Data and Computer Communications

Tenth Edition

by William Stallings

CHAPTER 5

Signal Encoding Techniques

“Thus one says, in general, that the function of the transmitter is to encode, and that of the receiver to decode, the message. The theory provides for very sophisticated transmitters and receivers—such, for example, as possess ‘memories,’ so that the way they encode a certain symbol of the message depends not only upon this one symbol but also upon previous symbols of the message and the way they have been encoded.”

—*The Mathematics of Communication*,
Scientific American, July 1949,
Warren Weaver

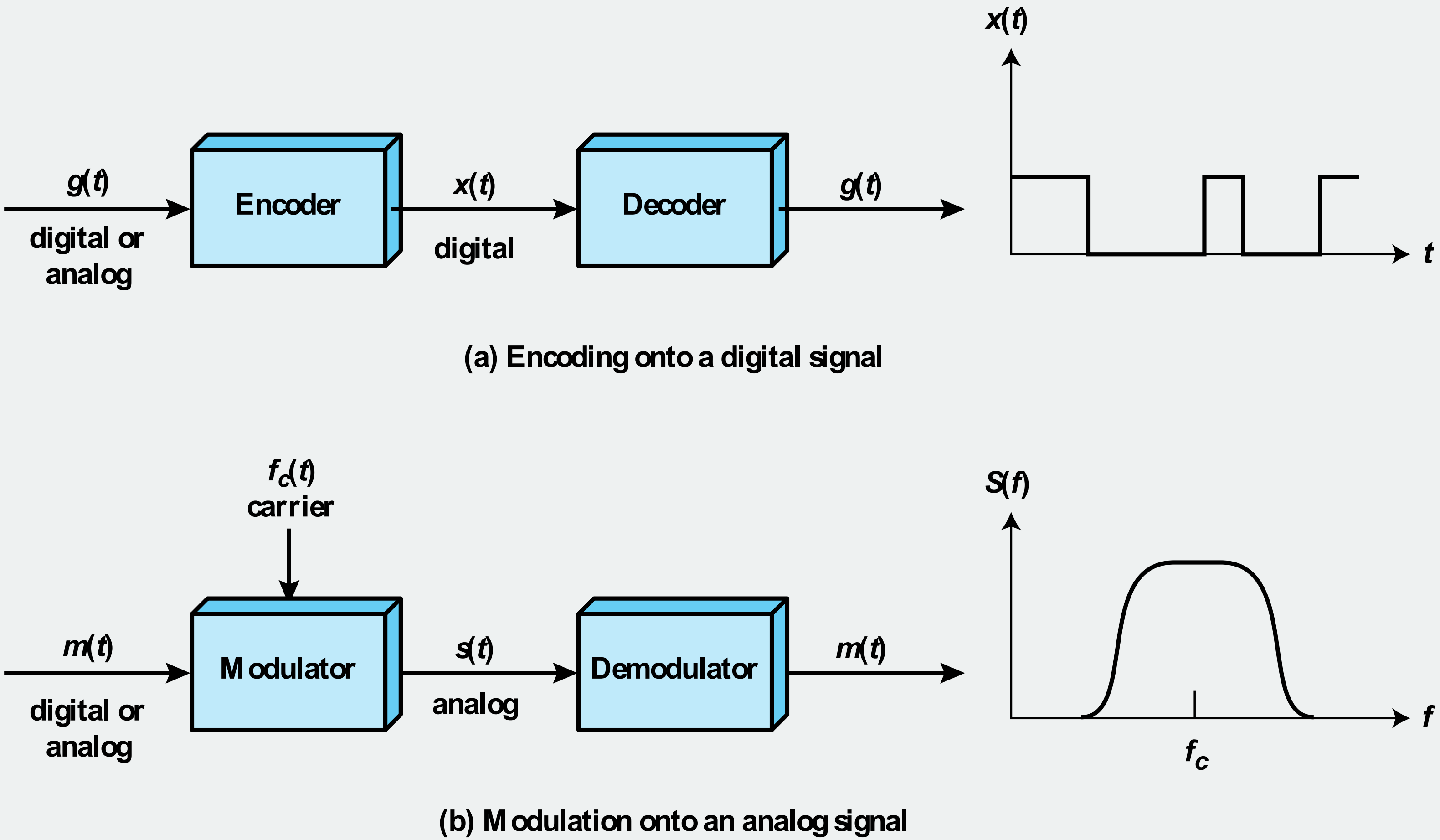


Figure 5.1 Encoding and Modulation Techniques

Digital Data, Digital Signal

- Digital signal
  - Sequence of discrete, discontinuous voltage pulses
  - Each pulse is a signal element
  - Binary data are transmitted by encoding each data bit into signal elements

Terminology

- **Unipolar** – all signal elements have the same sign
- **Polar** – one logic state represented by positive voltage and the other by negative voltage
- **Data rate** – rate, in bits per second that data are transmitted
- **Duration or length of a bit** – time taken for transmitter to emit the bit
- **Modulation rate** – rate at which the signal level is changed; the rate is expressed in baud, which means signal elements per second
- **Mark and space** – refer to the binary digits 1 and 0

Table 5.1

Key Data Transmission Terms

Term	Units	Definition
Data element	Bits	A single binary one or zero
Data rate	Bits per second (bps)	The rate at which data elements are transmitted
Signal element	Digital: a voltage pulse of constant amplitude Analog: a pulse of constant frequency, phase, and amplitude	That part of a signal that occupies the shortest interval of a signaling code
Signaling rate or modulation rate	Signal elements per second (baud)	The rate at which signal elements are transmitted

Interpreting Signals

Tasks involved in interpreting digital signal at the receiver:

- Timing of bits - when they start and end
- Signal levels

Factors affecting signal interpretation:

- Signal to noise ratio
- Data rate
- Bandwidth

Nonreturn to Zero-Level (NRZ-L)
0 = high level
1 = low level

Nonreturn to Zero Inverted (NRZI)
0 = no transition at beginning of interval (one bit time)
1 = transition at beginning of interval

Bipolar-AMI
0 = no line signal
1 = positive or negative level, alternating for successive ones

Pseudoternary
0 = positive or negative level, alternating for successive zeros
1 = no line signal

Manchester
0 = transition from high to low in middle of interval
1 = transition from low to high in middle of interval

Differential Manchester
Always a transition in middle of interval
0 = transition at beginning of interval
1 = no transition at beginning of interval

B8ZS
Same as bipolar AMI, except that any string of eight zeros is replaced by a string with two code violations

HDB3
Same as bipolar AMI, except that any string of four zeros is replaced by a string with one code violation

Table 5.2

Definition of Digital Signal Encoding Formats

(This table can be found on page 177 in the textbook)

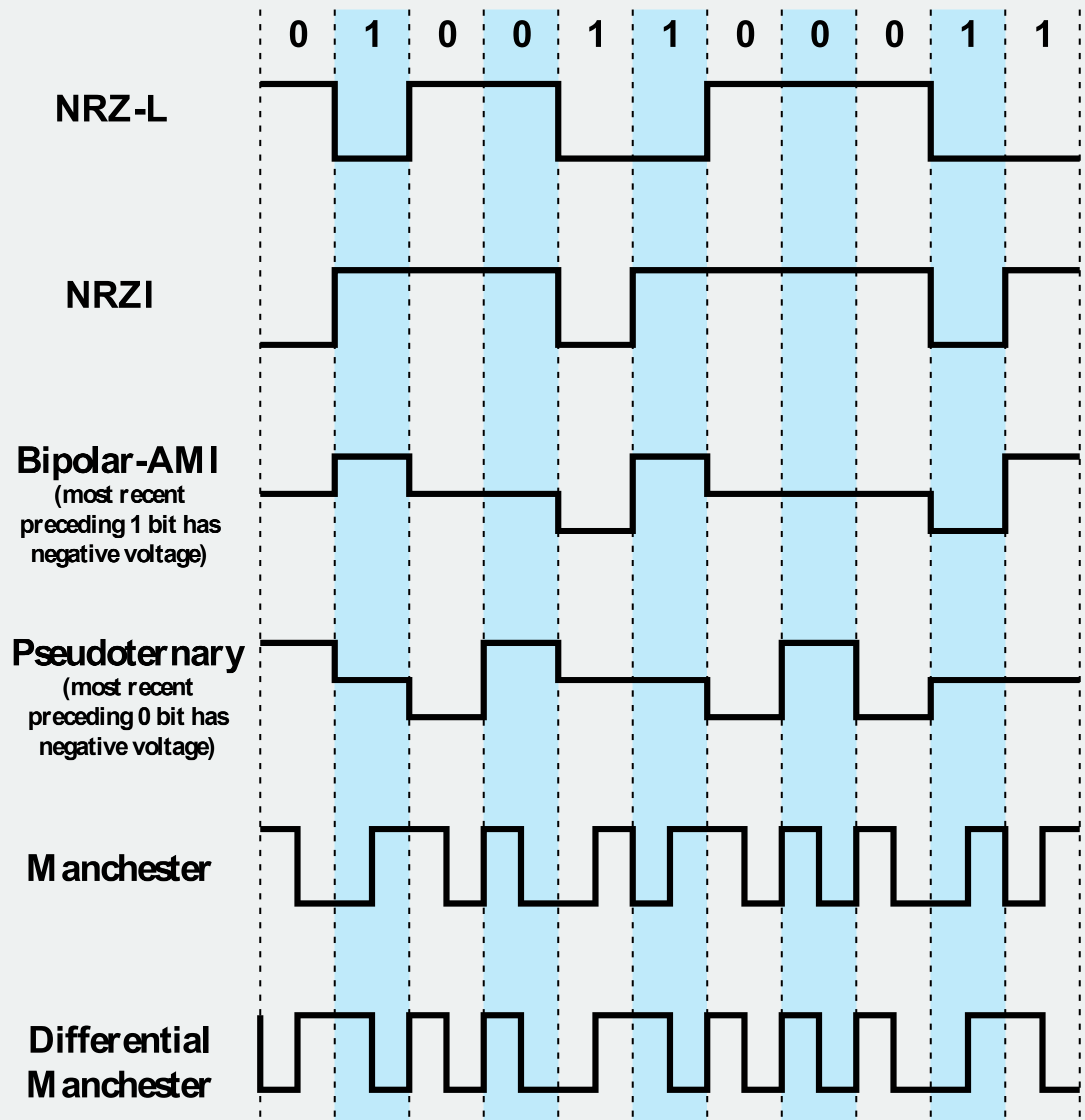


Figure 5.2 Digital Signal Encoding Formats

Encoding Schemes

Signal spectrum	• A good signal design should concentrate the transmitted power in the middle of the transmission bandwidth
Clocking	• Need to synchronize transmitter and receiver either with an external clock or sync mechanism
Error detection	• Responsibility of a layer of logic above the signaling level that is known as data link control
Signal interference and noise immunity	• Certain codes perform better in the presence of noise
Cost and complexity	• The higher the signaling rate the greater the cost

