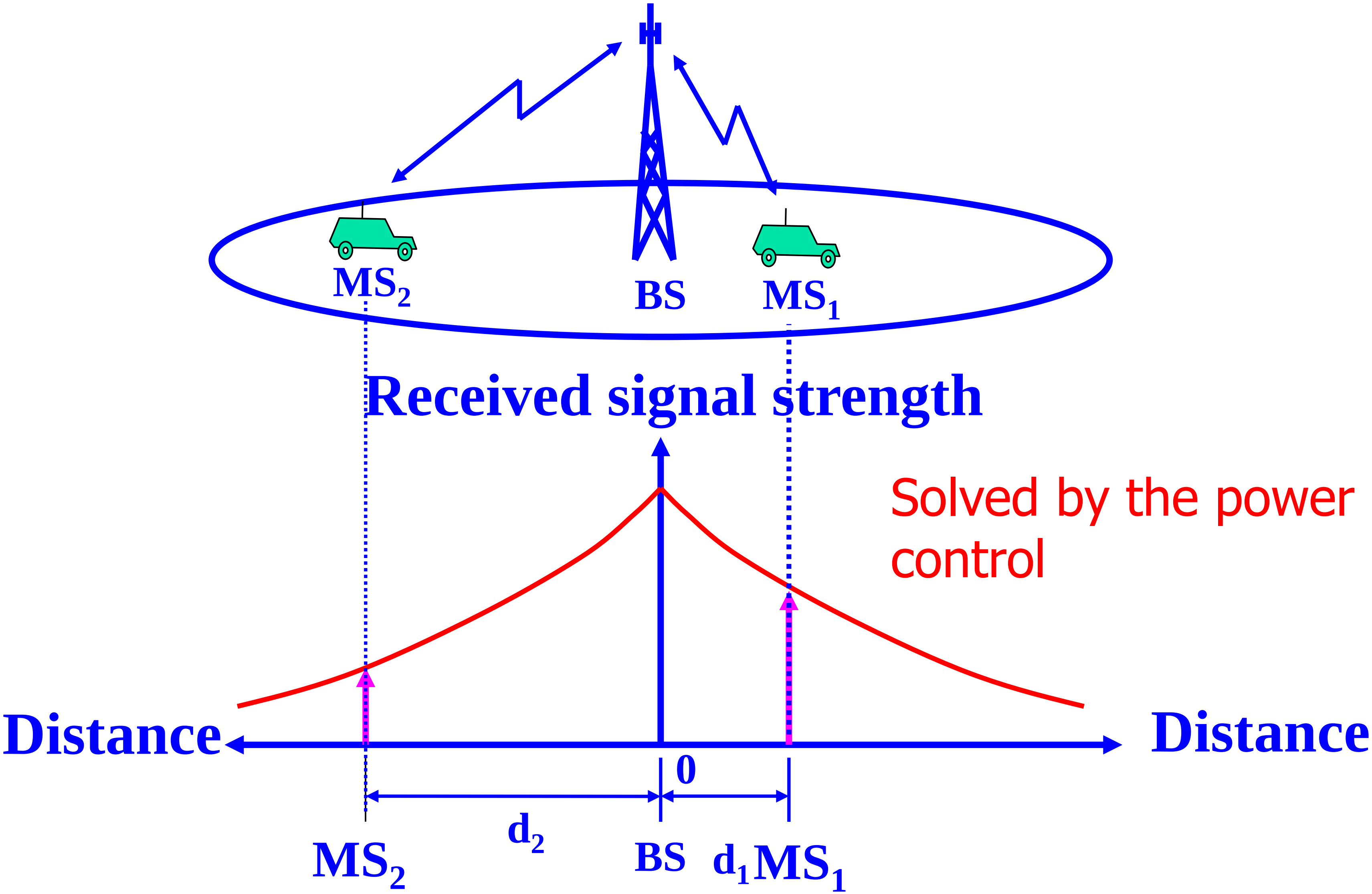


Fast-Frequency Hopping Spread Spectrum (FHSS)

