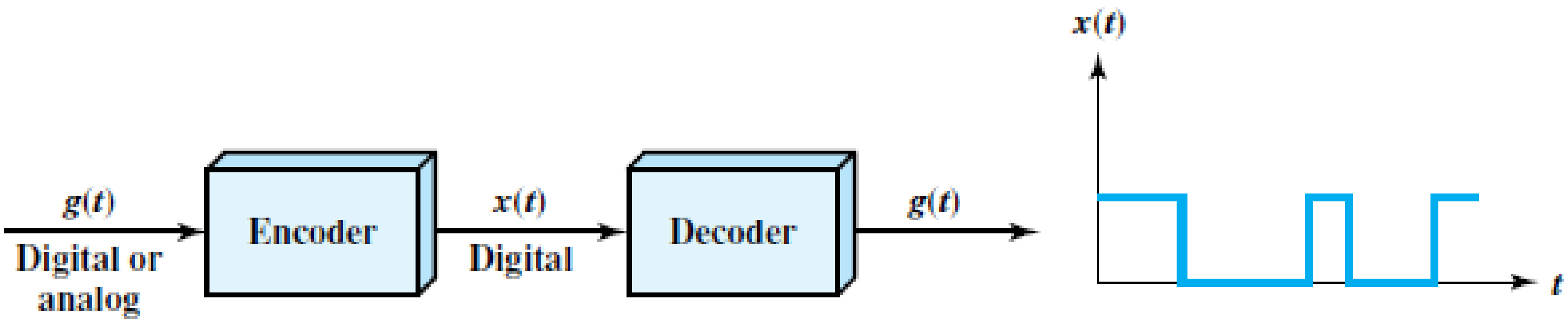
K. N. Toosi
University of Technology

Computer Networks 1

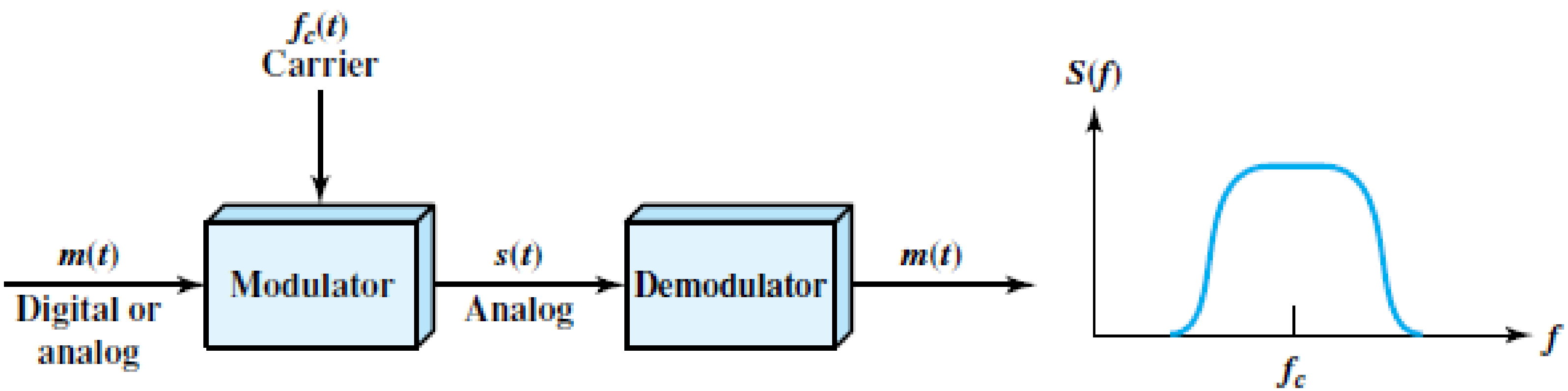
ENCODING AND MODULATION

Fatemeh Rezaei

ENCODING AND MODULATION TECHNIQUES



(a) Encoding onto a digital signal



(b) Modulation onto an analog signal

OUTLINE

- Digital Data, Digital Signals
- Digital Data, Analog Signals
- Analog Data, Digital Signals
- Analog Data, Analog Signals

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

KEY DATA TRANSMISSION TERMS

- **Unipolar signaling**
  - Signal elements all have the same algebraic sign
  - All positive or negative
- **Polar signaling**
  - One logic state is represented by a positive voltage level
  - The other by a negative voltage level
- **Mark**
  - Binary digits 1
- **Space**
  - Binary digits 0

DIGITAL DATA, DIGITAL SIGNAL

DIGITAL DATA, DIGITAL SIGNAL

- The simplest form
  - Assigning one voltage level to binary one and another to binary zero
- More complex encoding schemes
  - Using to improve performance

EVALUATING FACTORS OF ENCODING TECHNIQUES

- Signal spectrum
- Clocking
- Error detection
- Signal interference and noise immunity
- Cost and complexity

SIGNAL SPECTRUM

- Codes can be designed with the aim of shaping the spectrum of the transmitted signal
- Lack of high-frequency components
  - Less bandwidth is required for transmission
- lack of a direct-current (dc) component
  - AC coupling via transformer is possible
  - Providing excellent electrical isolation
  - Reducing interference

SIGNAL SPECTRUM

- The magnitude of the effects of signal distortion and interference depend on the spectral properties of the transmitted signal.
- Transmission characteristics of a channel are worse near the band edges
  - A good signal design should concentrate the transmitted power in the middle of the transmission bandwidth.
  - Smaller distortion in the received signal

EVALUATING FACTORS OF ENCODING TECHNIQUES

- Clocking
  - Need to determine the beginning and end of each bit position
  - Providing some synchronization mechanism in the transmitted signal by suitable encoding
- Error detection
  - having some error detection capability built into the physical signaling encoding scheme
  - Permitting errors to be detected more quickly