Nonreturn to Zero

- Easiest way to transmit digital signals is to use two different voltages for 0 and 1 bits
- Voltage level is constant during a bit interval
  - No transition (no return to a zero voltage level)
  - Absence of voltage for 0, constant positive voltage for 1
  - More often, a negative voltage represents one value and a positive voltage represents the other (NRZ-L)

Non-return to Zero Inverted (NRZI)

- Non-return to zero, invert on ones
- Maintains a constant voltage pulse for duration of a bit time
- Data are encoded as presence or absence of signal transition at the beginning of the bit time
  - Transition (low to high, high to low) denotes binary 1
  - No transition denotes binary 0

Is an example of differential encoding

- Data are represented by changes rather than levels
- More reliable to detect a transition in the presence of noise than to compare a value to a threshold
- Easy to lose sense of polarity

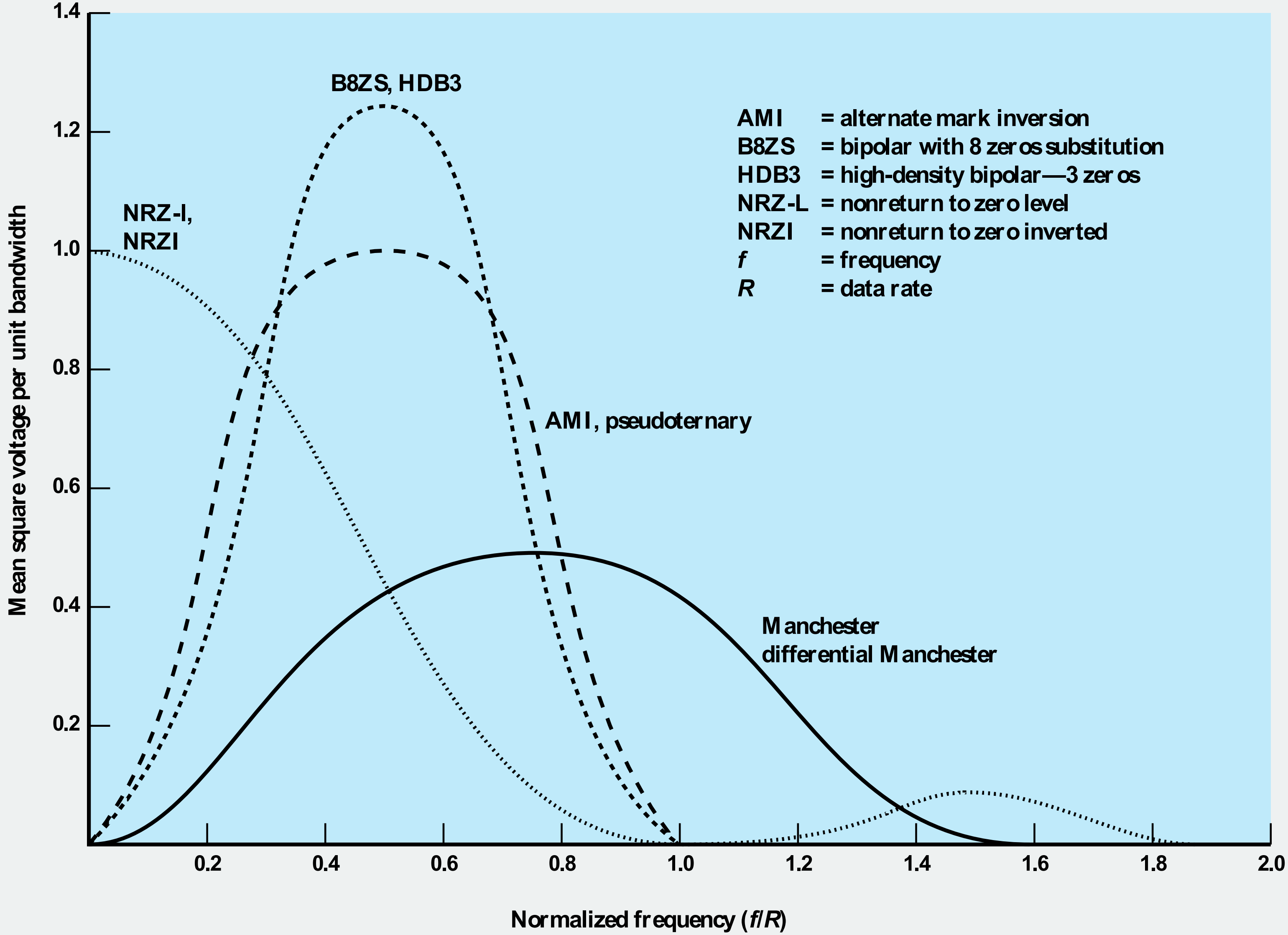


Figure 5.3 Spectral Density of Various Signal Encoding Schemes

Multilevel Binary Bipolar-AMI

- Use more than two signal levels
- Bipolar-AMI
  - Binary 0 represented by no line signal Binary 1 represented by positive or negative pulse
  - Binary 1 pulses alternate in polarity
  - No loss of sync if a long string of 1s occurs
  - No net dc component
  - Lower bandwidth
  - Easy error detection

Multilevel Binary Pseudoternary

- Binary 1 represented by absence of line signal (zero voltage)
- Binary 0 represented by alternating positive and negative pulses
- No advantage or disadvantage over bipolar-AMI and each is the basis of some applications

Multilevel Binary Issues

- Synchronization with long runs of 0's or 1's
  - Can insert additional bits that force transitions
  - Scramble data
- Not as efficient as NRZ
  - Each signal element only represents one bit
    - Receiver distinguishes between three levels: +A, -A, 0
  - A 3 level system could represent $\log_2 3 = 1.58$ bits
  - Requires approximately 3dB more signal power for same probability of bit error

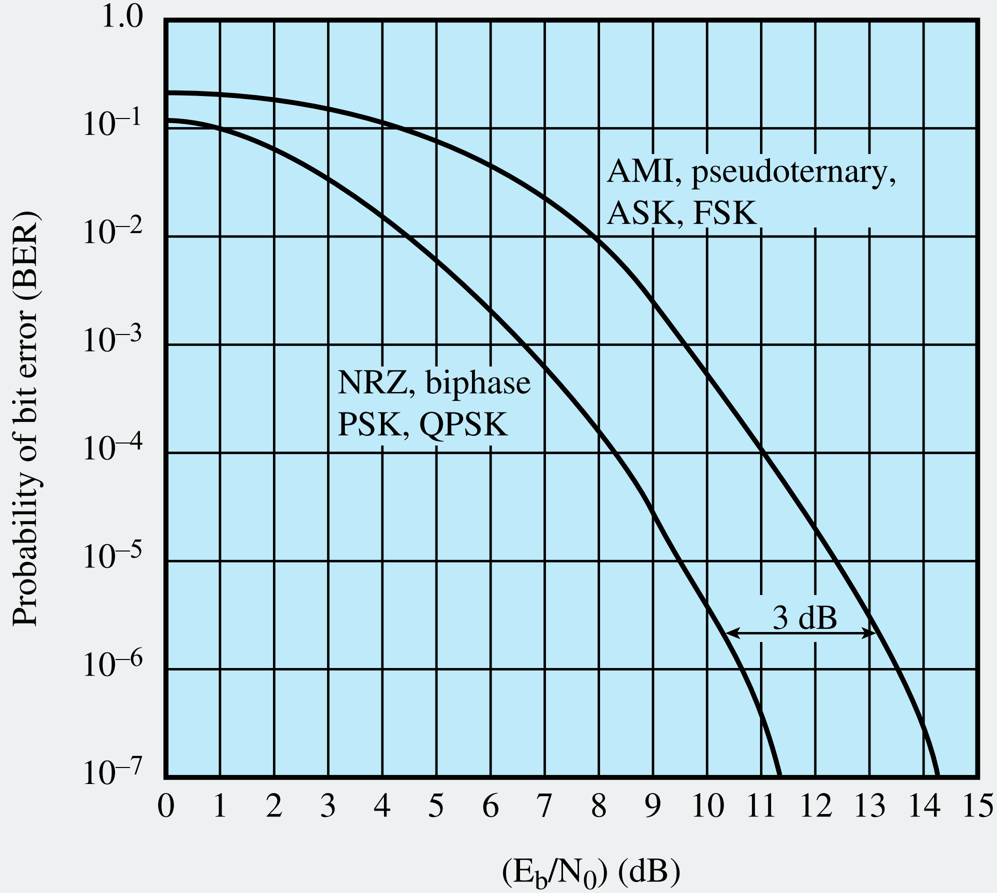


Figure 5.4 Theoretical Bit Error Rate for Various Encoding Schemes

Manchester Encoding

- There is a transition at the middle of each bit period
- Midbit transition serves as a clocking mechanism and also as data
- Low to high transition represents a 1
- High to low transition represents a 0

Differential Manchester Encoding

- Midbit transition is only used for clocking
- The encoding of a 0 is represented by the presence of a transition at the beginning of a bit period
- A 1 is represented by the absence of a transition at the beginning of a bit period
- Has the added advantage of employing differential encoding

Biphase Pros and Cons

Pros

- Synchronization
- No dc component
- Has error detection

Cons

- At least one transition per bit time and may have two
- Maximum modulation rate is twice NRZ
- Requires more bandwidth