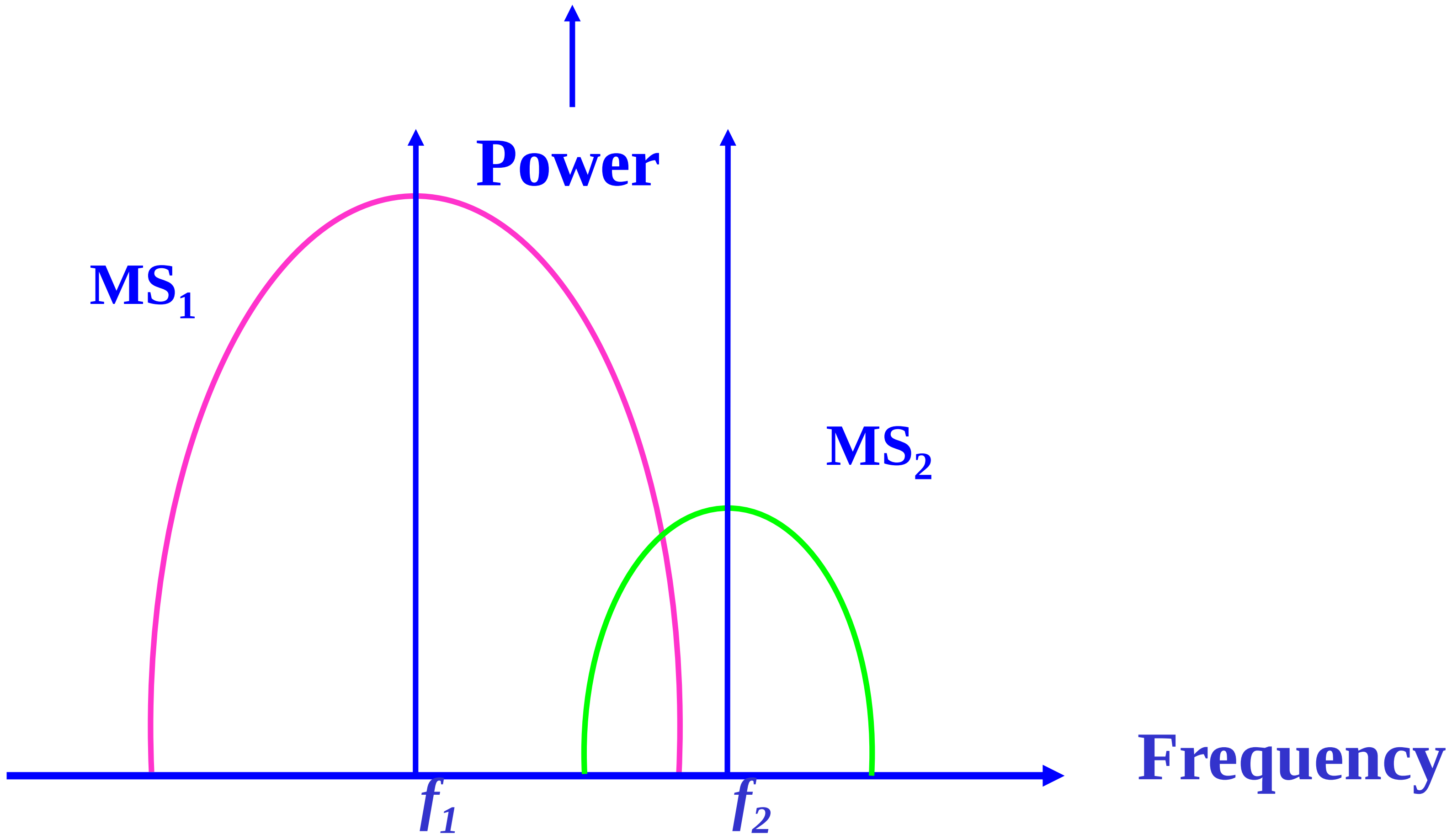


Multiple hops per data bit

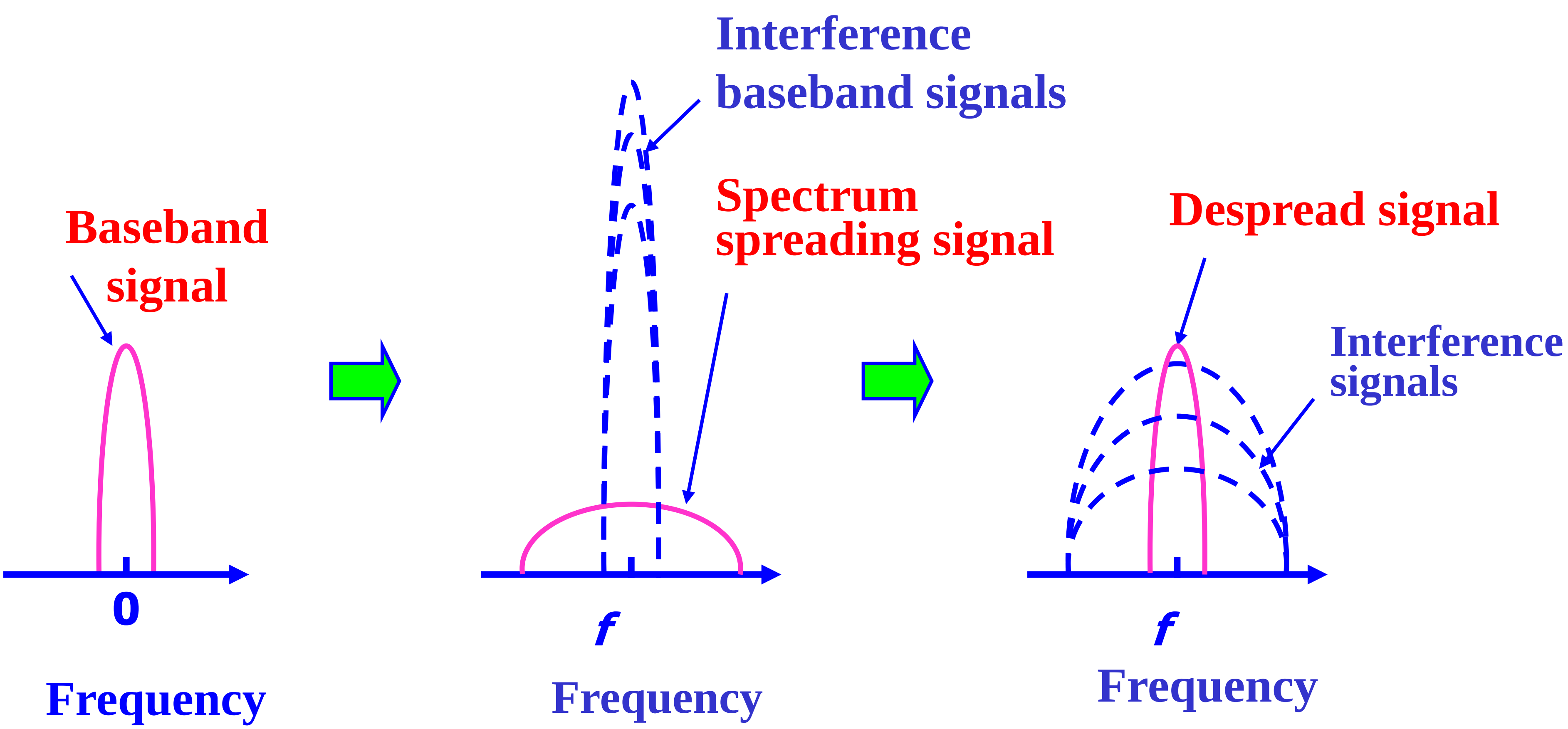
Near-far Problem



Adjacent Channel Interference



Interference in Spread Spectrum

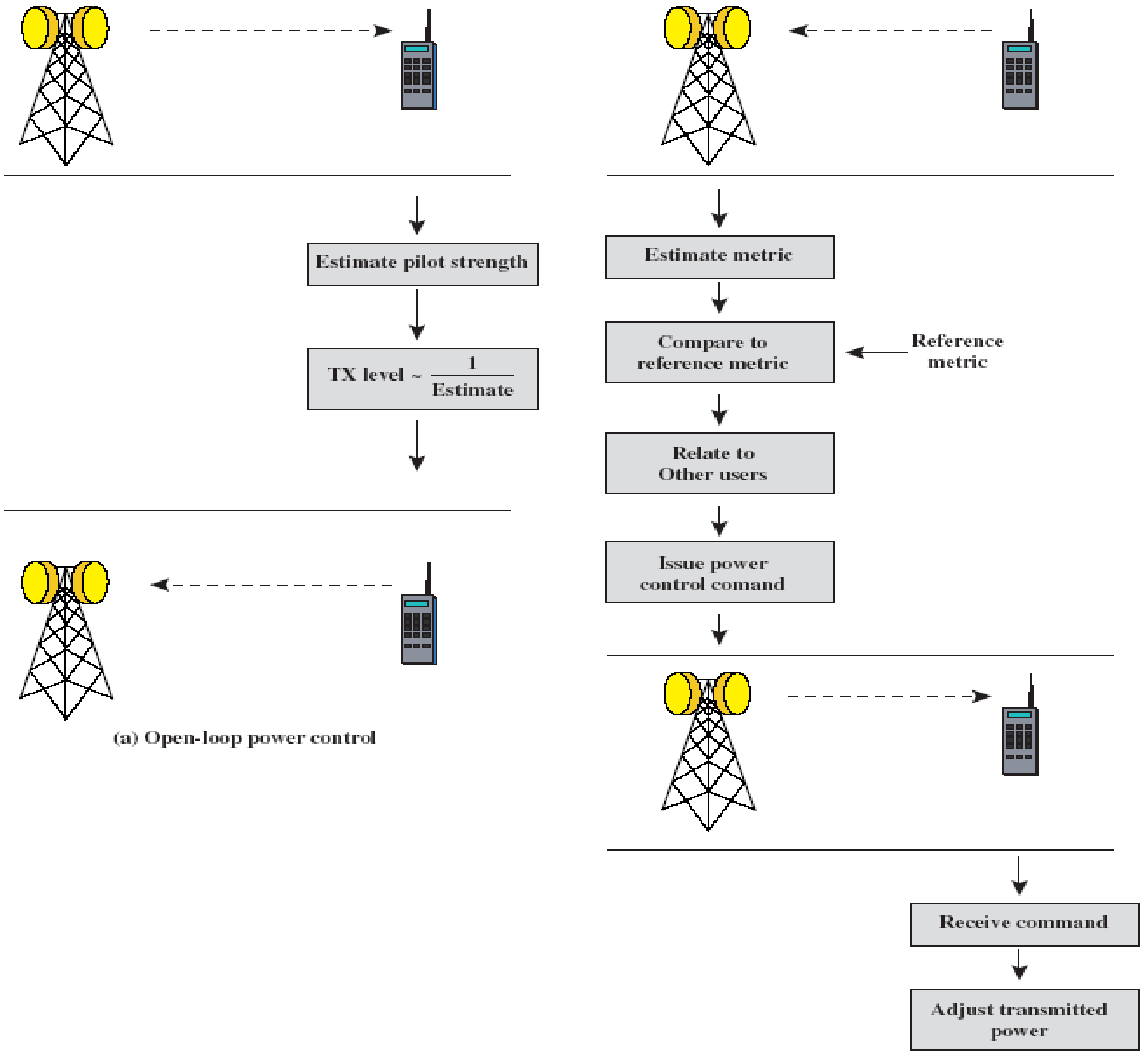


Power Control

- Design issues making it desirable to include dynamic power control in a cellular system
  - Received power must be sufficiently above the background noise for effective communication
  - Desirable to minimize power in the transmitted signal from the mobile
    - Reduce cochannel interference, alleviate health concerns, save battery power
  - In SS systems using CDMA, it's desirable to equalize the received power level from all mobile units at the BS

Types of Power Control

- Open-loop power control
  - Depends solely on mobile unit
  - No feedback from BS
  - Not as accurate as closed-loop, but can react quicker to fluctuations in signal strength
- Closed-loop power control
  - Adjusts signal strength in reverse channel based on metric of performance
  - BS makes power adjustment decision and communicates to mobile on control channel



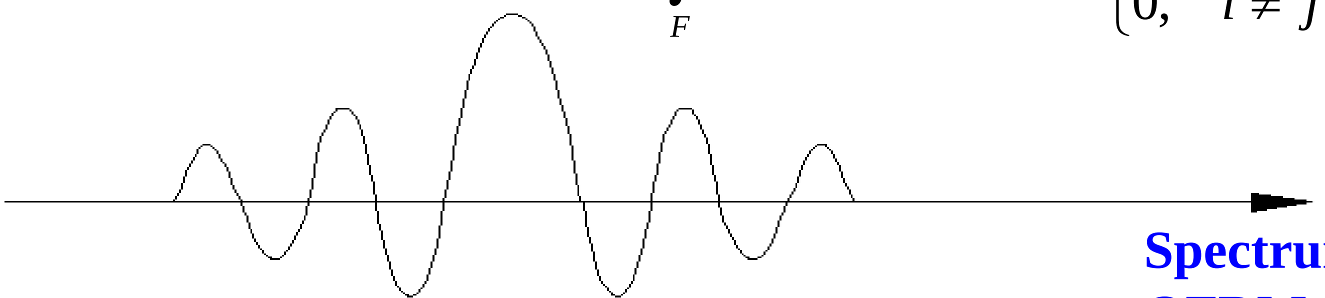
(a) Open-loop power control

(b) Closed-loop power control

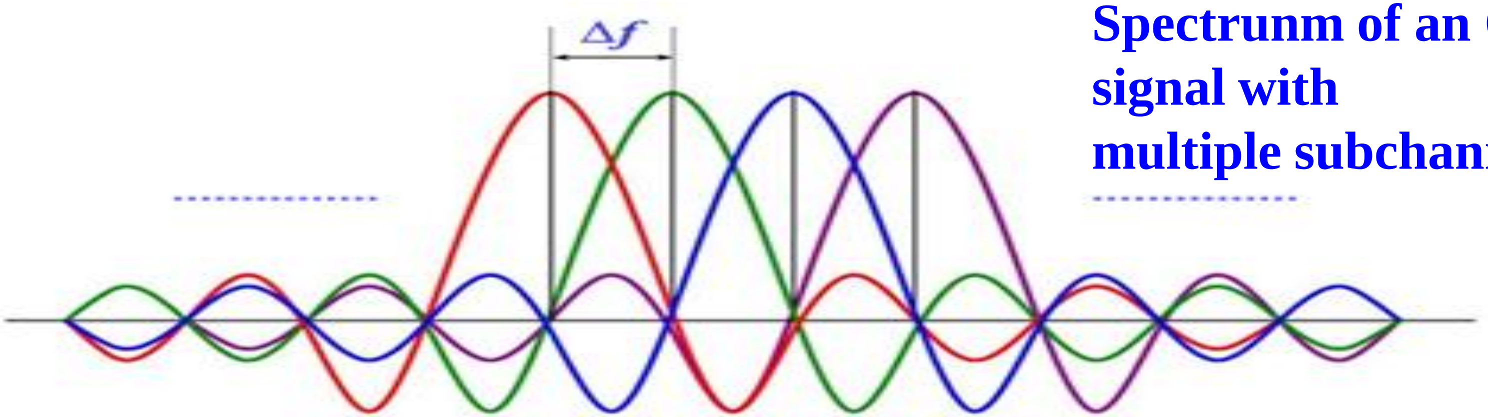
Orthogonal Frequency Division Multiplexing (OFDM)

- ✓ **Divide a channels into multiple sub-channels and do parallel transmission**
- ✓ **Orthogonality of two signals in OFDM can be given by:**

$$\int_F s_i(f,t)s_j^*(f,t)dt = \begin{cases} 1, & i = j \\ 0, & i \neq j \end{cases}, \quad i,j = 1,2,\dots,k$$