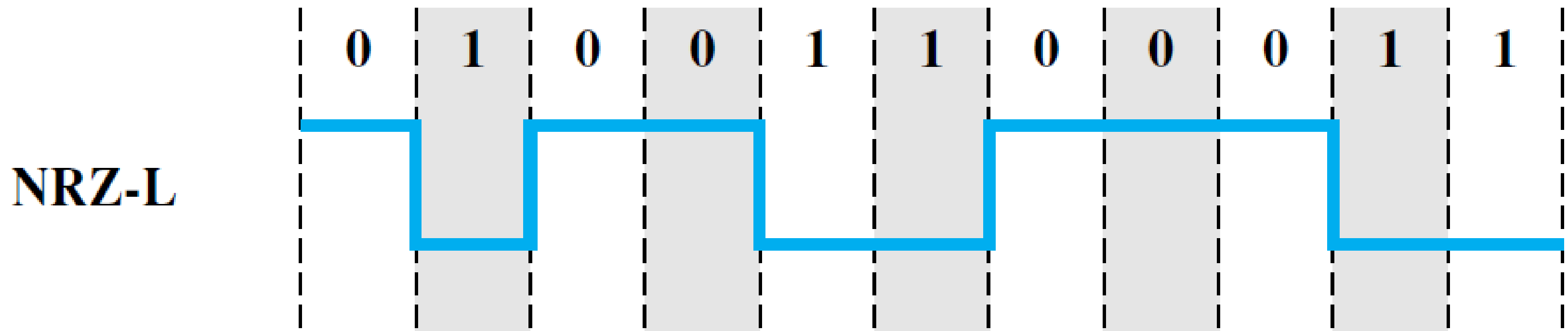
EVALUATING FACTORS OF ENCODING TECHNIQUES

- Signal interference and noise immunity
  - Certain codes exhibit superior performance in the presence of noise.
  - Performance is usually expressed in terms of a BER
- Cost and complexity
  - The higher the signaling rate to achieve a given data rate, the greater the cost
  - Some codes require a signaling rate that is greater than the actual data rate

Nonreturn to Zero-Level (NRZ-L)

0 = high level

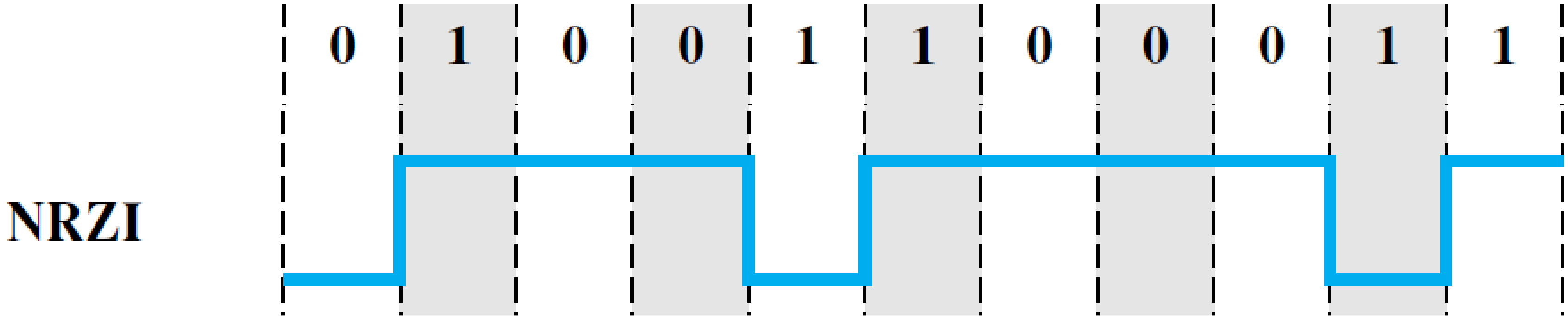
1 = low level



Nonreturn to Zero Inverted (NRZI)

0 = no transition at beginning of interval (one bit time)

1 = transition at beginning of interval



DIFFERENTIAL ENCODING

- Information is represented in terms of the changes between successive signal elements rather than the signal elements themselves
- More reliable to detect a transition in the presence of noise than to compare a value to a threshold
- It is easy to lose the sense of the polarity of the signal
  - Accidentally all 1s and 0s for NRZ-L will be inverted
  - Not happening with differential encoding

K. N. Toosi
University of Technology

NRZ CODES

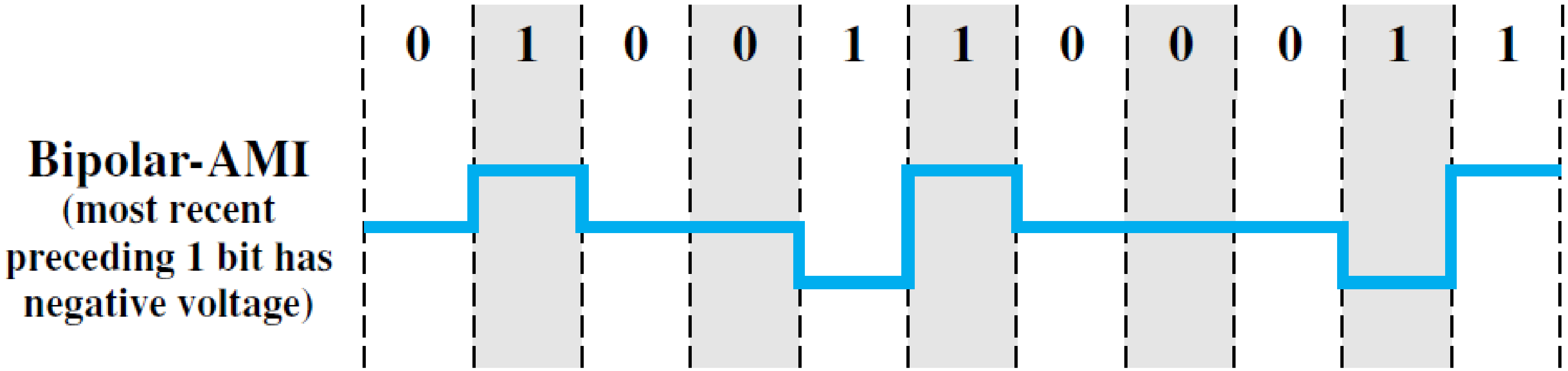
+	-
Used for digital magnetic recording	Unattractive for signal transmission applications
Make efficient use of bandwidth	Lack of synchronization capability
Easiest to engineer	Presence of a dc component

MULTILEVEL BINARY CODES

Bipolar-AMI (Alternate Mark Inversion)

0 = no line signal

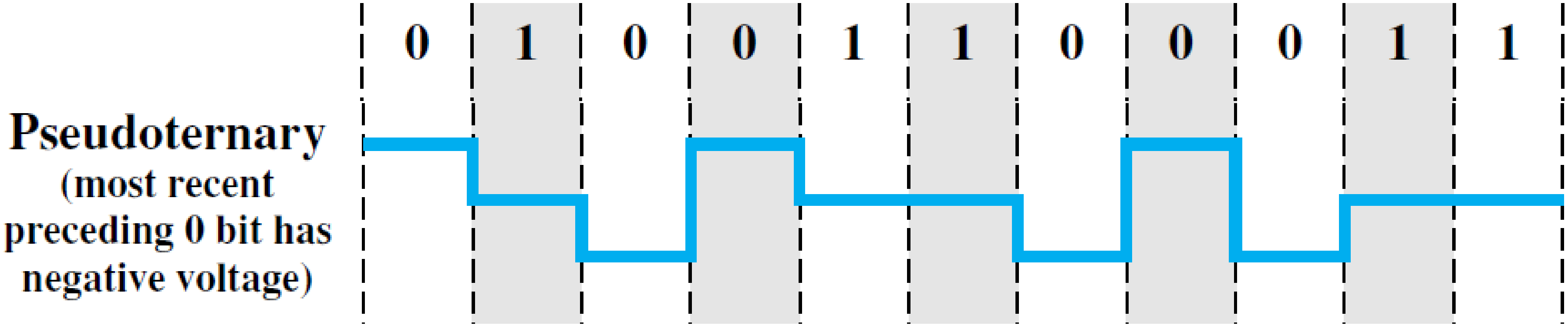
1 = positive or negative level, alternating for successive ones