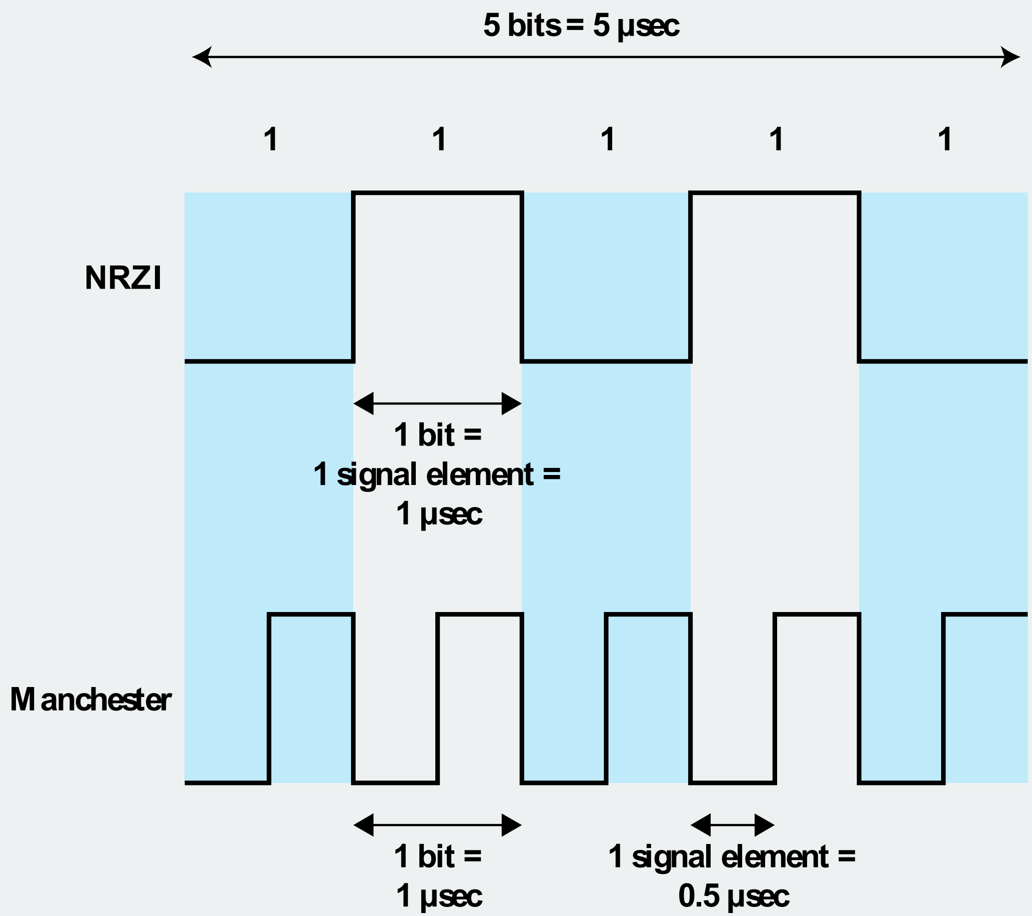


Figure 5.5 A Stream of Binary Ones at 1 Mbps

Table 5.3

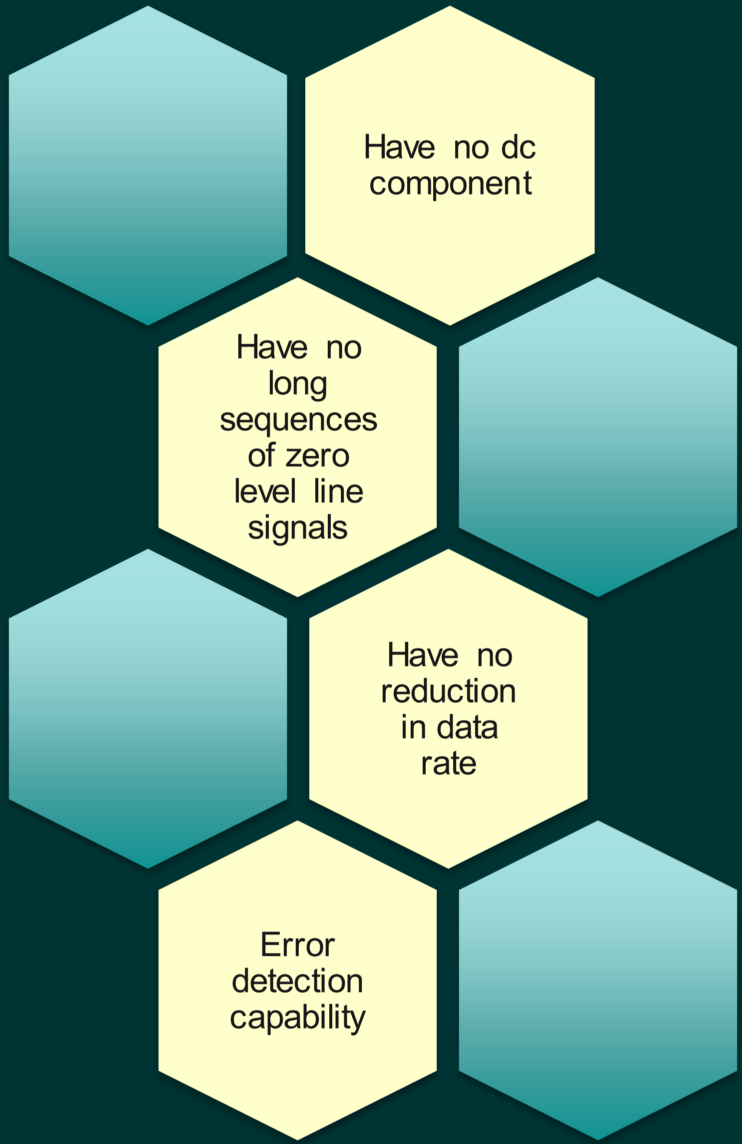
Normalized Signal Transition Rate of Various Digital Signal Encoding Schemes

	Minimum	101010. . .	Maximum
NRZ-L	0 (all 0s or 1s)	1.0	1.0
NRZI	0 (all 0s)	0.5	1.0 (all 1s)
Bipolar-AMI	0 (all 0s)	1.0	1.0
Pseudoternary	0 (all 1s)	1.0	1.0
Manchester	1.0 (1010 . . .)	1.0	2.0 (all 0s or 1s)
Differential Manchester	1.0 (all 1s)	1.5	2.0 (all 0s)

Scrambling

- Use scrambling to replace sequences that would produce constant voltage
- These filling sequences must:
  - Provide sufficient transitions for the receiver's clock to maintain synchronization
  - Be recognized by the receiver and replaced with the original data sequence
  - Be the same length as the original sequence so there is no data rate penalty

Design Goals



B8ZS

- Bipolar with 8-zeros substitution
- Coding scheme commonly used in North America
- Based on a bipolar-AMI
  - Amended with the following rules:
    - If an octet of all zeros occurs and the last voltage pulse preceding this octet was positive, then the eight zeros of the octet are encoded as 000+-0-+
    - If an octet of all zeros occurs and the last voltage pulse preceding this octet was negative, then the eight zeros of the octet are encoded as 000-+0+-

Table 5.4

HDB3 Substitution Rules

	Number of Bipolar Pulses (ones) since Last Substitution	
Polarity of Preceding Pulse	Odd	Even
−	000−	+00+
+	000+	−00−

Check if you know why DC is still zero!

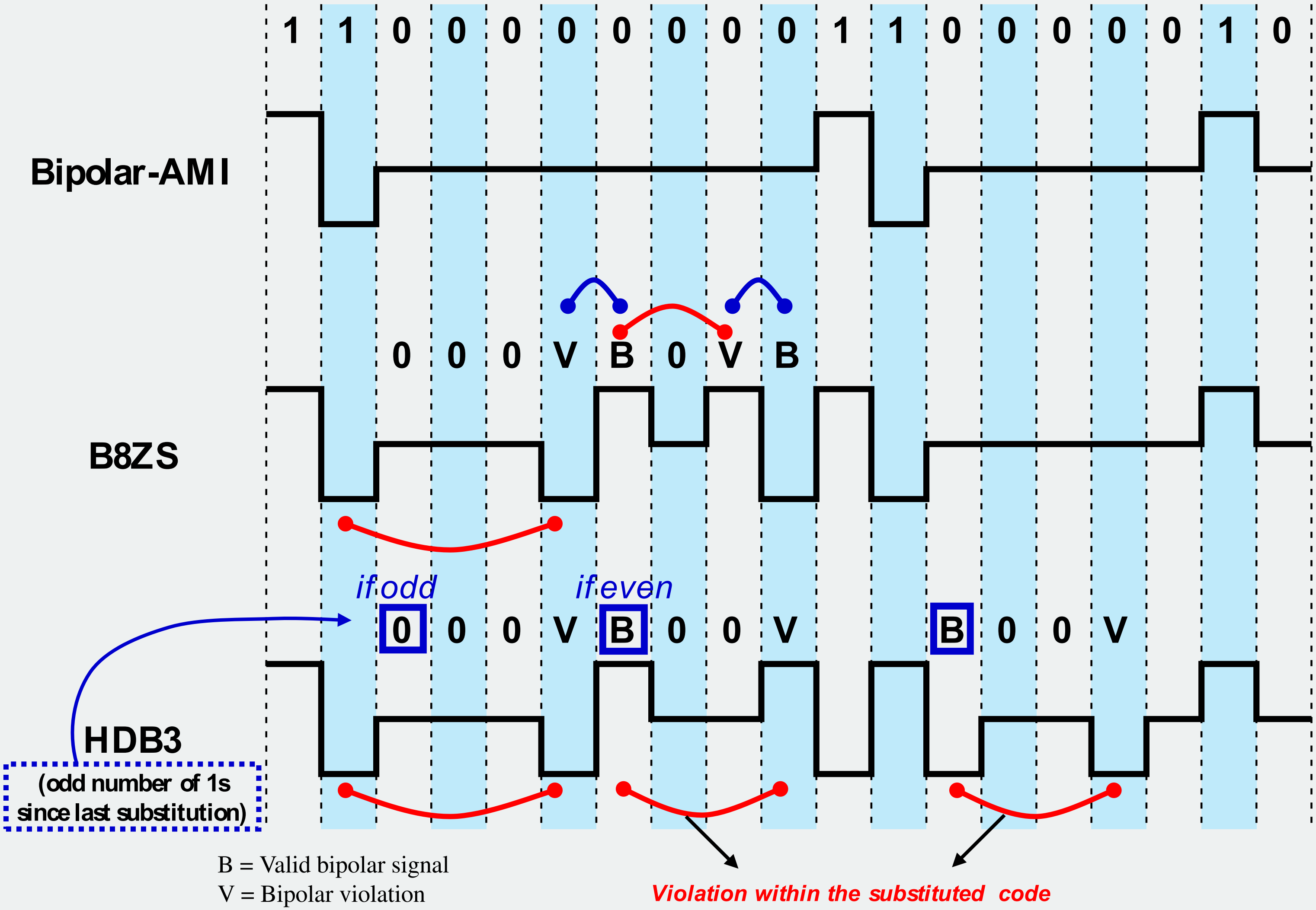


Figure 5.6 Encoding Rules for B8ZS and HDB3

Digital Data, Analog Signal

- Main use is public telephone system
  - Was designed to receive, switch, and transmit analog signals
  - Has a frequency range of 300Hz to 3400Hz
  - Is not at present suitable for handling digital signals from the subscriber locations
  - Uses modem (modulator-demodulator) to convert digital data to analog signals and vice versa