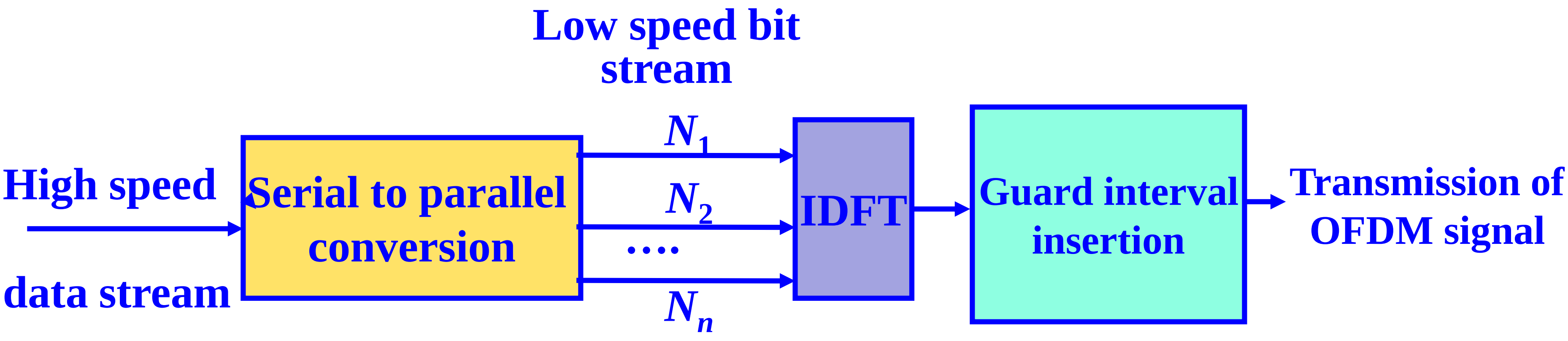


Spectrum of a single OFDM subchannel

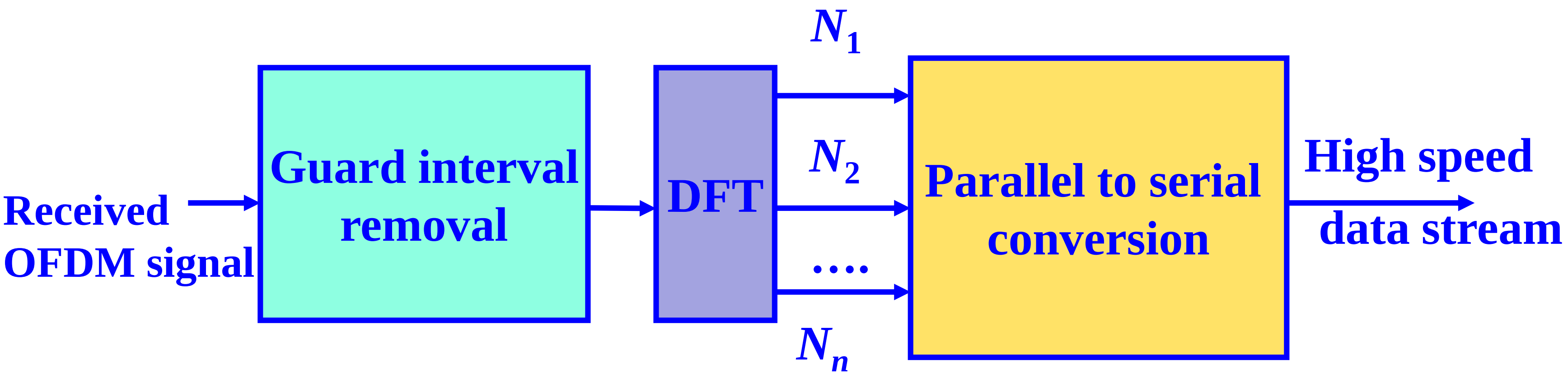


Spectrunm of an OFDM signal with multiple subchannels

Modulation/Demodulation Steps in OFDM



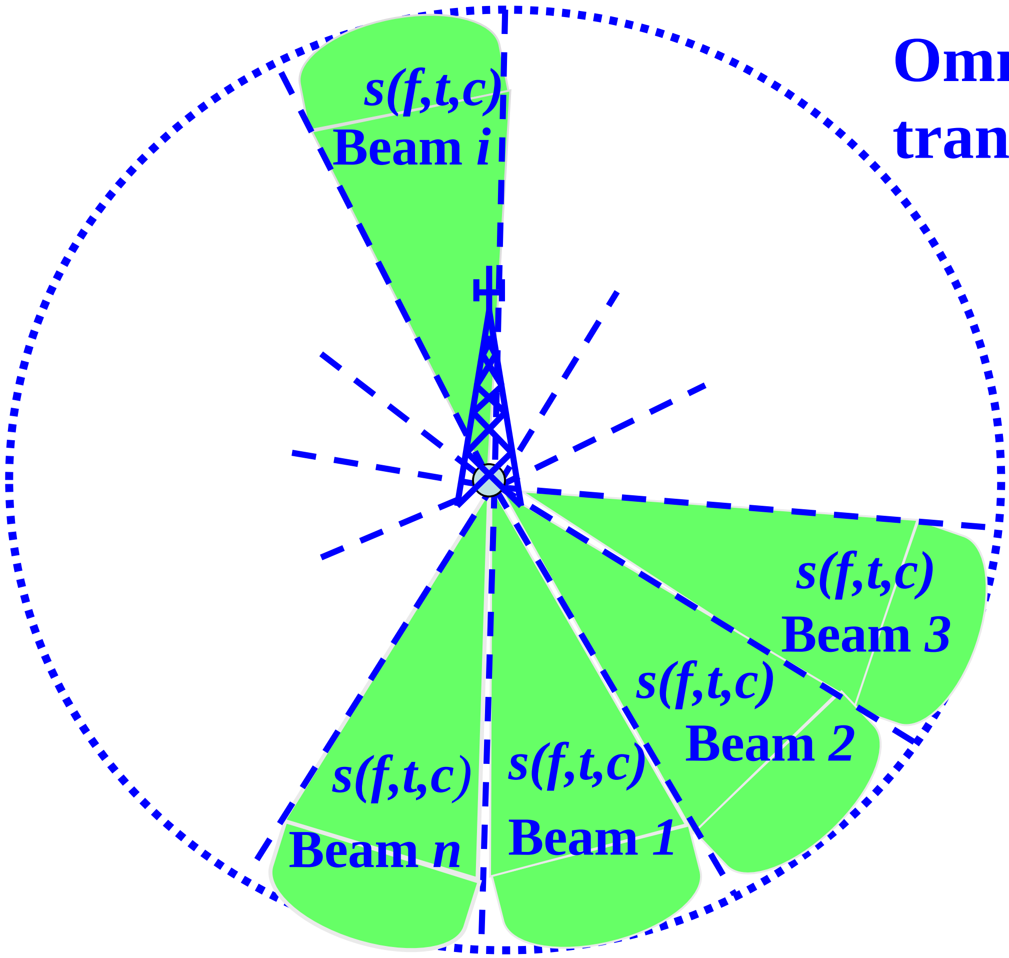
Modulation operation at the OFDM transmitter



Demodulation steps at the OFDM receiver

Space Division Multiple Access (SDMA)

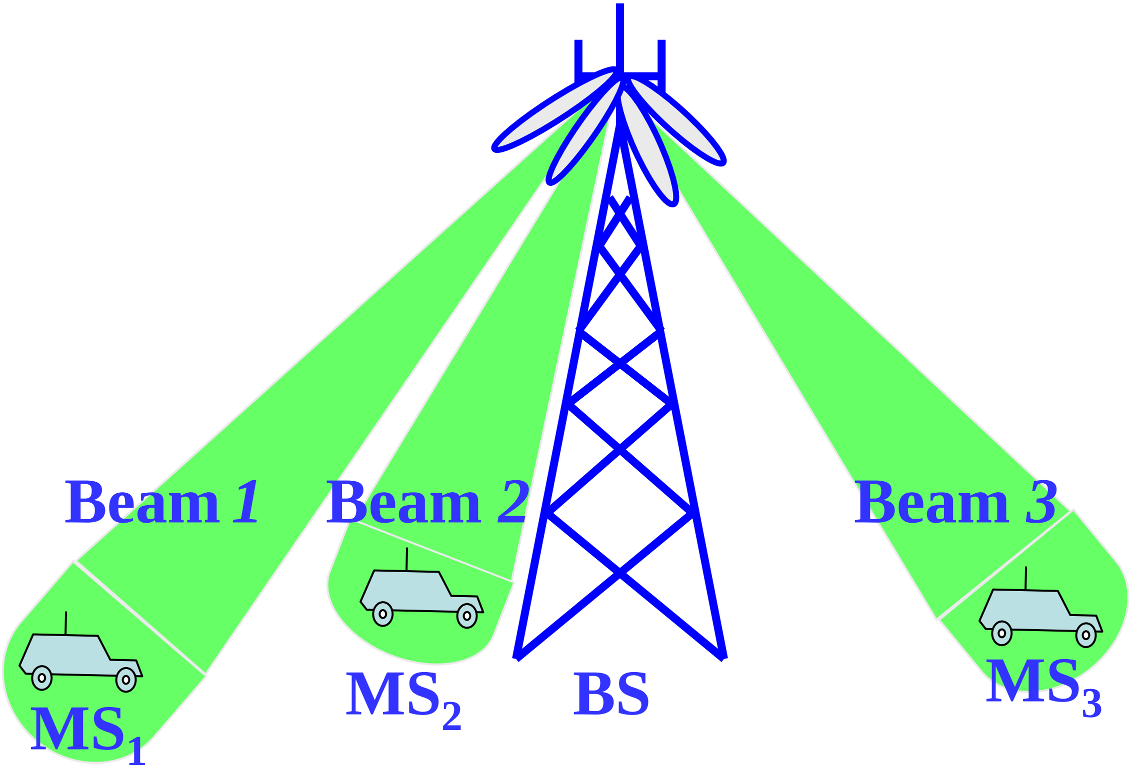
Space divided into spatially separate sectors



The concept of SDMA

Transmission in SDMA

- ✓ Noise and interference for each MS and BS is minimized
- ✓ Enhance the quality of communication link and increase overall system capacity
- ✓ Intra-cell channel reuse can be easily exploited