Pseudoternary

0 = positive or negative level, alternating for successive zeros

1 = no line signal



MULTILEVEL BINARY ADVANTAGES

- No loss of synchronization if a long string of 1s occurs
  - (A long string of 0s would still be a problem)
- No net dc component
  - Because the 1 signals alternate in voltage from positive to negative
- The bandwidth is less than the bandwidth for NRZ
- Simple means of error detection
  - Because of the pulse alternation property
  - Any isolated error causes a violation of this property

MULTILEVEL BINARY DISADVANTAGES

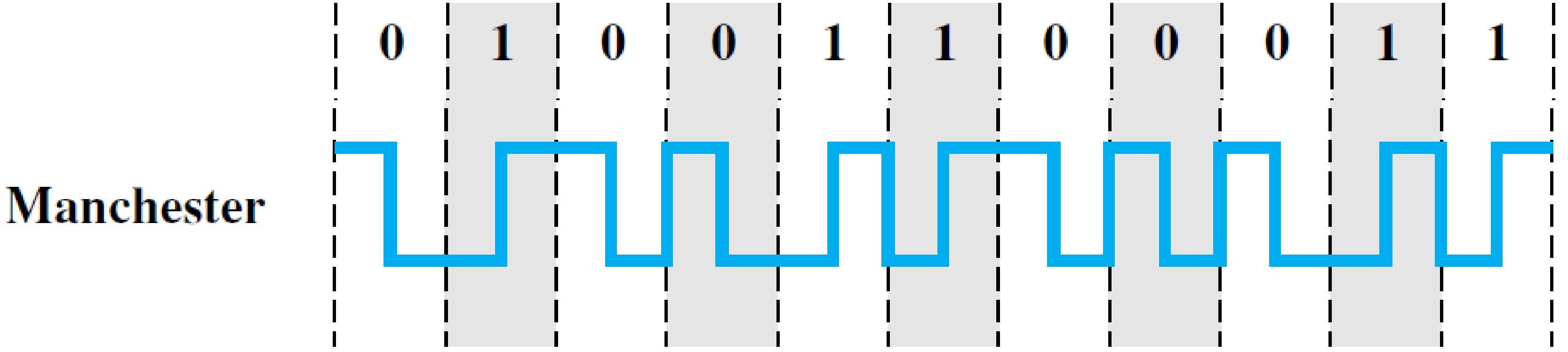
- The line signal may take on one of 3 levels
  - Each signal element, which could represent $log_2 3 = 1.58$ bits of information, bears only one bit of information.
  - Not as efficient as NRZ coding
- Receiver has to distinguish between 3 levels instead of just 2 levels
  - Requires approximately 3 dB more signal power for the same BER
- BER for NRZ codes, at a given SNR, is significantly less than that for multilevel binary

BIPHASE CODES

Manchester

0 = transition from high to low in middle of interval

1 = transition from low to high in middle of interval



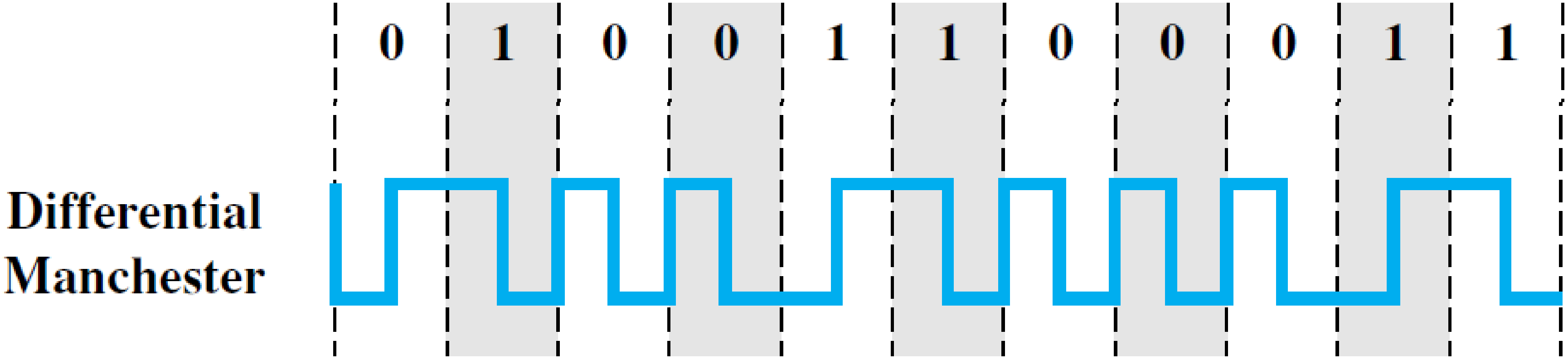
IEEE 802.3 (Ethernet) standard
for baseband coaxial cable and twisted-pair bus LANs