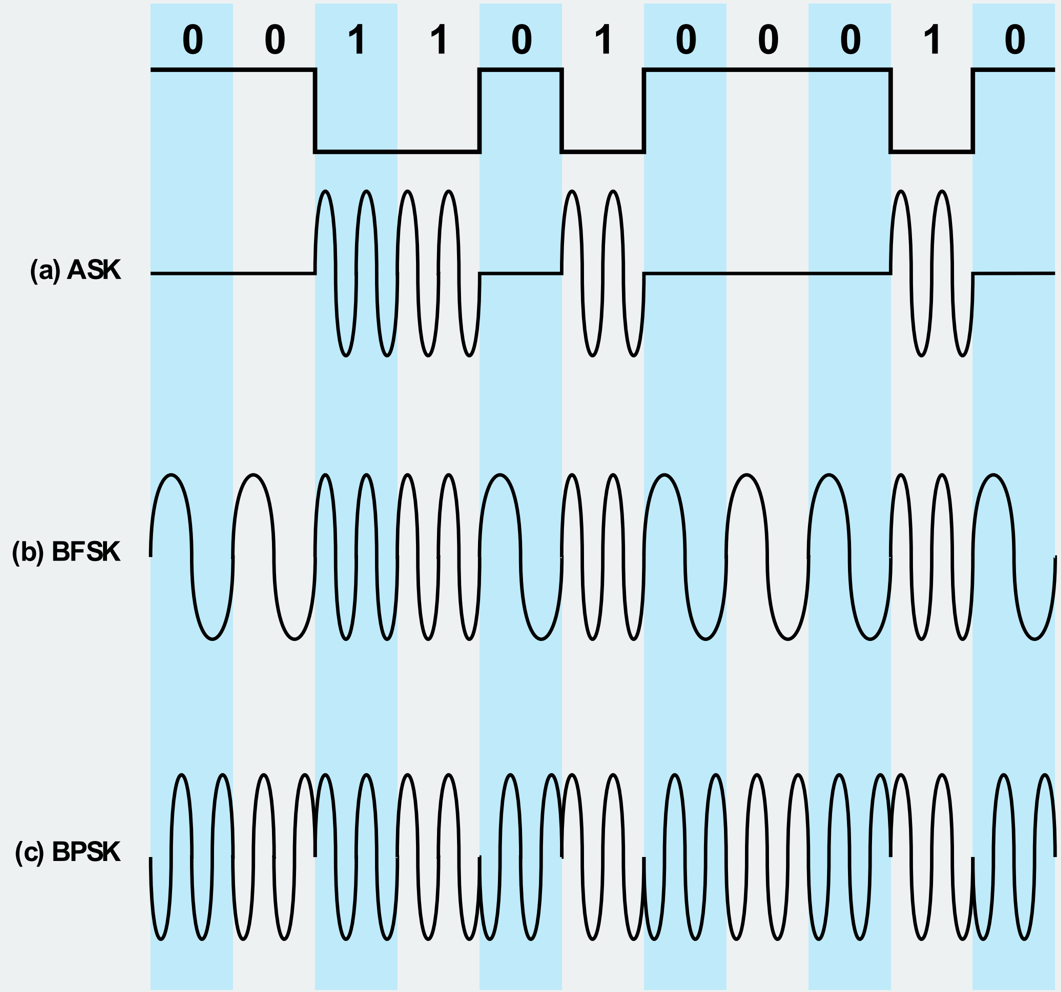


Figure 5.7 Modulation of Analog Signals for Digital Data

Amplitude Shift Keying (ASK)

- Encode 0/1 by different carrier amplitudes
  - Usually have one amplitude zero
- Susceptible to sudden gain changes
- Inefficient
- Used for:
  - Up to 1200bps on voice grade lines
  - Very high speeds over optical fiber

Binary Frequency Shift Keying (BFSK)

- Most common form of FSK
- Two binary values are represented by two different frequencies (near carrier)
- Less susceptible to error than ASK
- Used for:
  - Up to 1200bps on voice grade lines
  - High frequency radio
  - Even higher frequency on LANs using coaxial cable

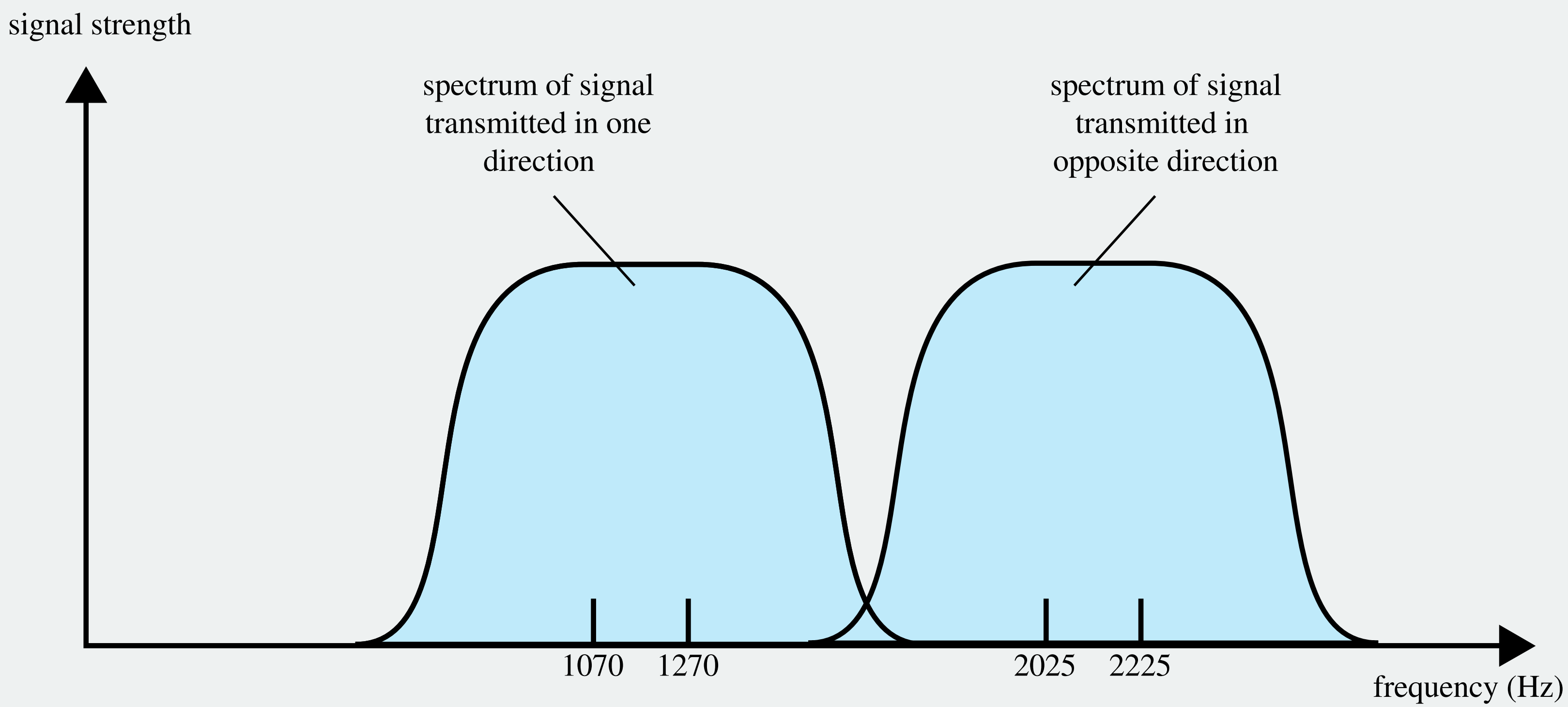


Figure 5.8 Full-Duplex FSK Transmission on a Voice-Grade Line

Multiple FSK (MFSK)

- Each signaling element represents more than one bit
- More than two frequencies are used
- More bandwidth efficient
- More susceptible to error

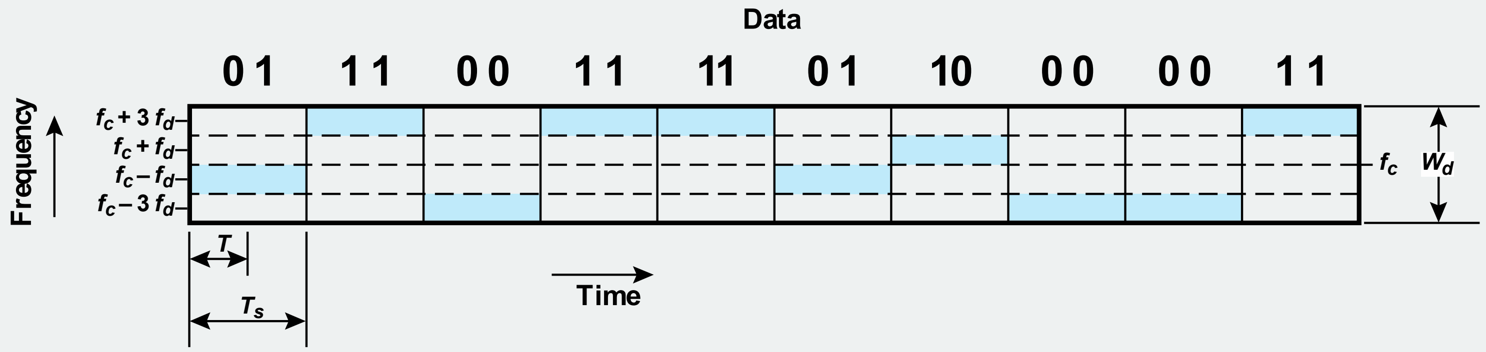


Figure 5.9 MFSK Frequency Use (M = 4)

Phase Shift Keying (PSK)

- The phase of the carrier signal is shifted to represent data
- Binary PSK
  - Two phases represent the two binary digits
- Differential PSK
  - Phase shifted relative to previous transmission rather than some reference signal

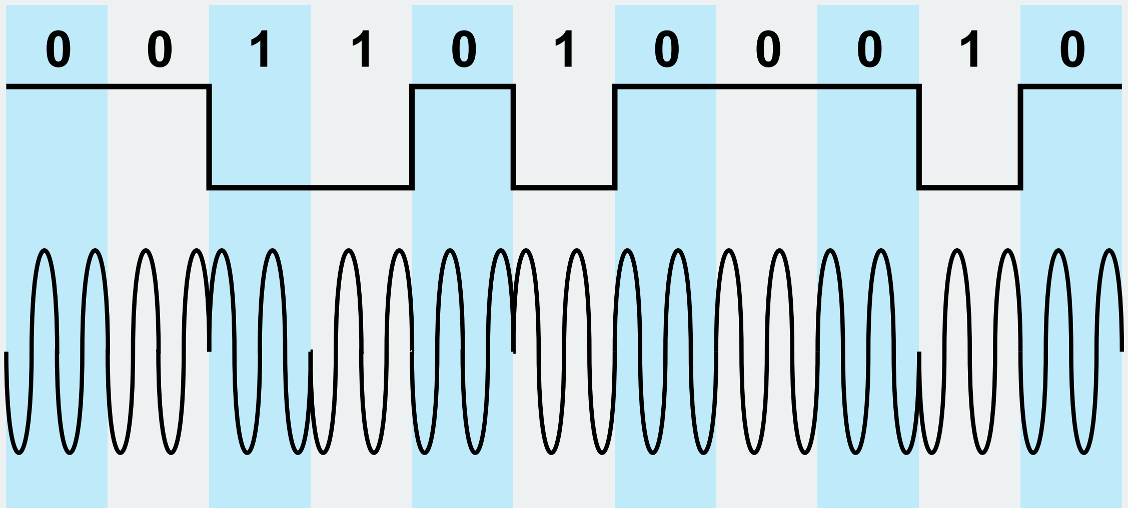


Figure 5.10 Differential Phase-Shift Keying (DPSK)