The basic structure of a SDMA system

Comparison of Various Multiple Division Techniques

Technique	FDMA	TDMA	CDMA	SDMA
Concept	Divide the frequency band into disjoint sub-bands	Divide the time into non-overlapping time slots	Spread the signal with orthogonal codes	Divide the space in to sectors
Active terminals	All terminals active on their specified frequencies	Terminals are active in their specified slot on same frequency	All terminals active on same frequency	Number of terminals per beam depends on FDMA/ TDMA/CDMA
Signal separation	Filtering in frequency	Synchronization in time	Code separation	Spatial separation using smart antennas
Handoff	Hard handoff	Hard handoff	Soft handoff	Hard and soft handoffs
Advantages	Simple and robust	Flexible	Flexible	Very simple, increases system capacity
Disadvantages	Inflexible, available frequencies are fixed, requires guard bands	Requires guard space, synchronization problem	Complex receivers, requires power control to avoid near-far problem	Inflexible, requires network monitoring to avoid intra cell handoffs
Current applications	Radio, TV and analog cellular	GSM and PDC	2.5G and 3G	Satellite systems, LTE

Modulation Techniques

- **Why need modulation?**
  - **Small antenna size**

    Antenna size is inversely proportional to frequency (wavelength)

    e.g., 3 kHz → 50 *km* antenna

    3 GHz → 5 *cm* antenna
  - **Reduces noise or distortion**
  - **Multiplexing techniques,**

    e.g., FDM, TDM, CDMA
  - **Encryption**
  - **…**

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

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**

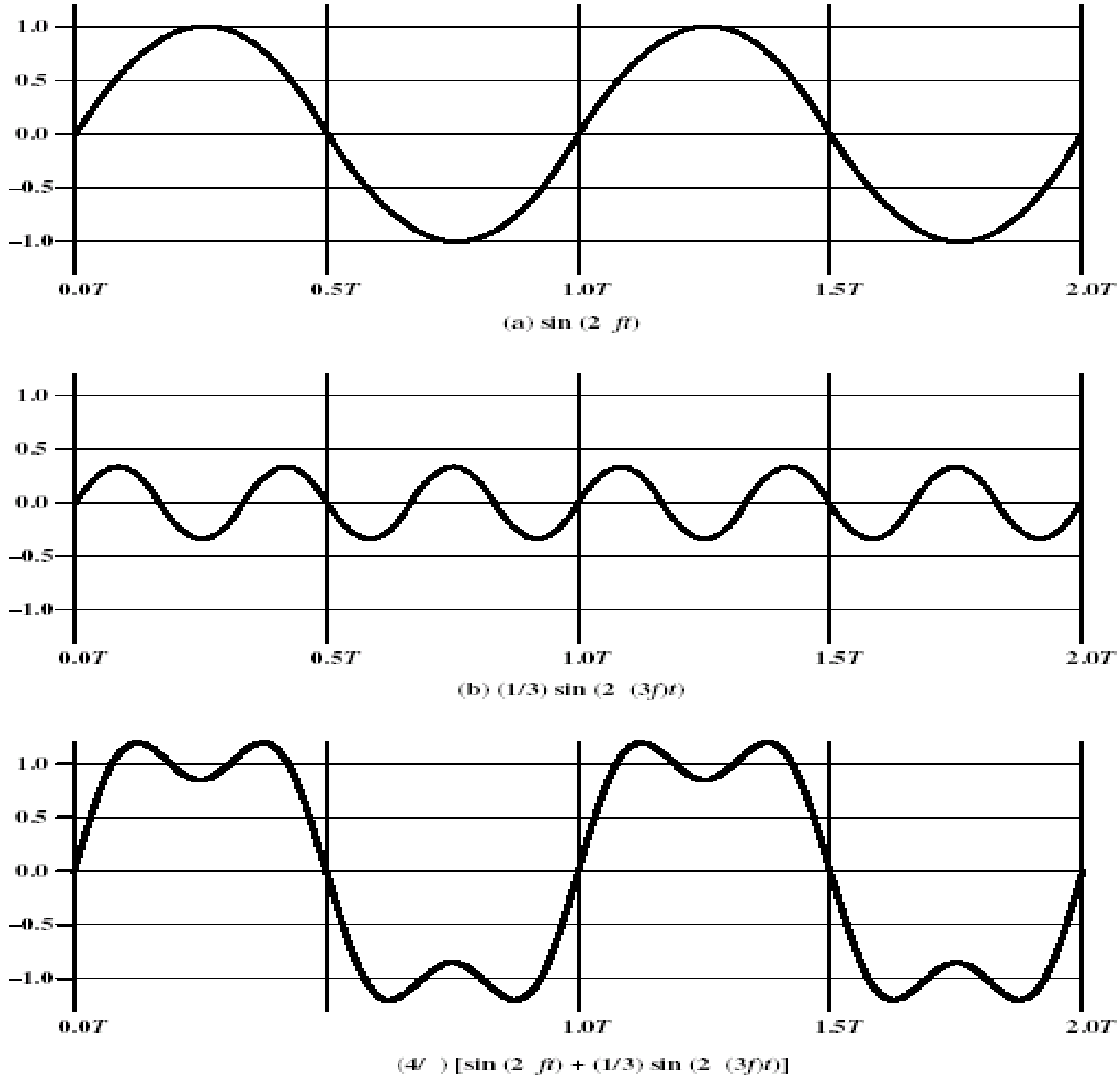
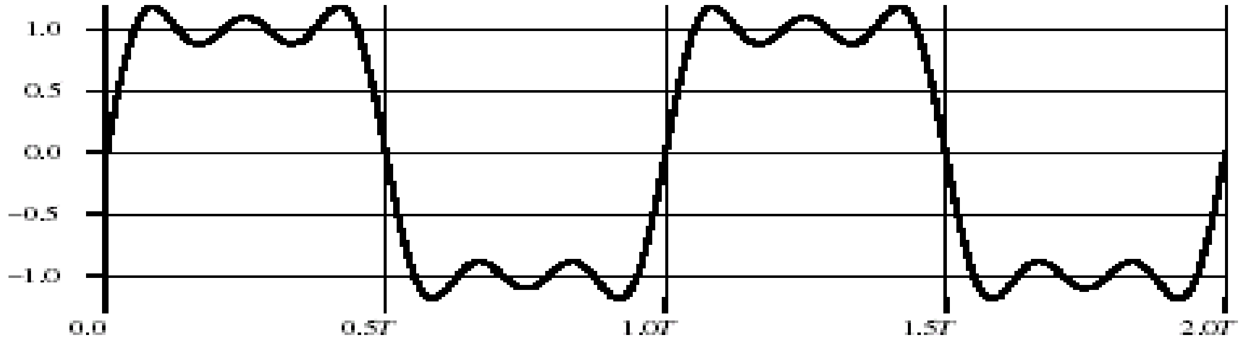
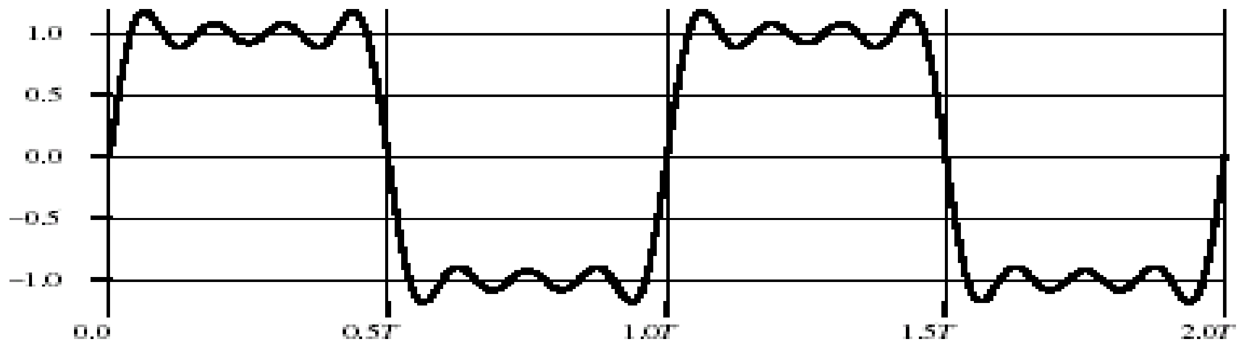


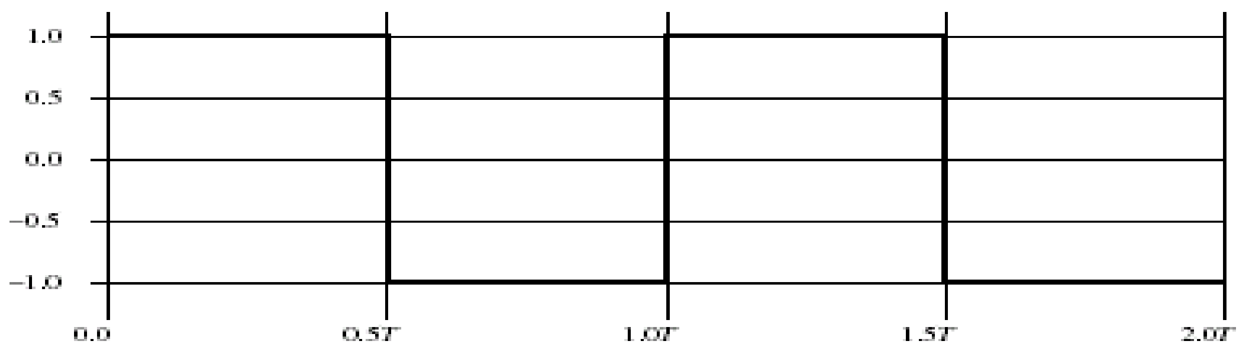
Figure 2.4 Addition of Frequency Components ($T = 1/f$)



(a) (4/) [sin (2 *ft*) + (1/3) sin (2 (3*f*)*t*) + (1/5) sin (2 (5*f*)*t*)]



(b) (4/) [sin (2 *ft*) + (1/3) sin (2 (3*f*)*t*) + (1/5) sin (2 (5*f*)*t*) + (1/7) sin (2 (7*f*)*t*)]