Differential Manchester

Always a transition in middle of interval

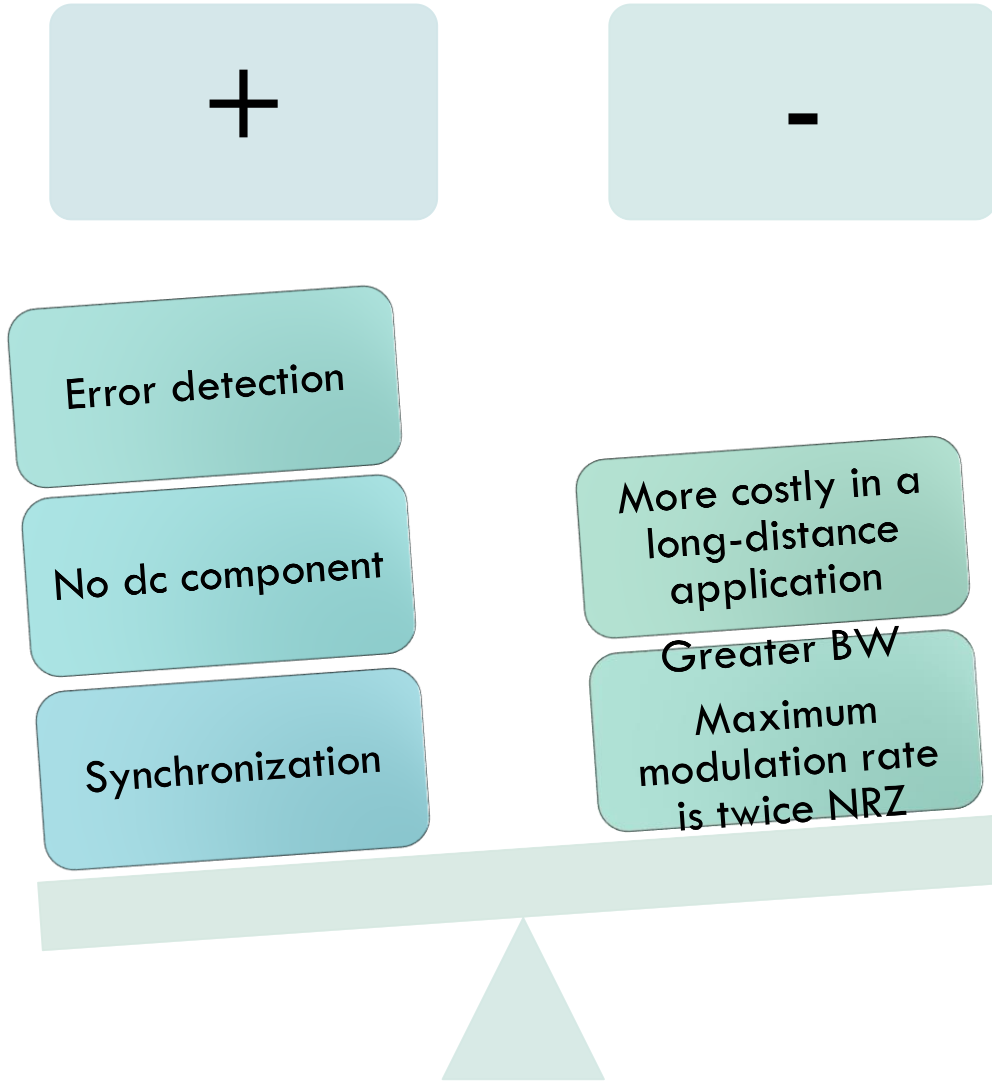
0 = transition at beginning of interval

1 = no transition at beginning of interval



IEEE 802.5 token ring LAN
using shielded twisted pair

BIPHASE CODES



SCRAMBLING TECHNIQUES

B8ZS

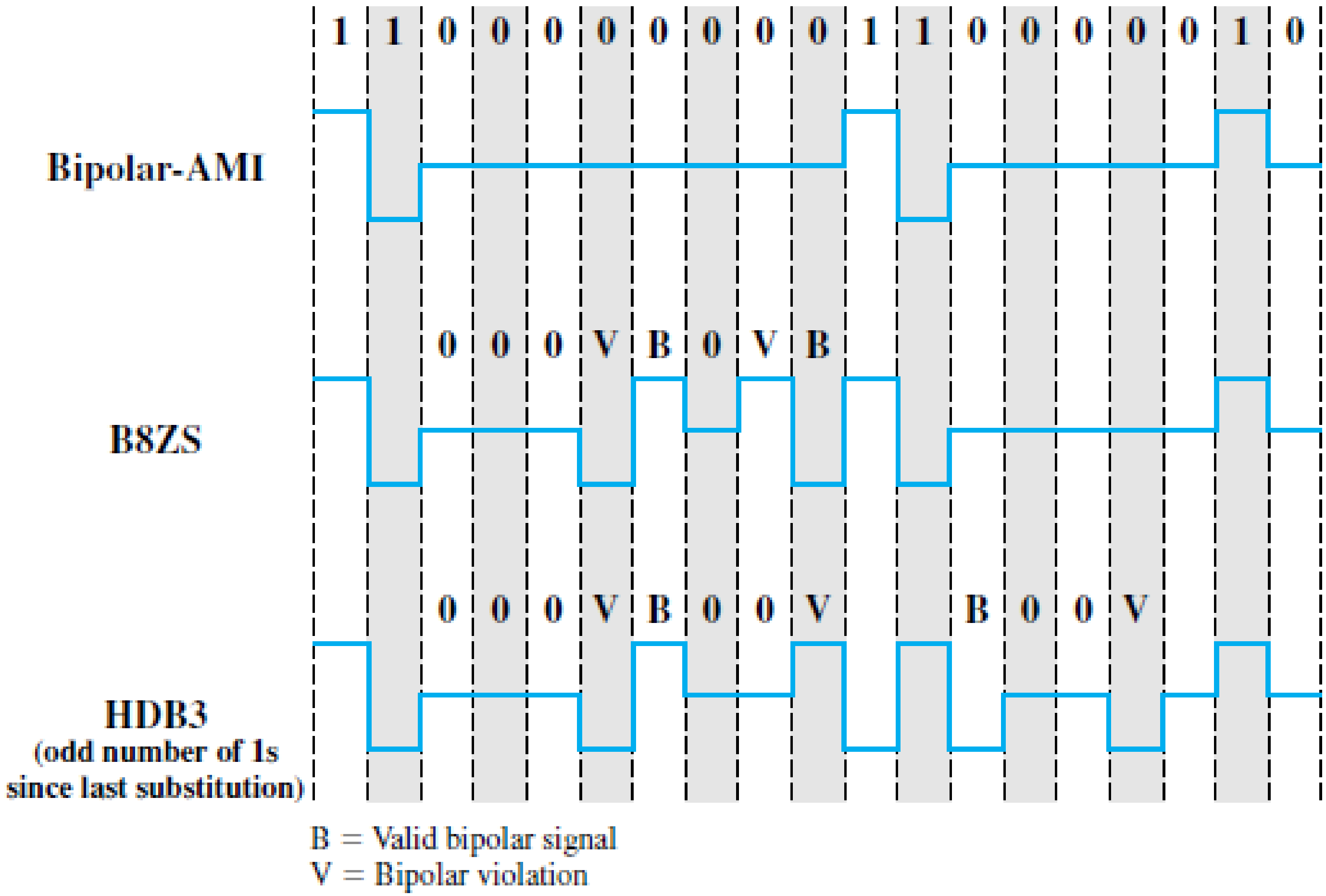
- **Bipolar with 8-Zeros Substitution**
- Same as bipolar AMI, except that any string of 8 zeros is replaced by a string with 2 code violations
- If an octet of all zeros occurs and the **last voltage** pulse preceding this octet was **positive**
  - The eight zeros are encoded as 000+-0-+
- If an octet of all zeros occurs and the **last voltage** pulse preceding this octet was **negative**
  - The eight zeros are encoded as 000-+0+-

HDB3

- High-Density Bipolar-3 zeros
- Same as bipolar AMI, except that any string of 4 zeros is replaced by a string with one code violation