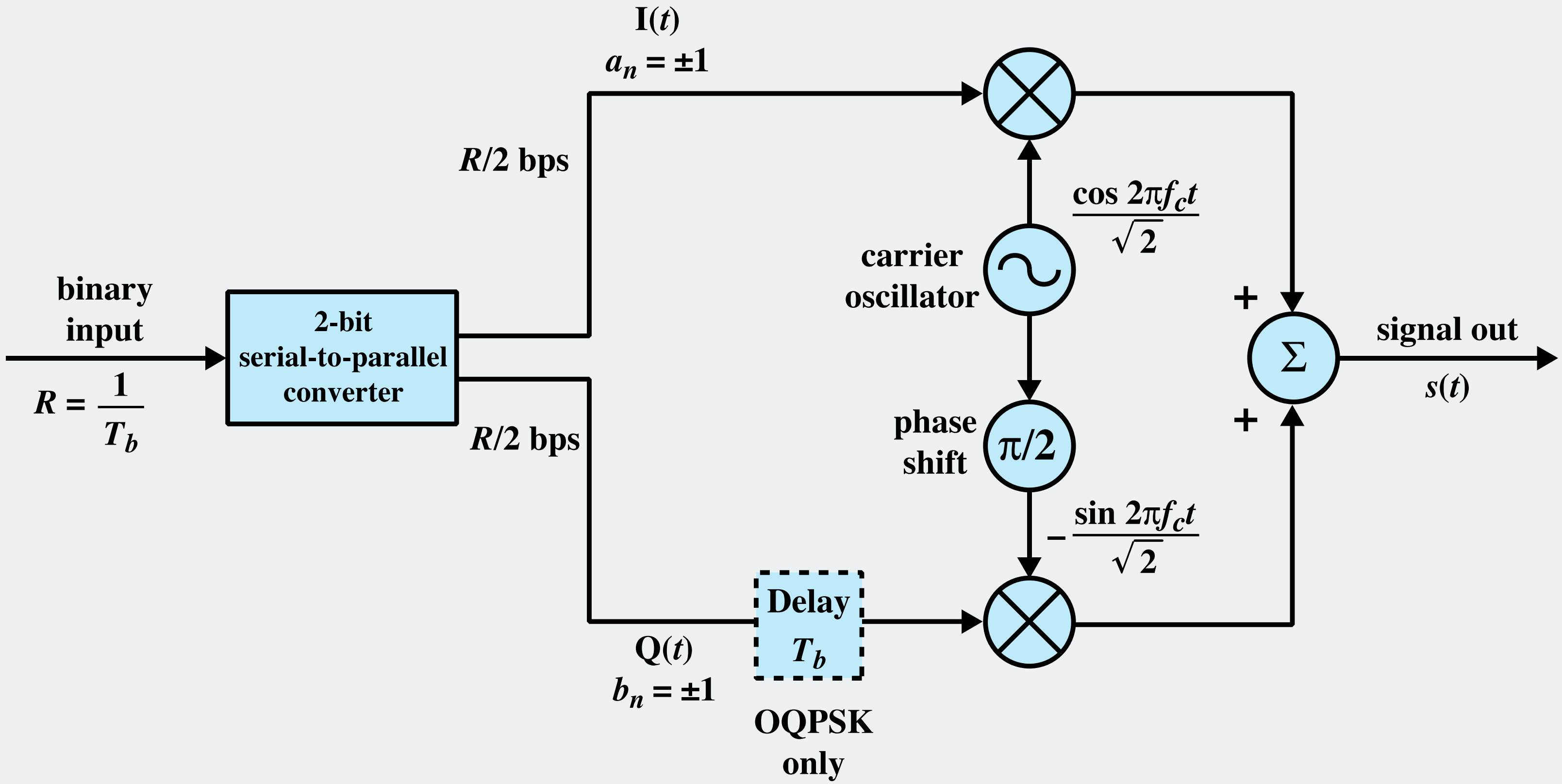
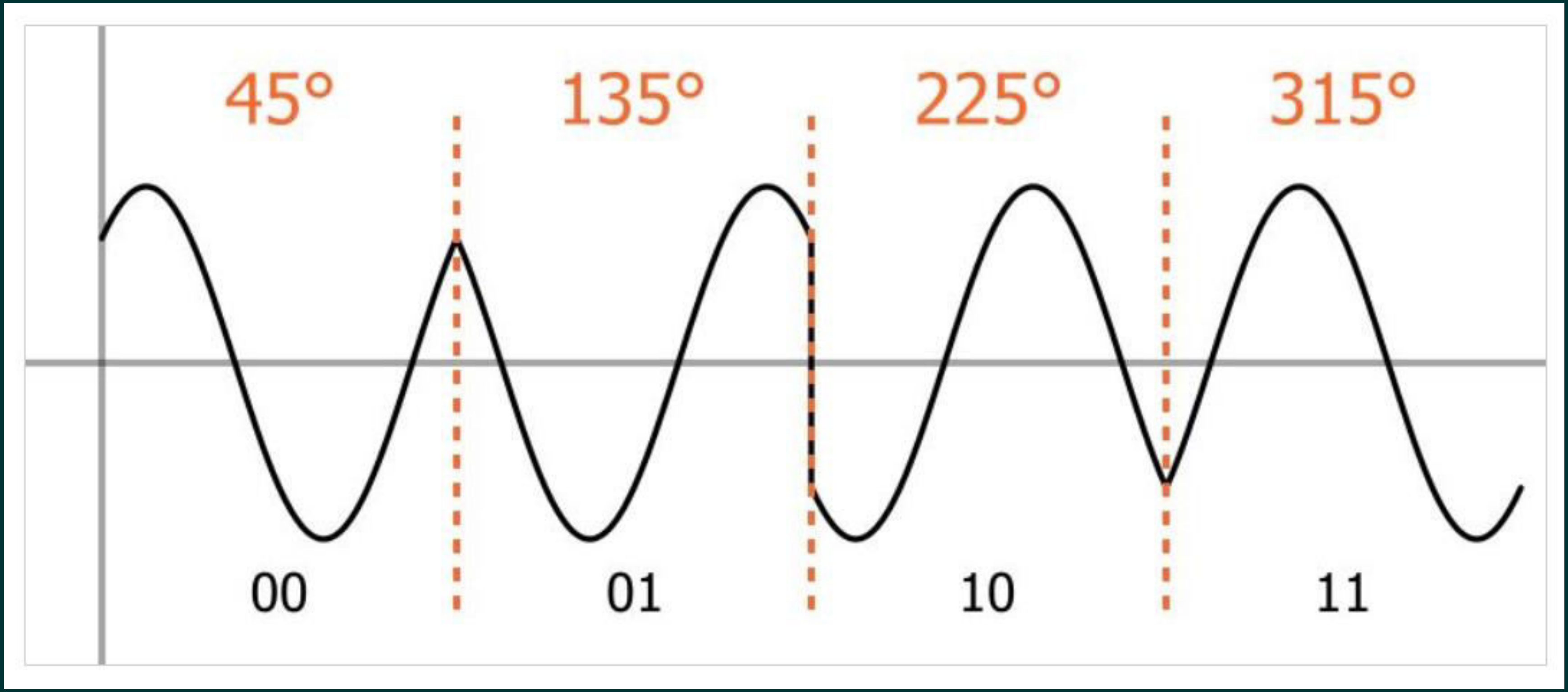


Figure 5.11 QPSK and OQPSK Modulators

Quadrature Phase Shift Keying (QPSK)



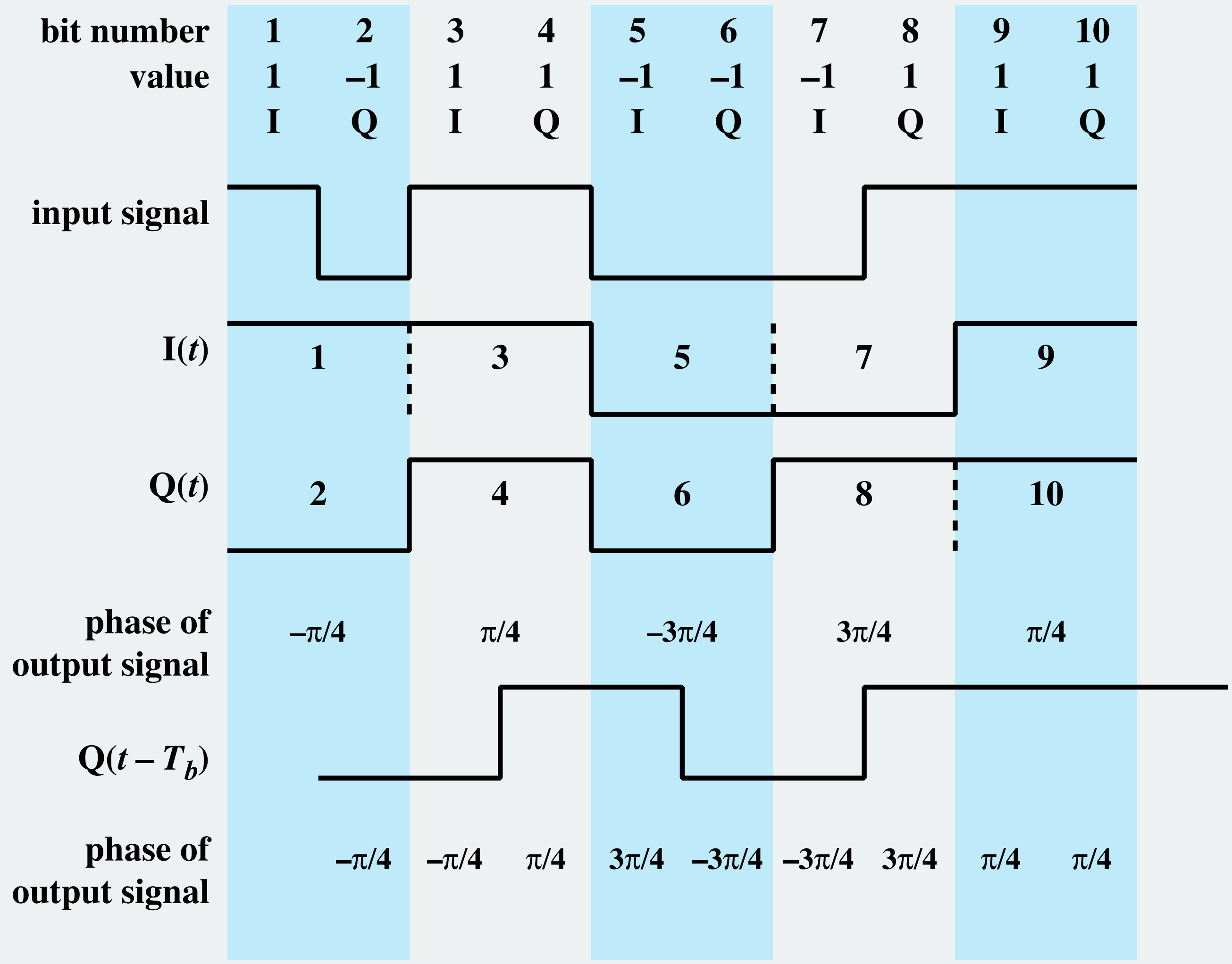


Figure 5.12 Example of QPSK and OQPSK Waveforms

Table 5.5

Bandwidth Efficiency (R/BT) for Various Digital-to-Analog Encoding Schemes

	$r = 0$	$r = 0.5$	$r = 1$
ASK	1.0	0.67	0.5
Multilevel FSK			
$M = 4, L = 2$	0.5	0.33	0.25
$M = 8, L = 3$	0.375	0.25	0.1875
$M = 16, L = 4$	0.25	0.167	0.125
$M = 32, L = 5$	0.156	0.104	0.078
PSK	1.0	0.67	0.5
Multilevel PSK			
$M = 4, L = 2$	2.00	1.33	1.00
$M = 8, L = 3$	3.00	2.00	1.50
$M = 16, L = 4$	4.00	2.67	2.00
$M = 32, L = 5$	5.00	3.33	2.50