(c) (4/) $\sum$ (1/*k*) sin (2 (*kf*)*t*), for *k* odd

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**

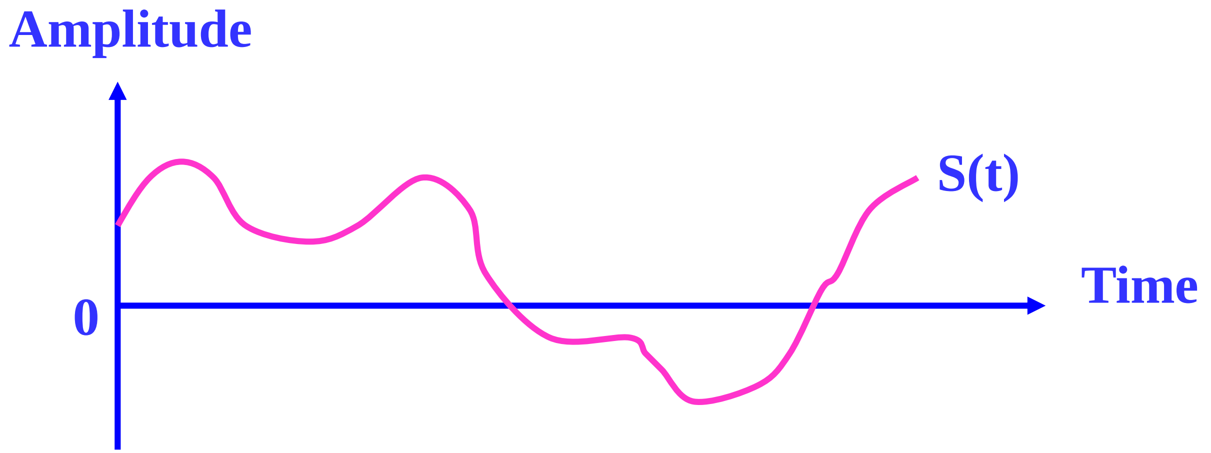
- **Shannon's Theorem: theoretical maximum that can be achieved** $C = B \log_2 (1 + S/N)$ **bits/sec**
  - **Where S is the signal power and N is noise power**

Modulation Techniques

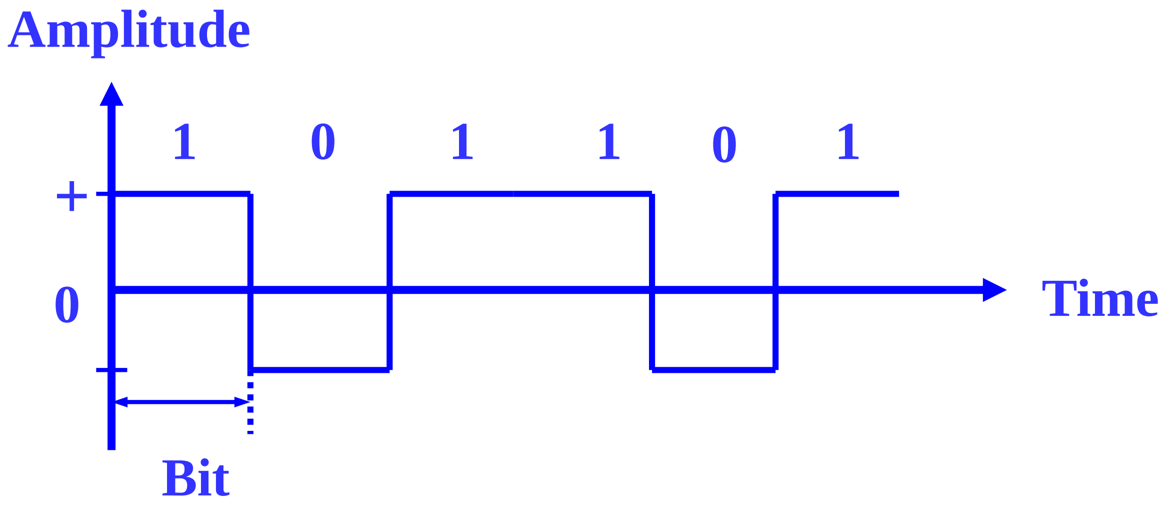
- **Analog Modulation: used for transmitting analog data**
  - **Amplitude Modulation (AM)**
  - **Frequency Modulation (FM)**
- **Digital Modulation: used for transmitting digital data**
  - **Amplitude Shift Keying (ASK)**
  - **Frequency Shift Keying (FSK)**
  - **Phase Shift Keying (PSK)**

Analog and Digital Signals

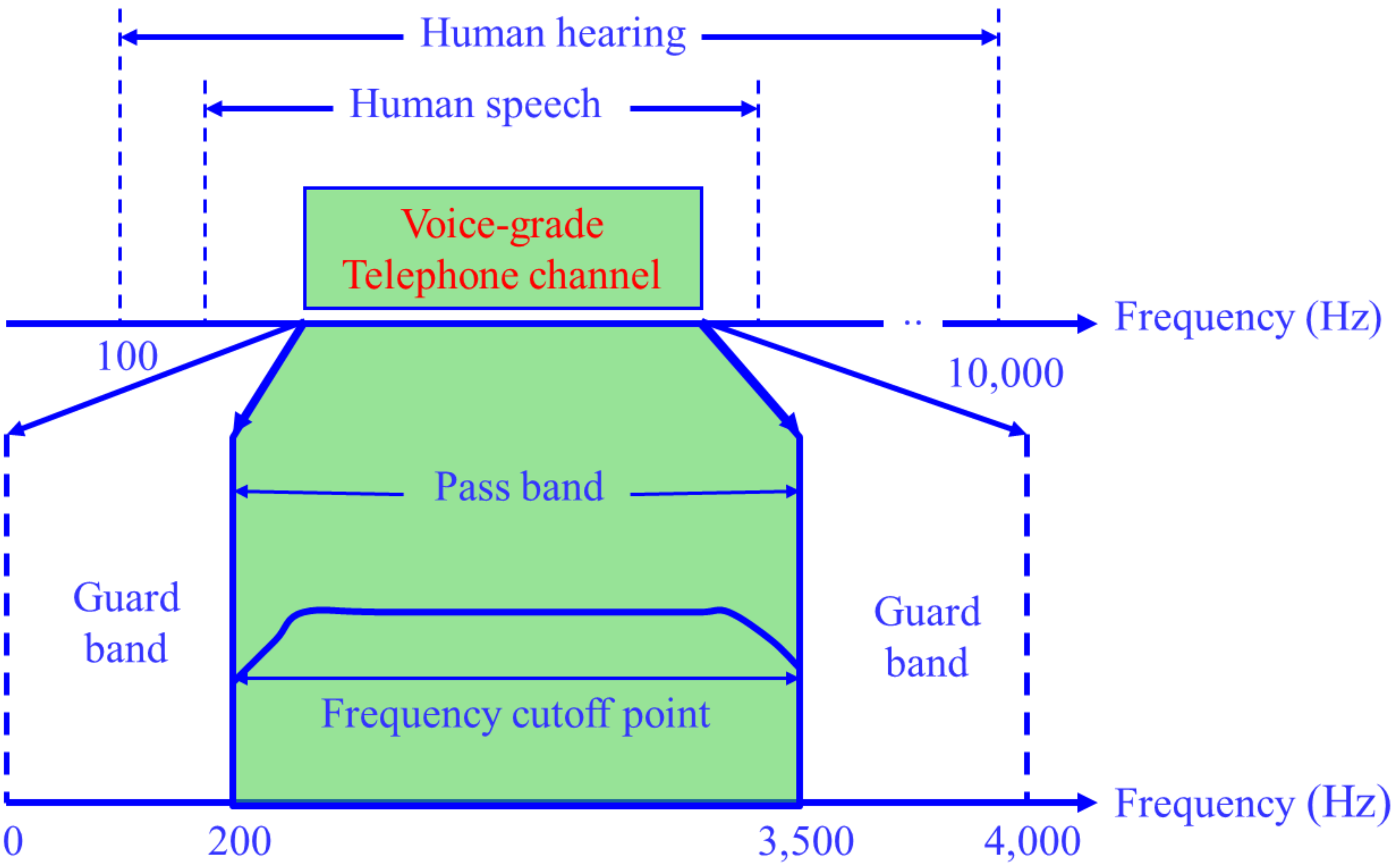
- Analog Signal (Continuous signal)



- Digital Signal (Discrete signal)