	Number of Bipolar Pulses (ones) since Last Substitution	
Polarity of Preceding Pulse	Odd	Even
–	0 0 0 –	+ 0 0 +
+	0 0 0 +	– 0 0 –

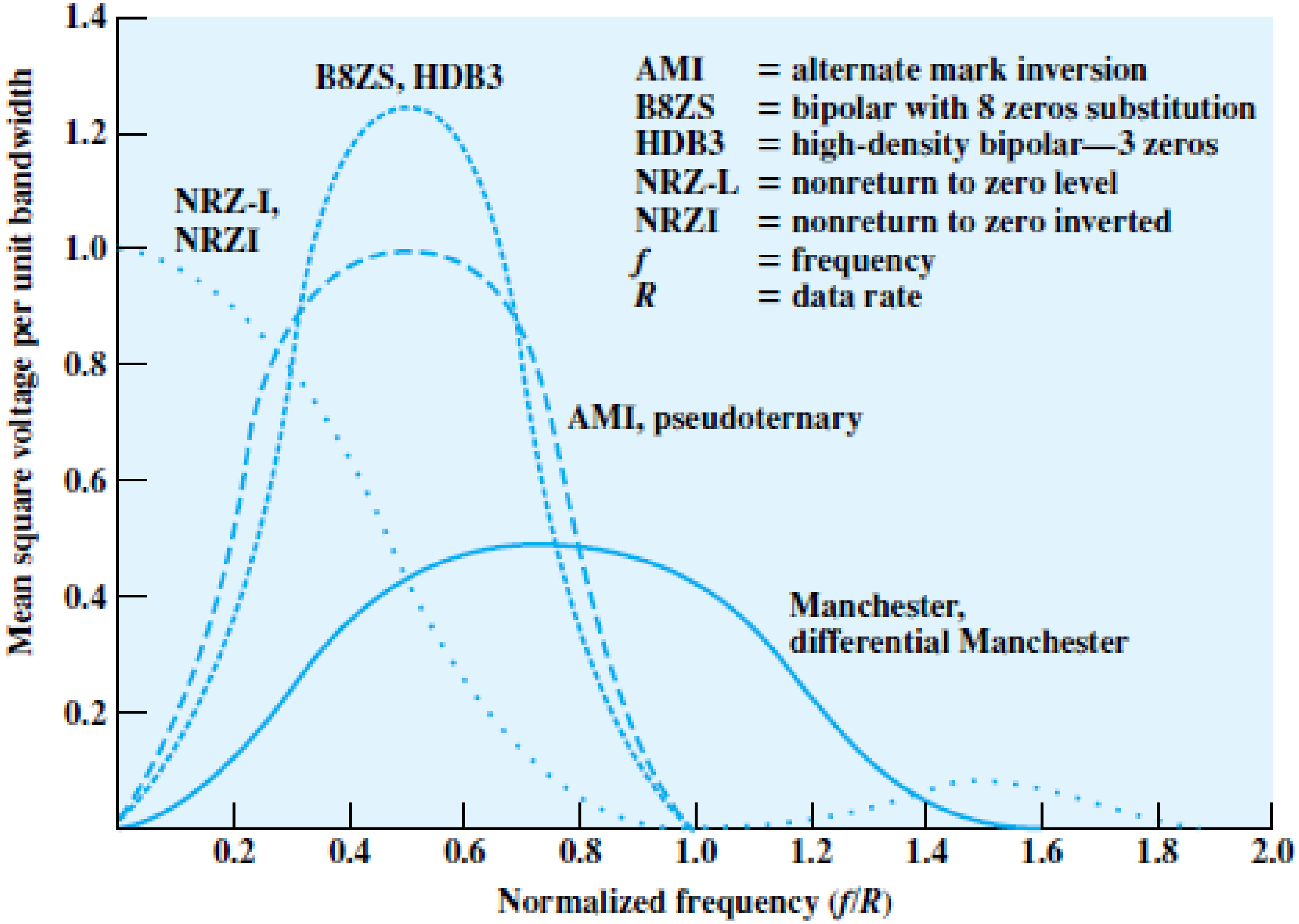
ENCODING RULES FOR B8ZS AND HDB3



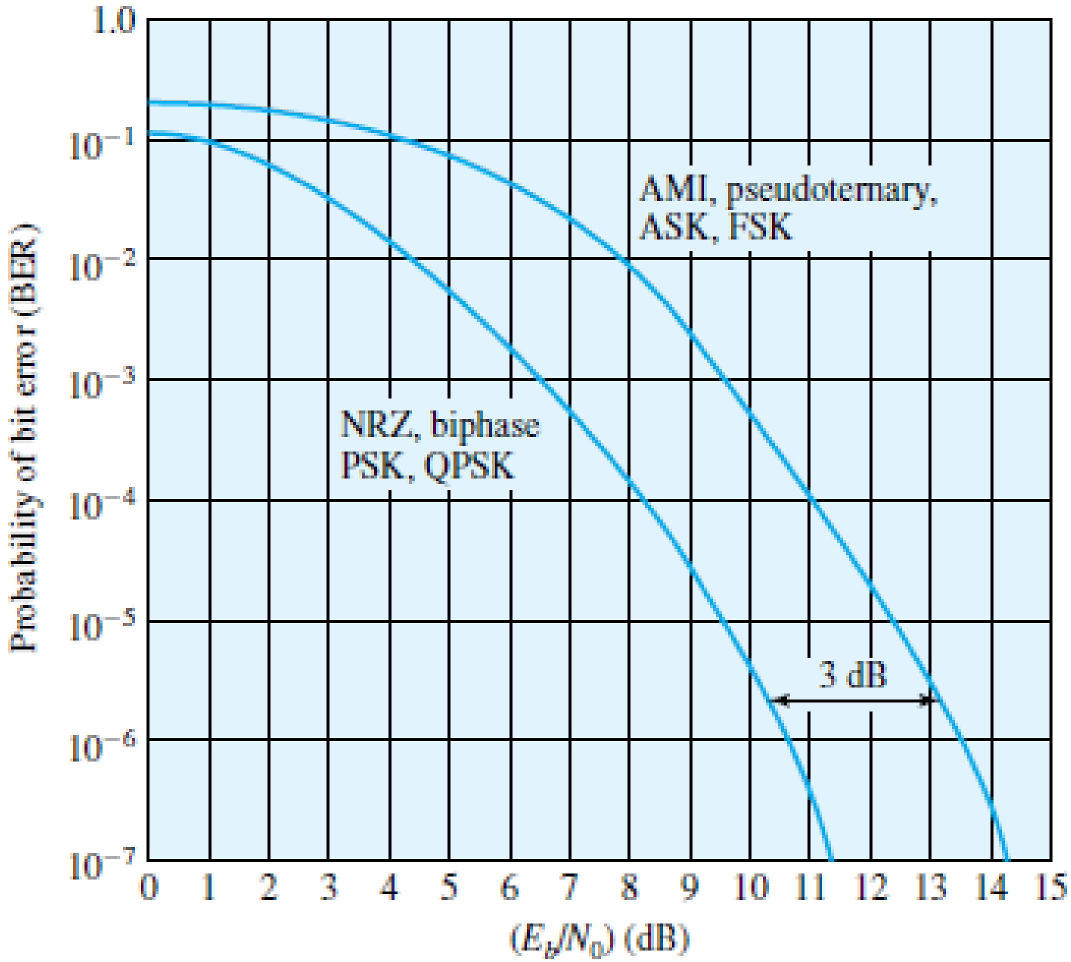
DESIGN GOALS FOR SCRAMBLING TECHNIQUES

- No dc component
- No long sequences of zero-level line signals
- No reduction in data rate
- Error-detection capability