Performance of Digital to Analog Modulation Schemes

Bandwidth

- ASK/PSK bandwidth directly relates to bit rate
- Multilevel PSK gives significant improvements

In presence of noise

- Bit error rate of PSK and QPSK are about 3dB superior to ASK and FSK
- MFSK and MPSK have tradeoff between bandwidth efficiency and error performance

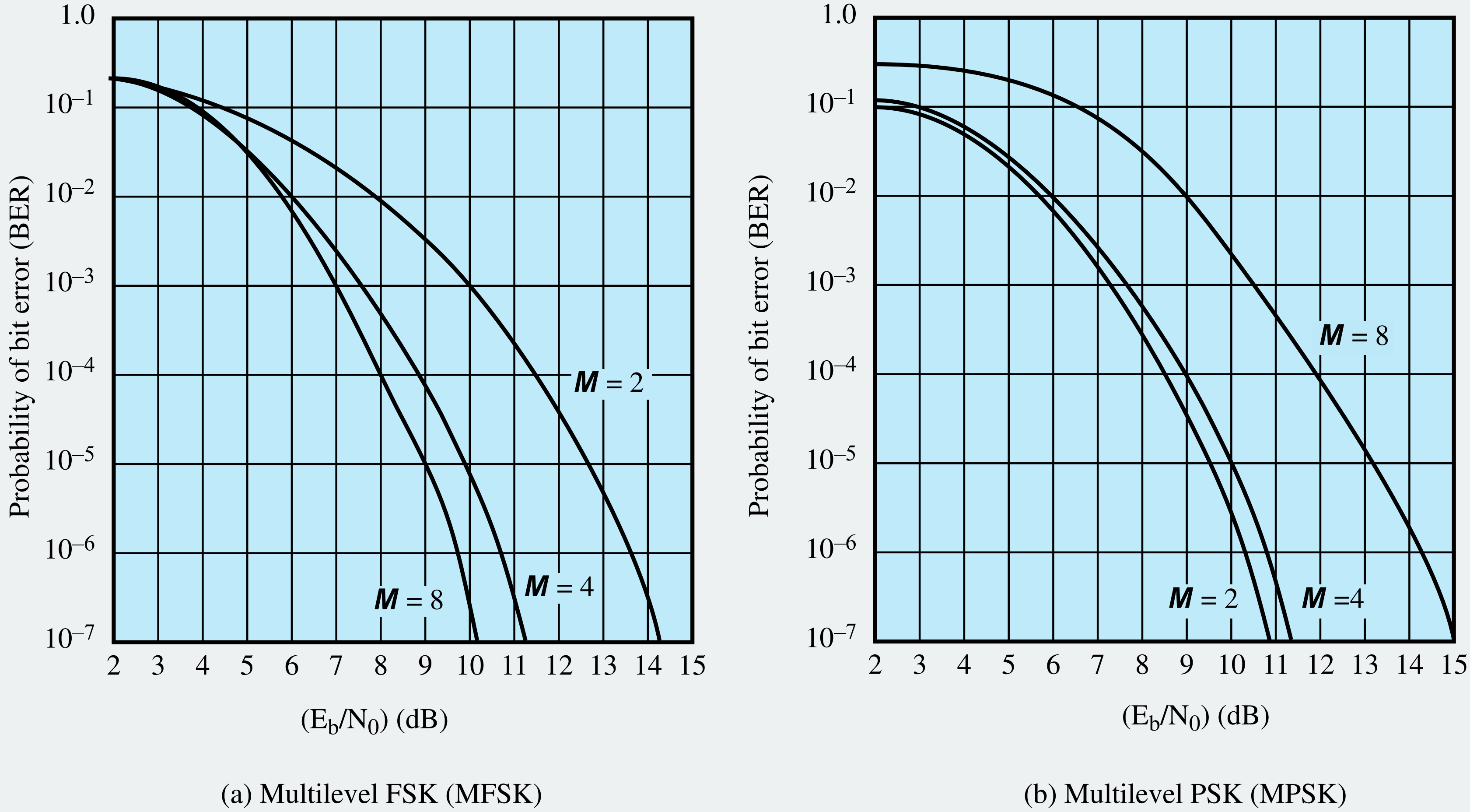


Figure 5.13 Theoretical Bit Error Rate for Multilevel FSK and PSK

Quadrature Amplitude Modulation (QAM)

- QAM is used in the asymmetric digital subscriber line (ADSL), in cable modems, and in some wireless standards
- Is a combination of ASK and PSK
- Logical extension of QPSK
- Send two different signals simultaneously on the same carrier frequency
  - Use two copies of carrier, one shifted 90°
  - Each carrier is ASK modulated
  - Two independent signals simultaneously transmitted over the same medium
  - At the receiver, the two signals are demodulated and the results are combined to produce the original binary input