Hearing, Speech, and Voice-band Channels



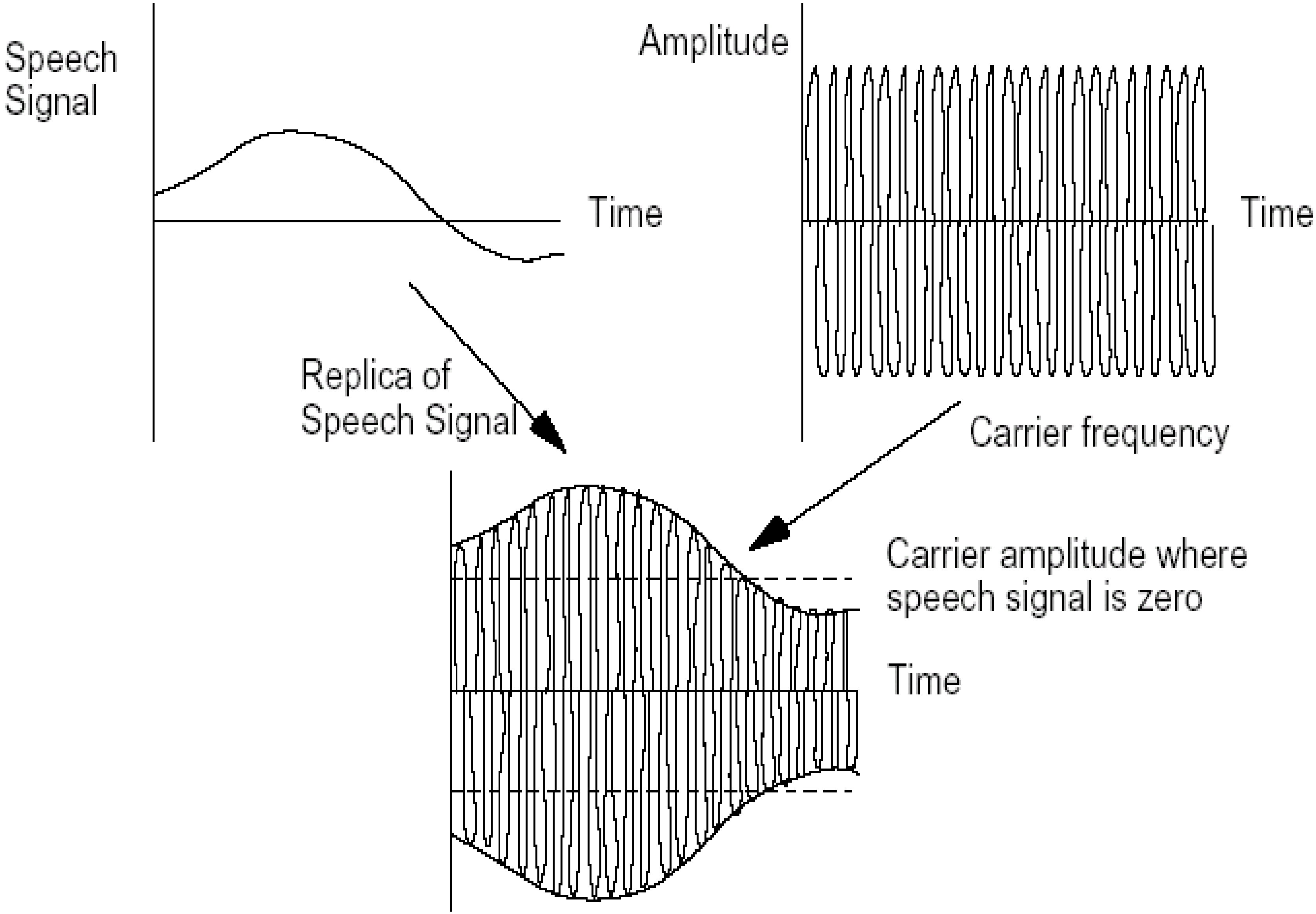
Amplitude Modulation

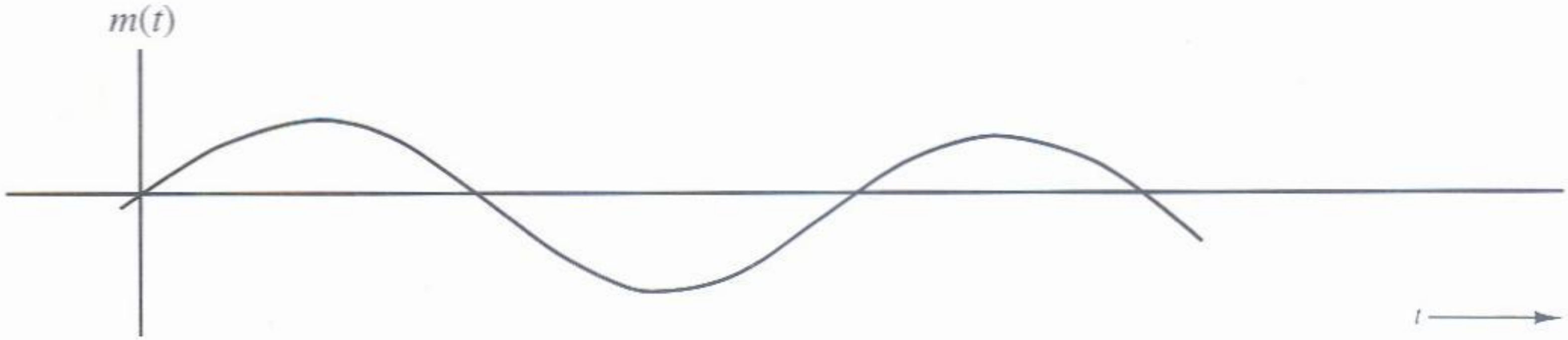
- **Amplitude Modulation**

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

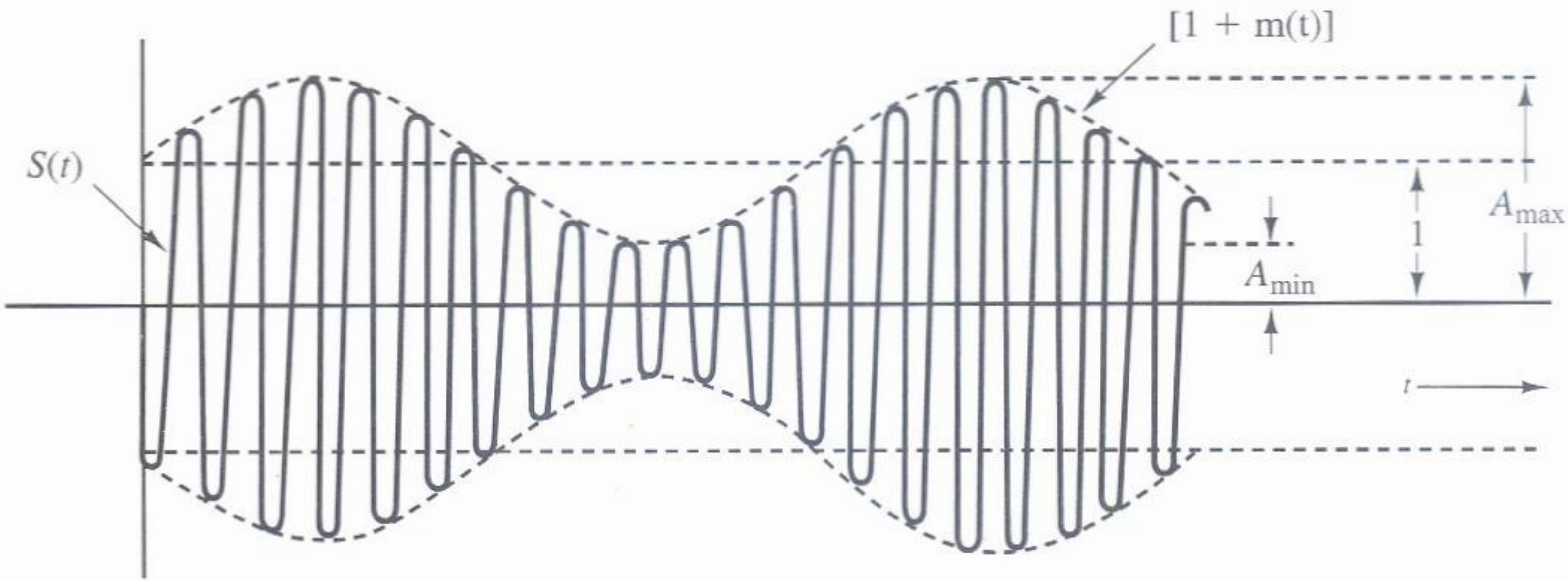
  - **$\cos 2\pi f_c t$ = carrier**
  - **$x(t)$ = input signal**
  - **n_a = modulation index ≤ 1**
    - ✓ **Ratio of amplitude of input signal to carrier**

Amplitude Modulation (AM)





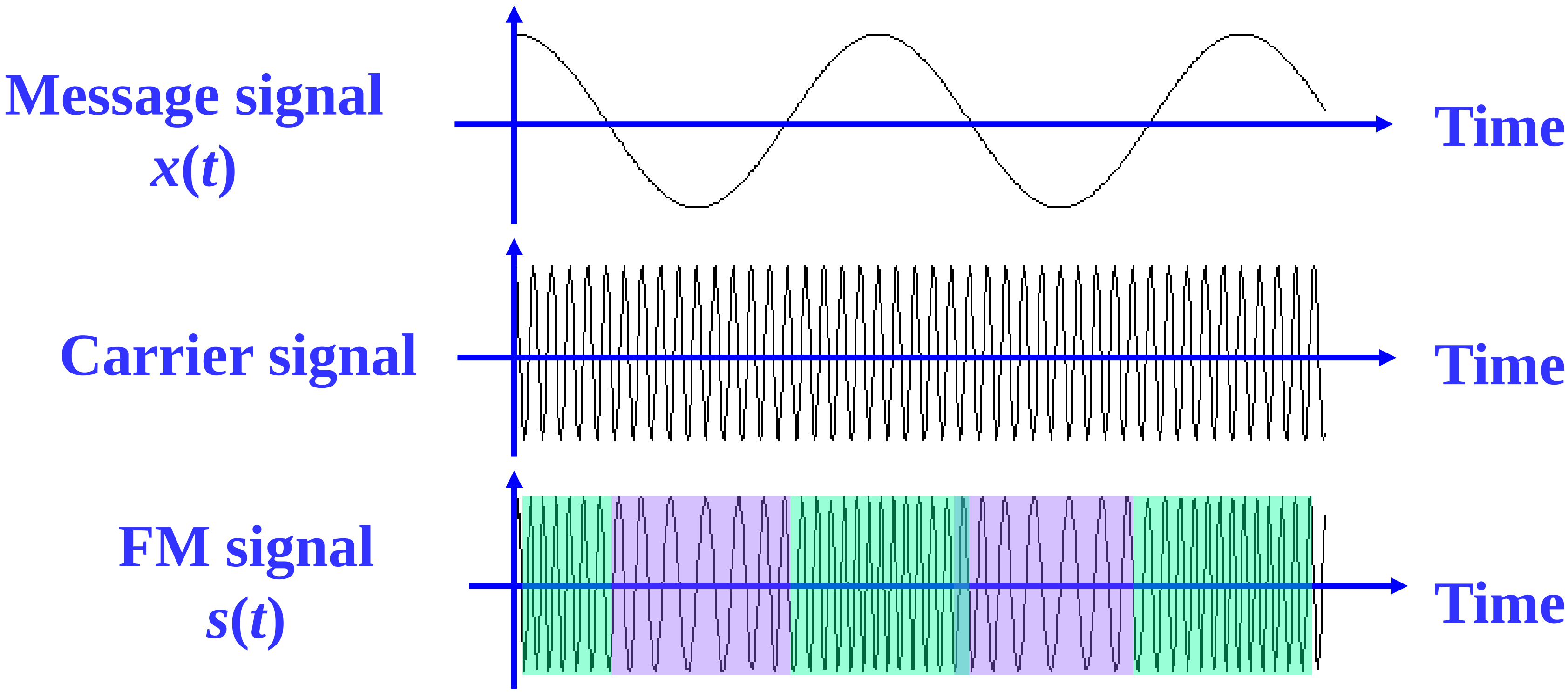
(a) Sinusoidal modulating wave



(b) Resulting AM signal

Figure 6.11 Amplitude Modulation

Frequency Modulation (FM)