SPECTRAL DENSITY OF VARIOUS SIGNAL ENCODING SCHEMES



THEORETICAL BIT ERROR RATE FOR VARIOUS ENCODING SCHEMES



MODULATION RATE

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

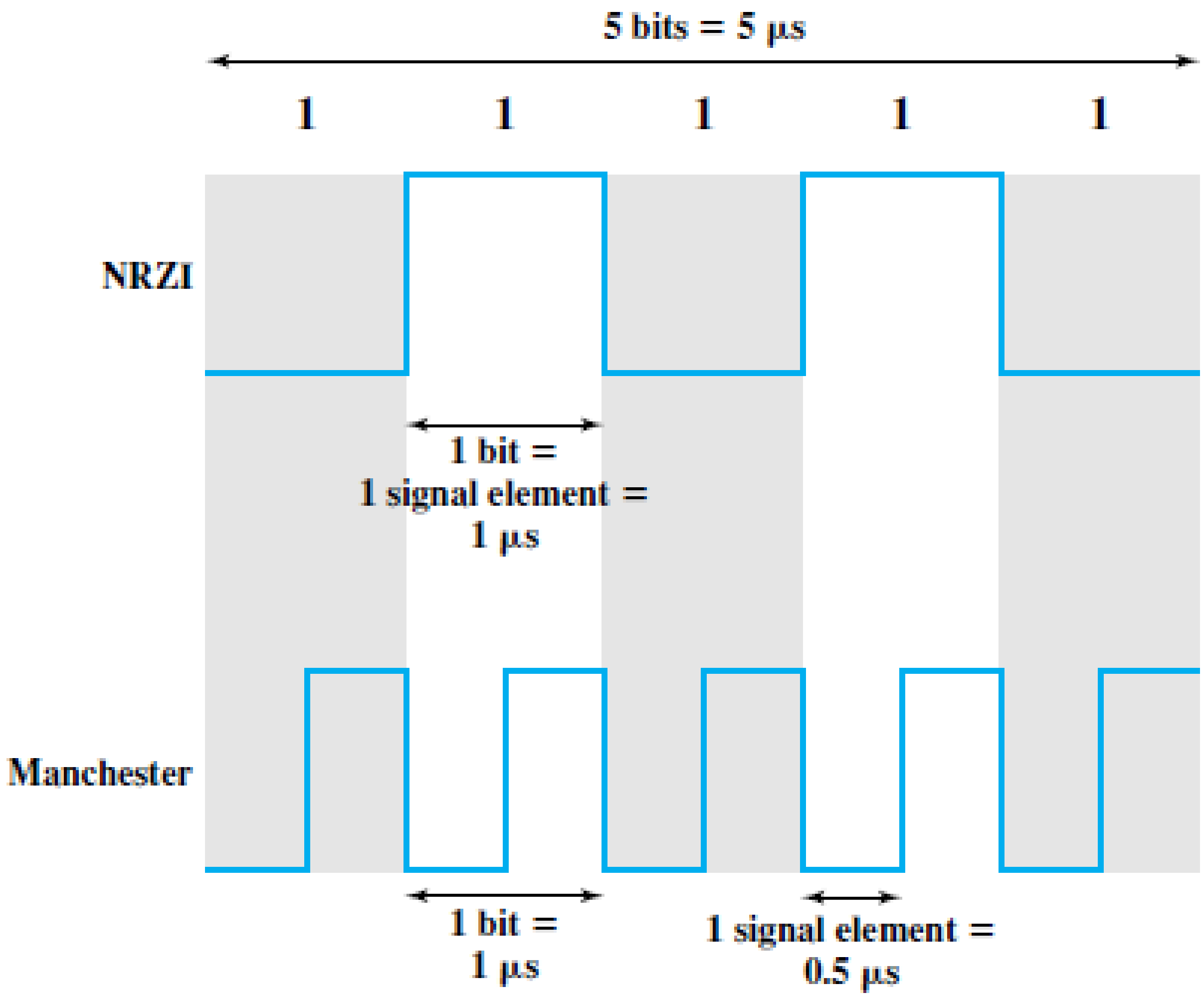
D = modulation rate, baud

R = data rate, bps

M = number of different signal elements $= 2^L$

L = number of bits per signal element

A STREAM OF BINARY ONES AT 1 MBPS



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)

DIGITAL DATA, ANALOG SIGNAL

ANALOG SIGNALING

- Carrier signal
  - A continuous constant-frequency signal
  - Its frequency is chosen to be compatible with the transmission medium
- Modulation
  - Process of encoding source data onto a carrier signal with frequency f_c