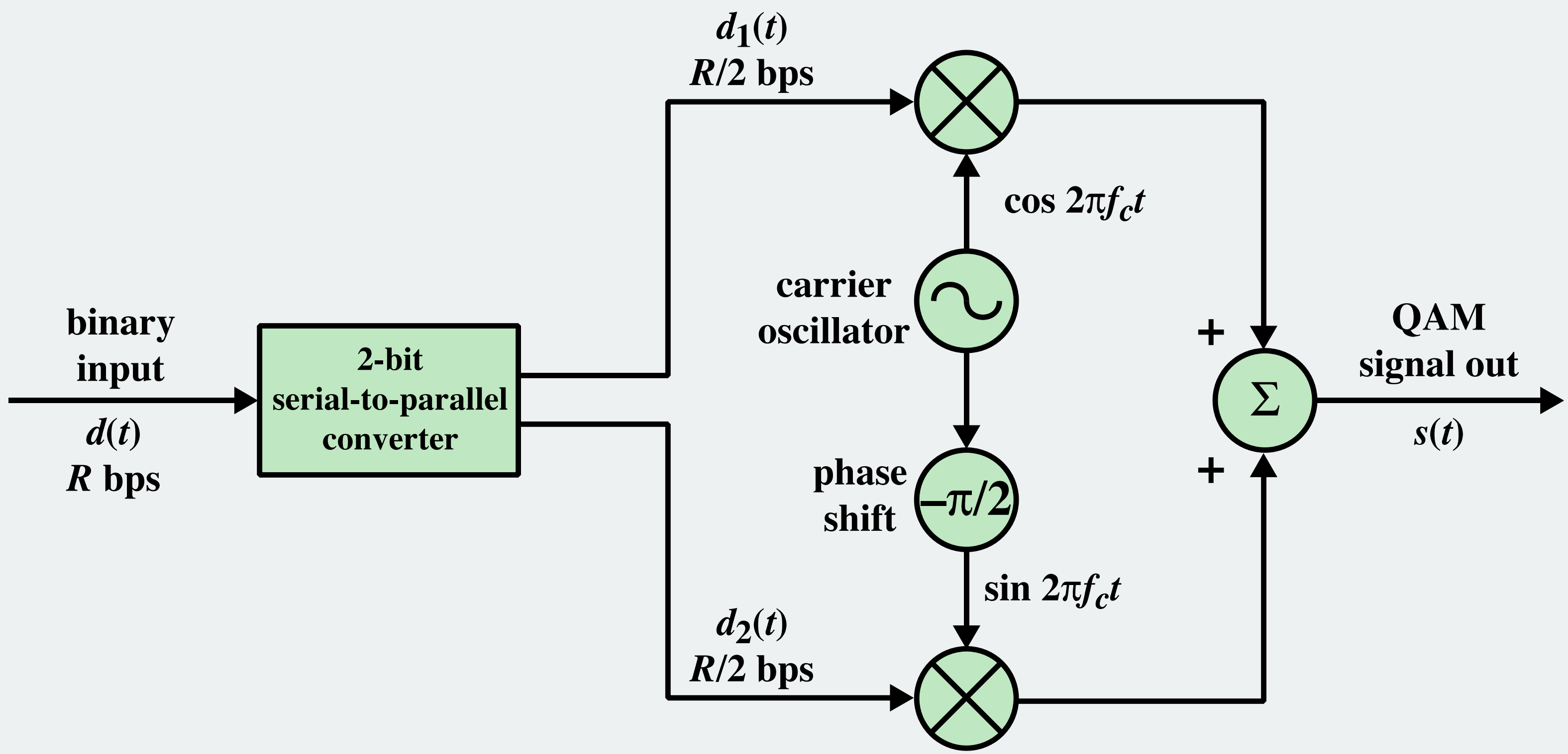


Figure 5.14 QAM Modulator

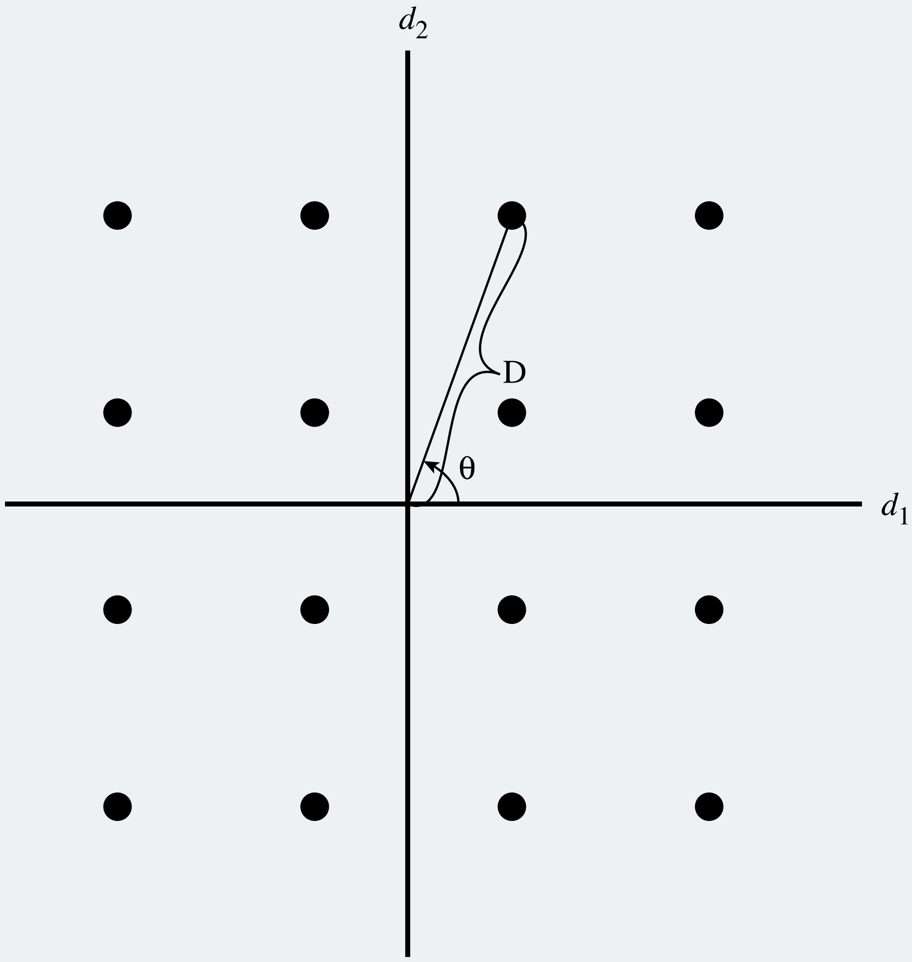


Figure 15.15 16-QAM Constellation

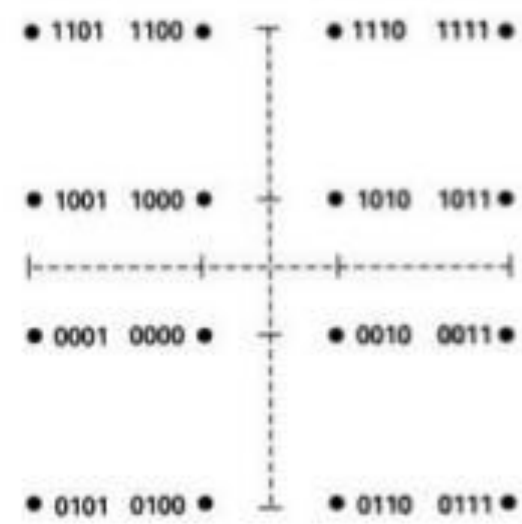
16QAM Generation – Output Phases

Binary input				16-QAM output	
Q	Q'	I	I'		
0	0	0	0	0.311 V	−135°
0	0	0	1	0.850 V	−165°
0	0	1	0	0.311 V	−45°
0	0	1	1	0.850 V	−15°
0	1	0	0	0.850 V	−105°
0	1	0	1	1.161 V	−135°
0	1	1	0	0.850 V	−75°
0	1	1	1	1.161 V	−45°
1	0	0	0	0.311 V	135°
1	0	0	1	0.850 V	165°
1	0	1	0	0.311 V	45°
1	0	1	1	0.850 V	15°
1	1	0	0	0.850 V	105°
1	1	0	1	1.161 V	135°
1	1	1	0	0.850 V	75°
1	1	1	1	1.161 V	45°

8 PHASES WITH SAME AMPLITUDE

4 PHASES WITH 2 AMPLITUDES EACH

(a)



(c)

Analog Data, Digital Signal

- Digitization is the conversion of analog data into digital data which can then:
  - Be transmitted using NRZ-L
  - Be transmitted using code other than NRZ-L
  - Be converted to analog signal
- Analog to digital conversion is done using a codec
  - Pulse code modulation
  - Delta modulation

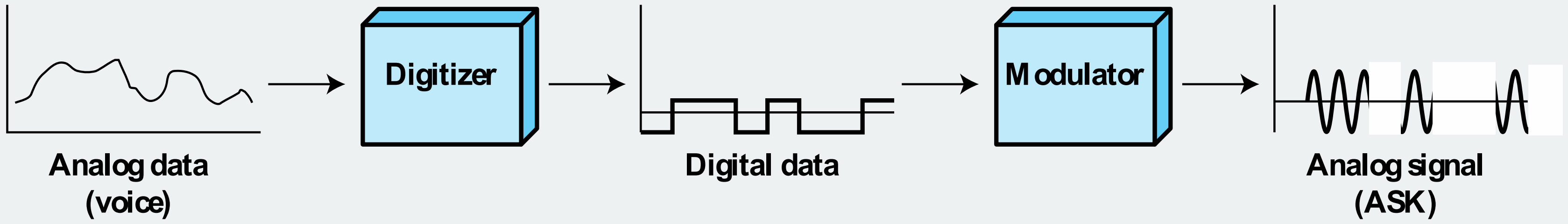
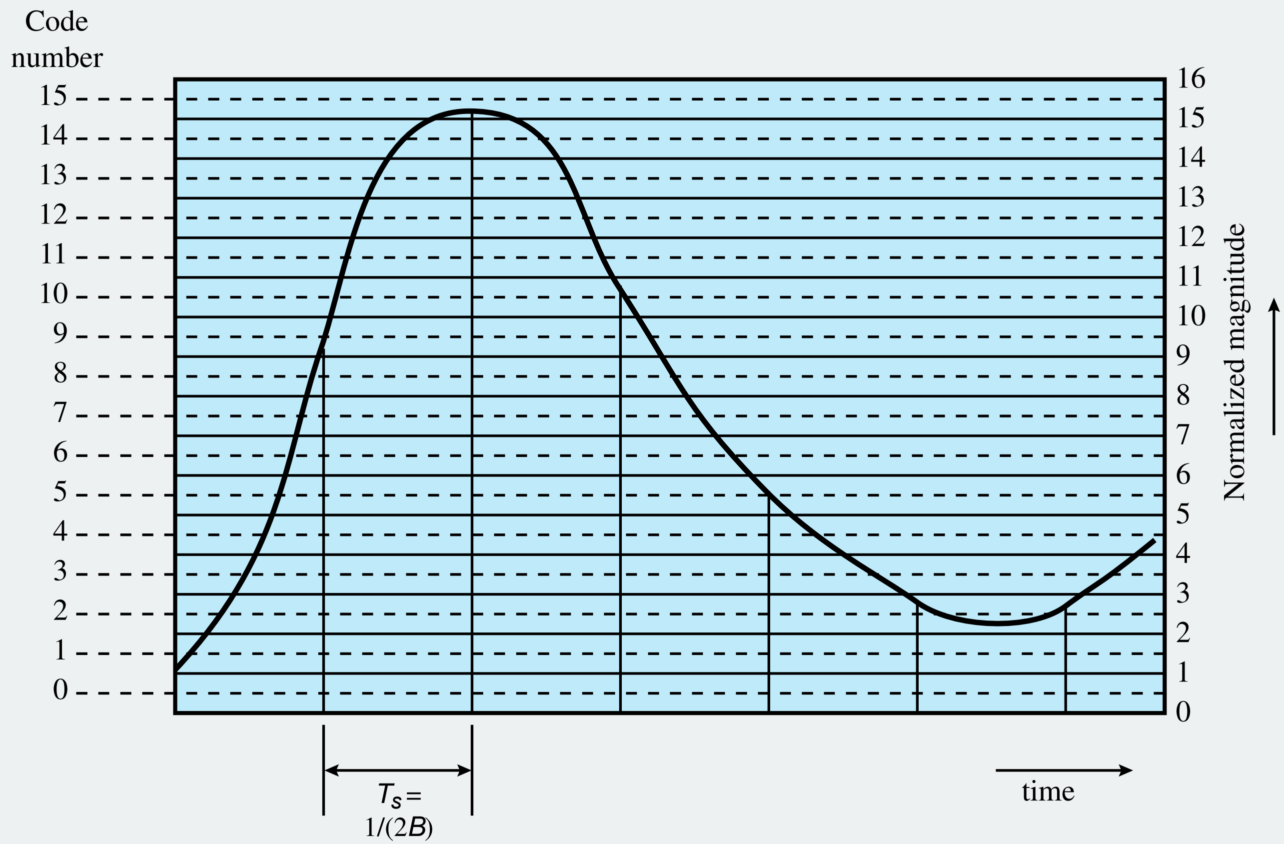


Figure 5.16 Digitizing Analog Data

Pulse Code Modulation (PCM)

- Based on the sampling theorem:
  - “If a signal *f(t)* is sampled at regular intervals of time and at a rate higher than twice the highest signal frequency, then the samples contain all the information of the original signal. The function *f(t)* may be reconstructed from these samples by the use of a lowpass filter.”
- Pulse Amplitude Modulation (PAM)
  - Analog samples
  - To convert to digital, each of these analog samples must be assigned a binary code



PAM value	1.1	9.2	15.2	10.8	5.6	2.8	2.7
quantized code number	1	9	15	10	5	2	2
PCM code	0001	1001	1111	1010	0101	0010	0010