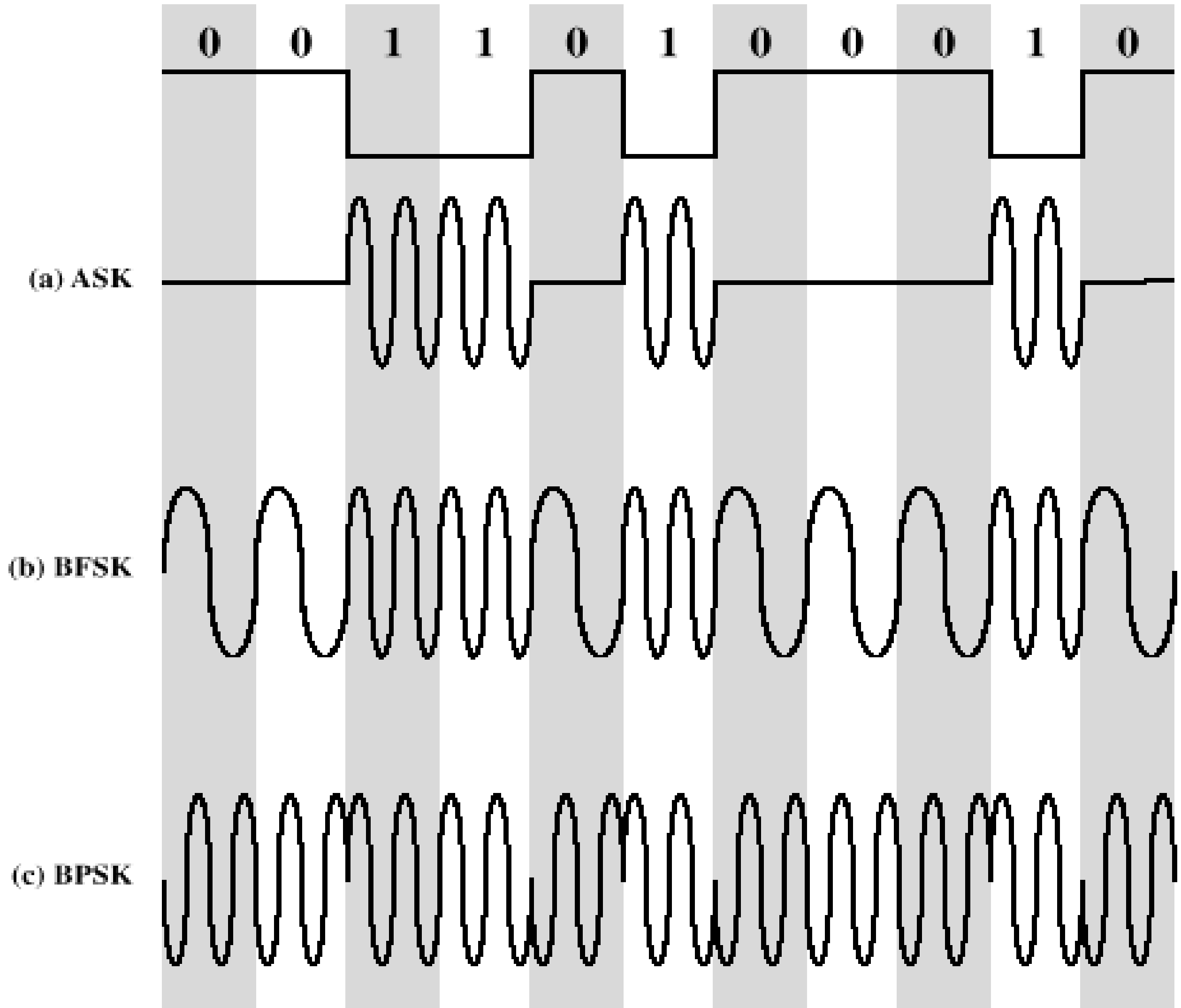
The modulated carrier signal *s*(*t*) is:

$$s(t) = A\cos\left((2\pi\ f_c t + 2\pi\ f_\Delta \int_{t_0}^{t} x(\tau)d\tau + \theta_0 \right)$$

Where f_Δ is the peak frequency deviation from the original frequency and $f_\Delta << f_c$

Basic Digital Modulation

- 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**

Frequency Shift Keying (FSK)

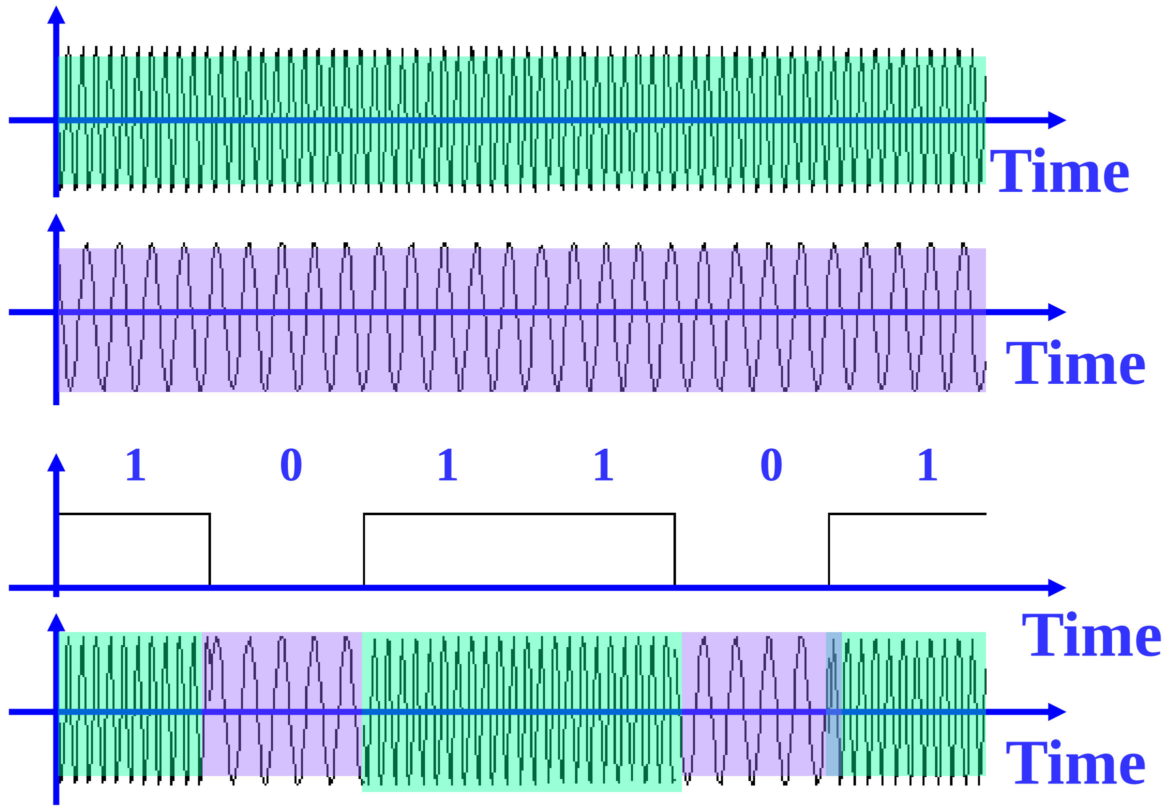
1/0 represented by two different frequencies

Carrier signal for message signal '1'

Carrier signal for message signal '0'

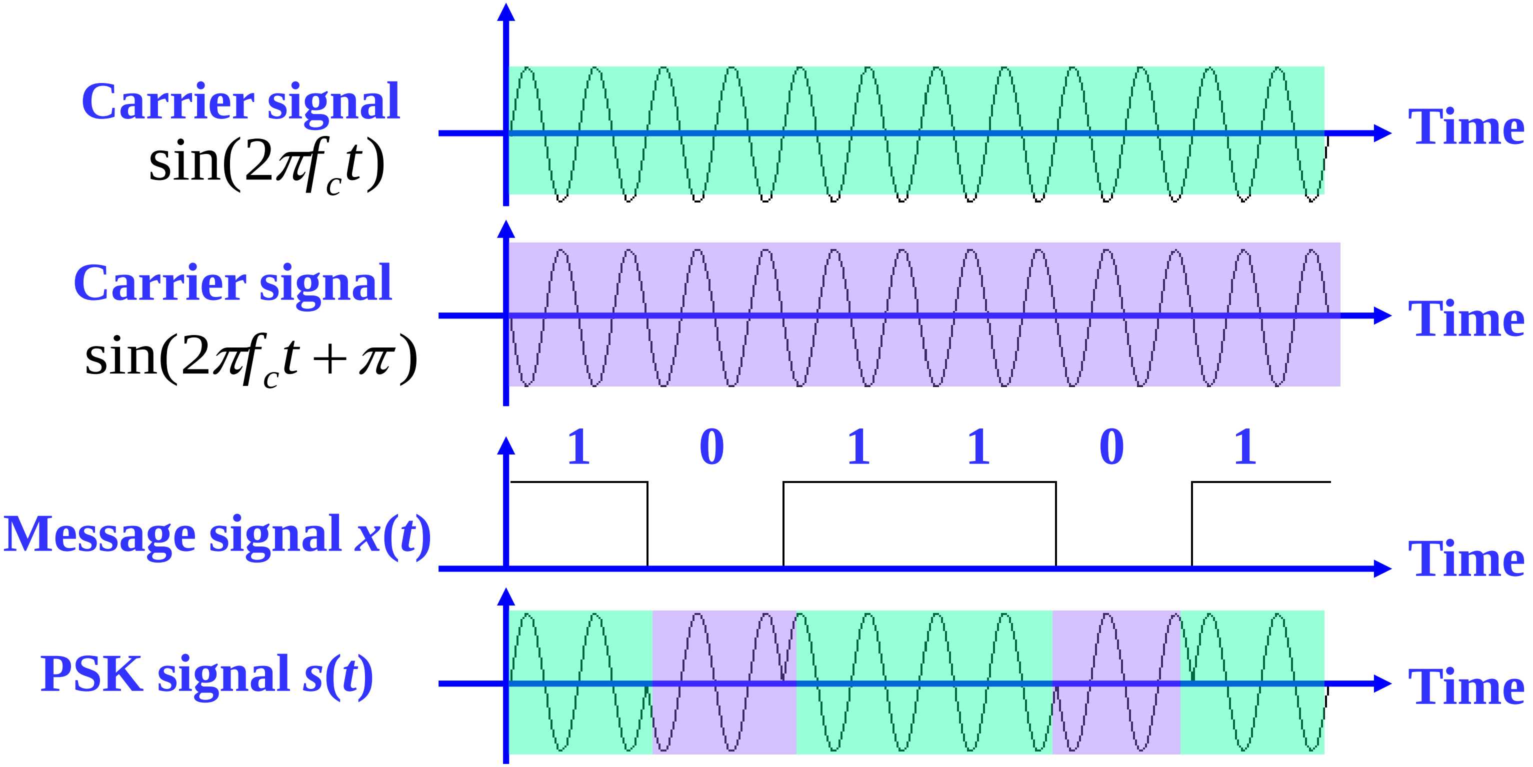
Message signal $x(t)$

FSK signal $s(t)$



Phase Shift Keying (PSK)