DIGITAL DATA, ANALOG SIGNAL

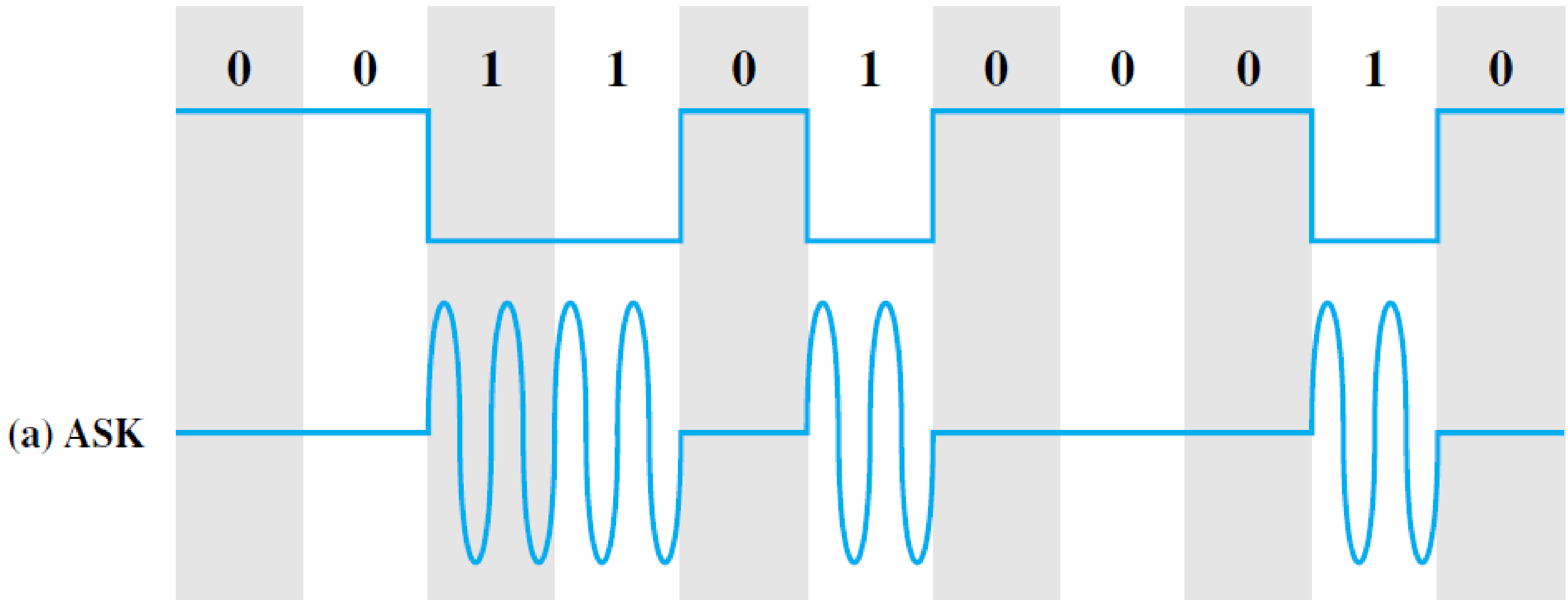
- A modem converts digital data to an analog signal
- To be transmitted over an analog line
- Altering one or more characteristics of a carrier signal to represent binary data

Basic techniques

- Amplitude shift keying (ASK)
- Frequency shift keying (FSK)
- Phase shift keying (PSK)

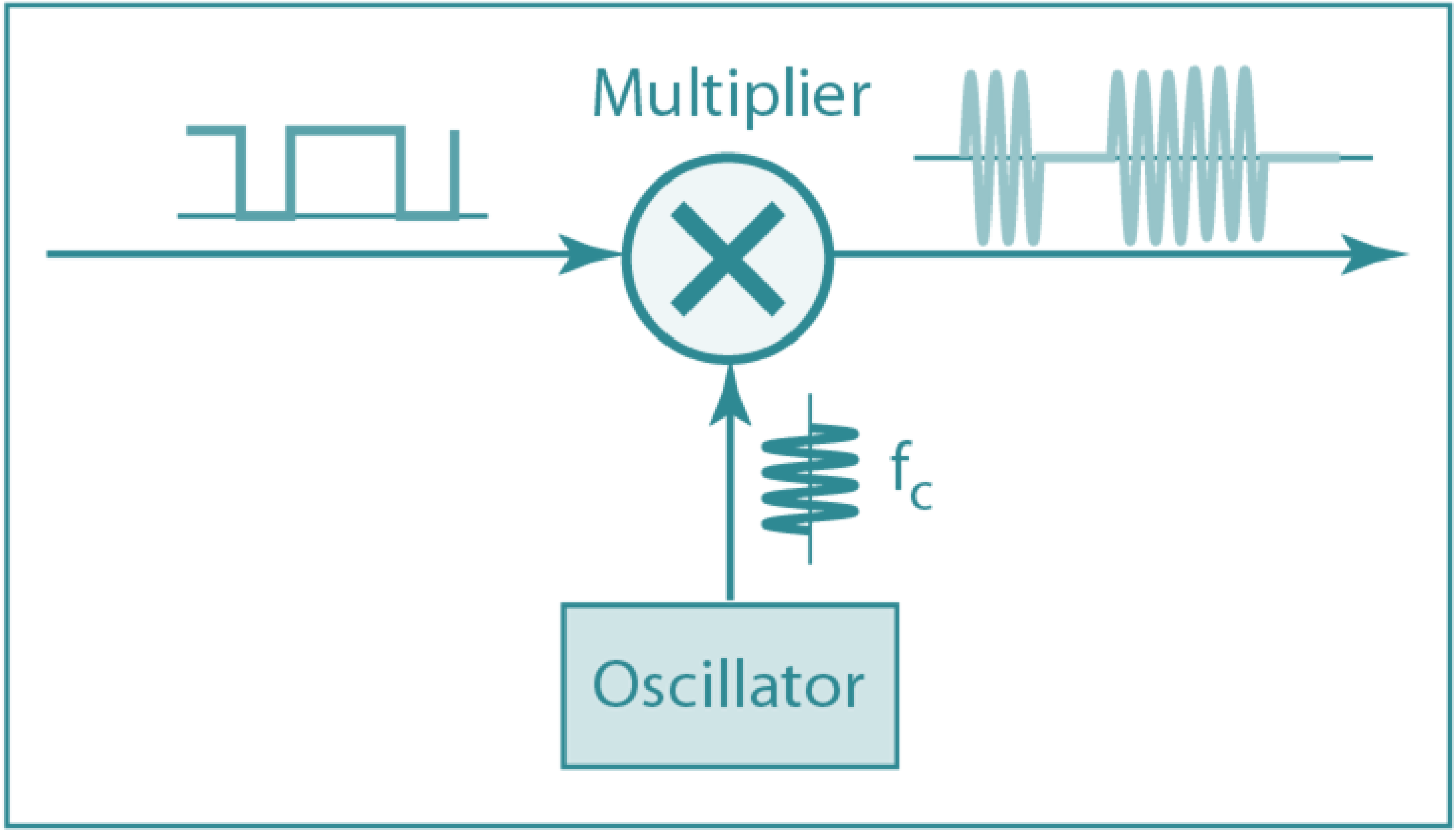
AMPLITUDE SHIFT KEYING (ASK)

AMPLITUDE SHIFT KEYING (ASK)