Figure 5.17 Pulse-Code Modulation Example

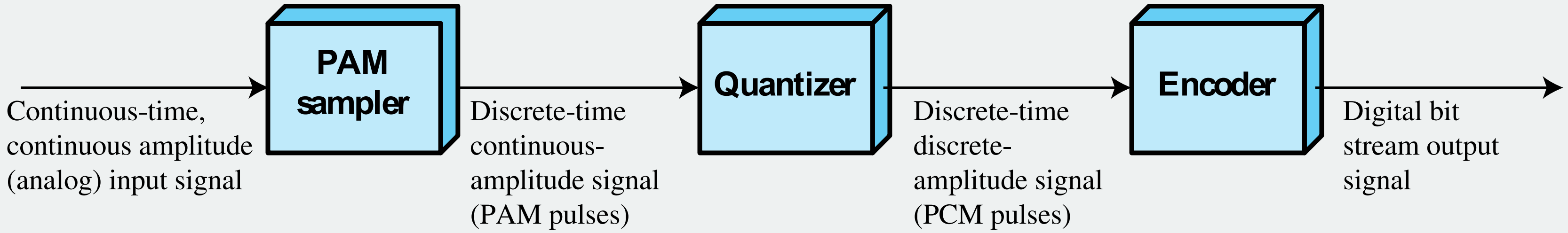


Figure 5.18 PCM Block Diagram

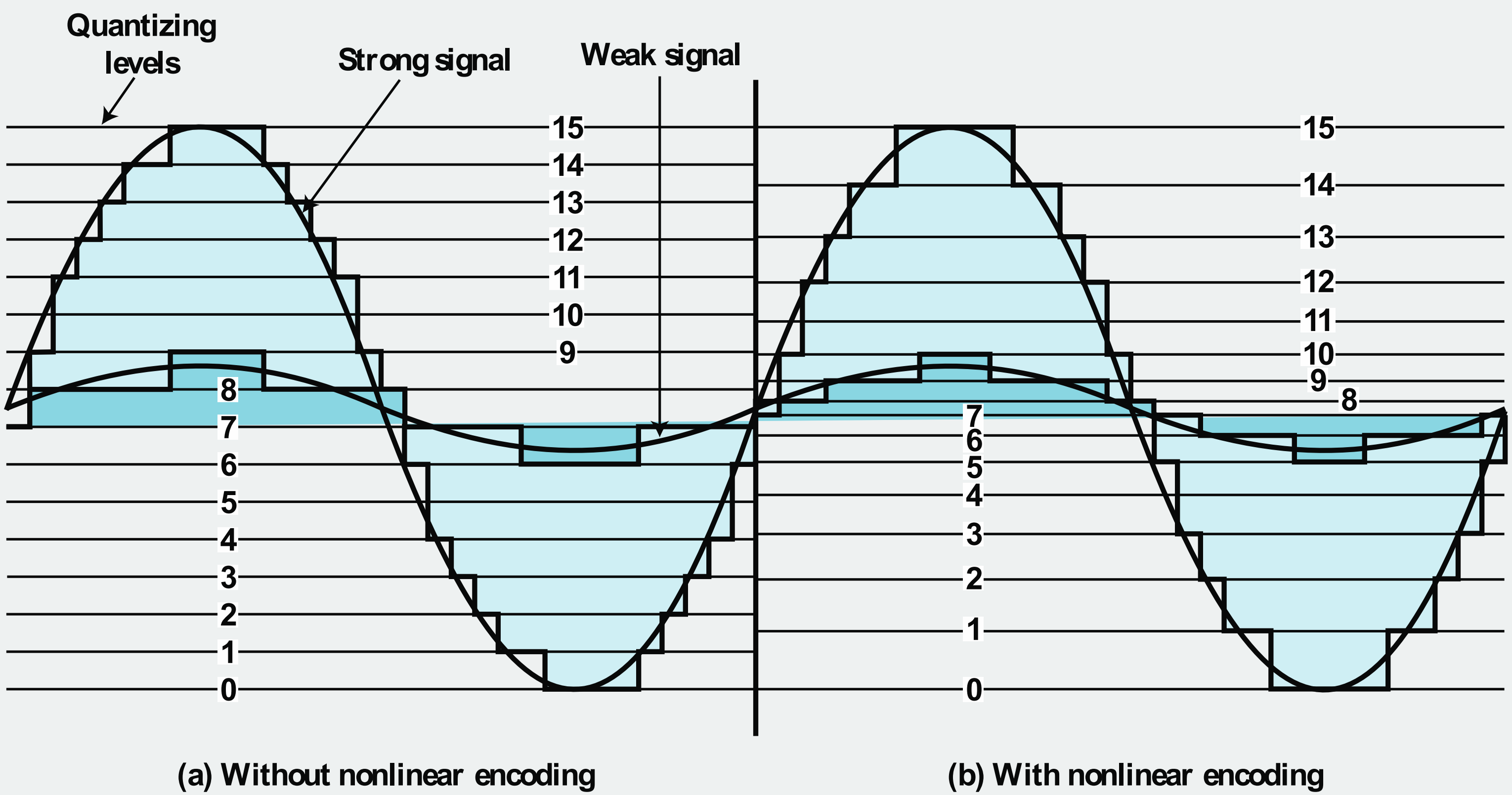


Figure 5.19 Effect of Nonlinear Coding

Delta Modulation (DM)

- Analog input is approximated by a staircase function
  - Can move up or down one quantization level (δ) at each sampling interval
- Has binary behavior
  - Function only moves up or down at each sampling interval
  - Output of the delta modulation process can be represented as a single binary digit for each sample
  - 1 is generated if the staircase function is to go up during the next interval, otherwise a 0 is generated

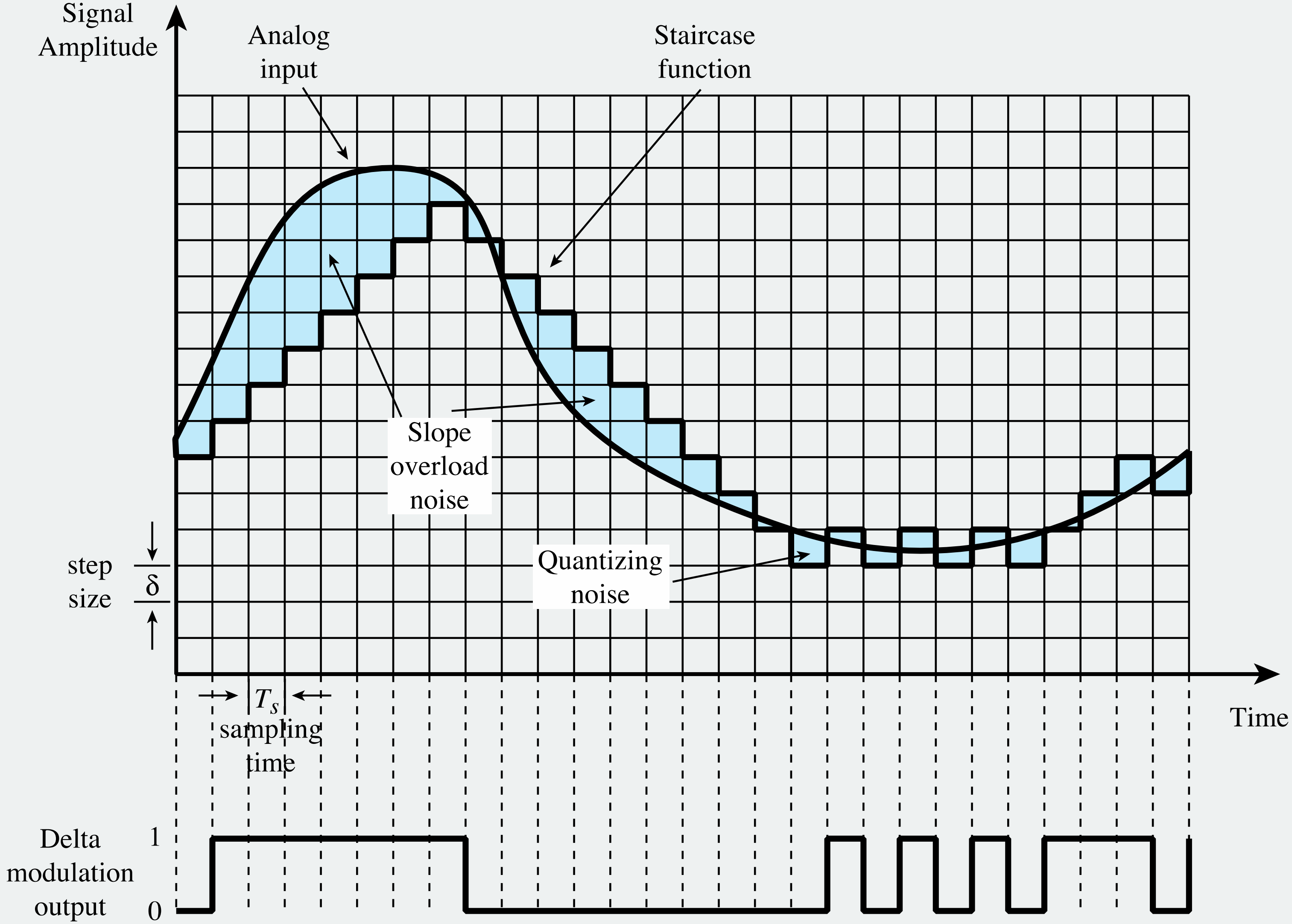


Figure 5.21 Example of Delta Modulation

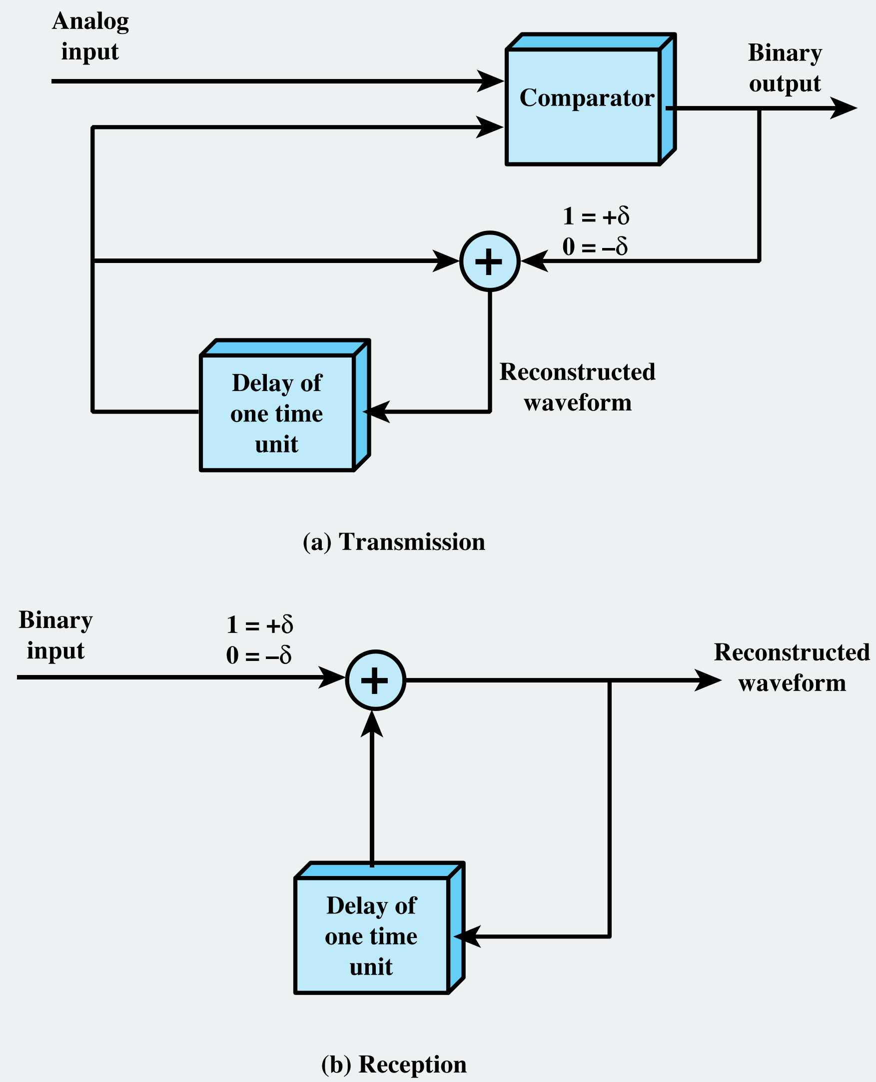


Figure 5.22 Delta Modulation

Summary

- Digital data, digital signals
  - Nonreturn to zero (NRZ)
  - Multilevel binary
  - Biphase
  - Modulation rate
  - Scrambling techniques
- Analog data, digital signals
  - Pulse code modulation
  - Delta modulation (DM)
  - Performance
- Digital data, analog signals
  - Amplitude shift keying
  - Frequency shift keying
  - Phase shift keying
  - Performance
  - Quadrature amplitude modulation