- Use alternative sine wave phases to encode bits



Quadrature Phase Shift Keying (QPSK)

✓ Four different phase shifts used are:

$$\begin{cases} \phi_{0,0} = 0 \\ \phi_{0,1} = \pi / 2 \\ \phi_{1,0} = \pi \\ \phi_{1,1} = 3\pi / 2 \end{cases} \quad \textbf{or} \quad \begin{cases} \phi_{0,0} = \pi / 4 \\ \phi_{0,1} = 3\pi / 4 \\ \phi_{1,0} = -3\pi / 4 \\ \phi_{1,1} = -\pi / 4 \end{cases}$$

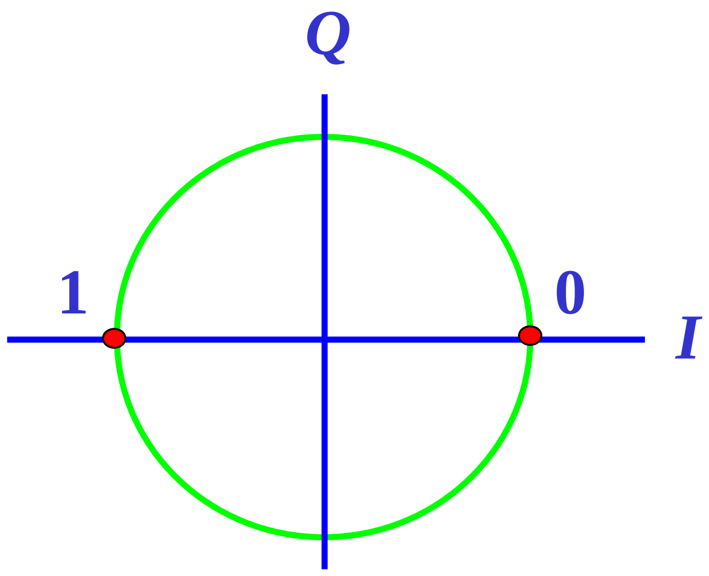
I (in-phase) and Q (quadrature) modulation used

Phase-Shift Keying (PSK)

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

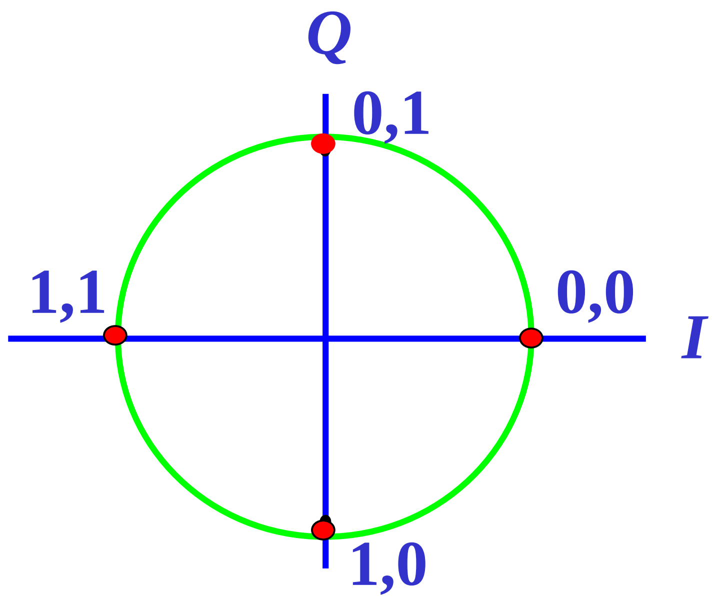
$$
s(t) = \begin{cases} A\cos\left(2\pi f_c t + \dfrac{\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t + \dfrac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t - \dfrac{3\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t - \dfrac{\pi}{4}\right) & 10 \end{cases}
$$

QPSK Signal Constellation



(a) BPSK

(Binary Phase Shift Keying)



(b) QPSK

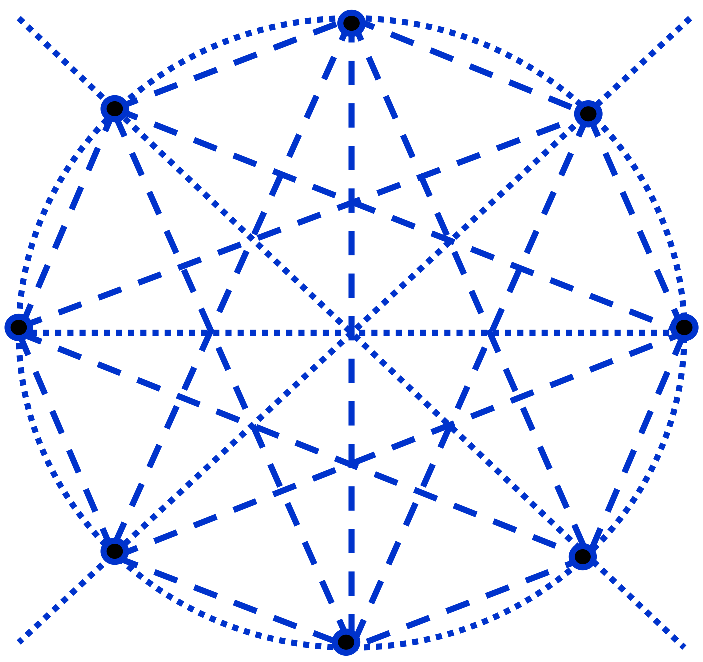
(Quadrature Phase Shift Keying)

π/4 QPSK

- ✓ **The phase of the carrier is:** $\theta_k = \theta_{k-1} + \phi_k$ **, where θ_k is carrier phase shift corresponding to input bit pairs.**
- ✓ **If θ_0=0, input bit stream is [1011], then:**

$$\theta_1 = \theta_0 + \phi_1 = -\pi / 4$$

$$\theta_2 = \theta_1 + \phi_2 = -\pi / 4 + \pi / 4 = 0$$



All possible states in π/4 QPSK

Quadrature Amplitude Modulation (QAM)

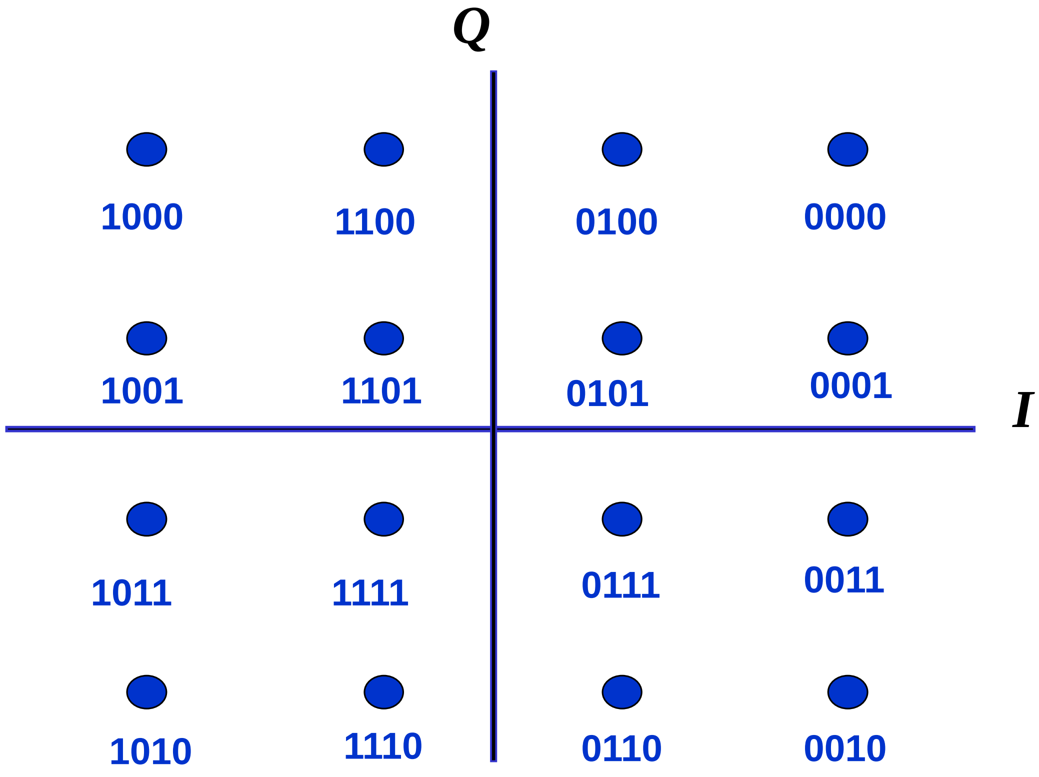
Combination of AM and PSK: modulate signals using two measures of amplitude and four possible phase shifts

A representative QAM Table

Bit sequence represented	Amplitude	Phase shift
000	1	0
001	2	0
010	1	$\pi/2$
011	2	$\pi/2$
100	1	π
101	2	π
110	1	$3\pi/2$
111	2	$3\pi/2$

Quadrature Amplitude Modulation (QAM)

- ✓ **Two carriers out of phase by 90 degrees are amplitude modulated**



Rectangular constellation of 16QAM

Homework

- Exercises: 7.2, 7.7, 7.10, 7.17, 7.18, 7.21 (Select anyone)
- Experiment (Announced by TA)