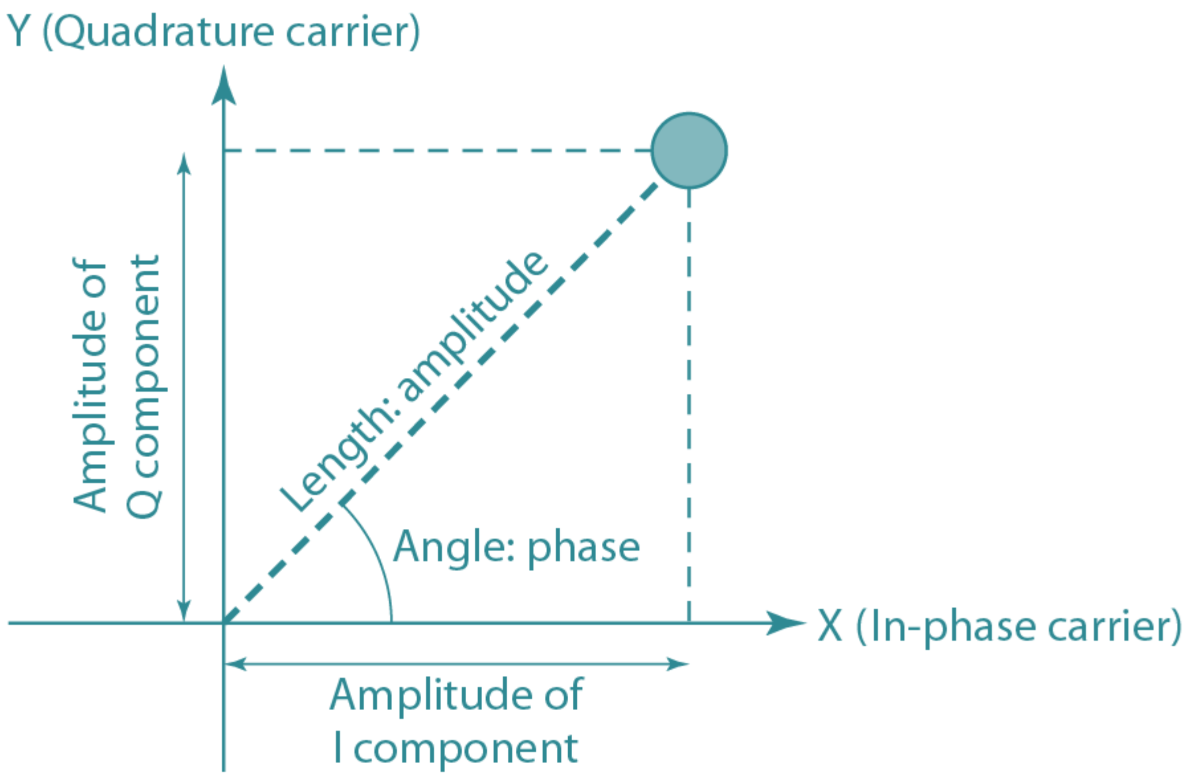
$$s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ 0 & \text{binary } 0 \end{cases}$$

IMPLEMENTATION OF BINARY ASK



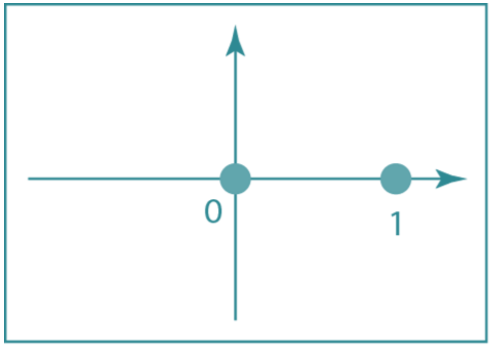
CONSTELLATION DIAGRAM

- Helps define the amplitude and phase of a signal element



ASK

- BASK: Simplest form → On-Off Keying (OOK)



- Values represented by different amplitudes of the carrier sine wave
- Susceptible to noise and sudden changes in gain
- Up to 1200bps on voice grade lines
- Used over optical fiber

FREQUENCY SHIFT KEYING (FSK)

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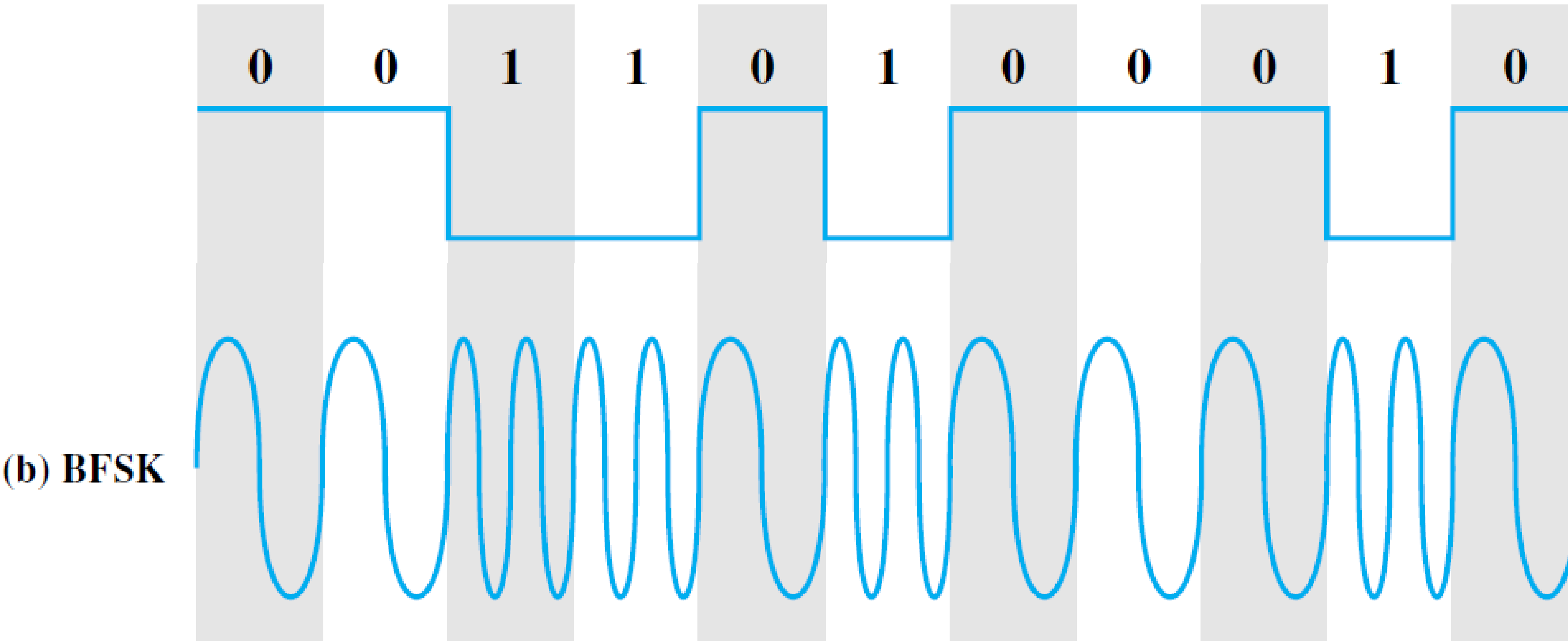
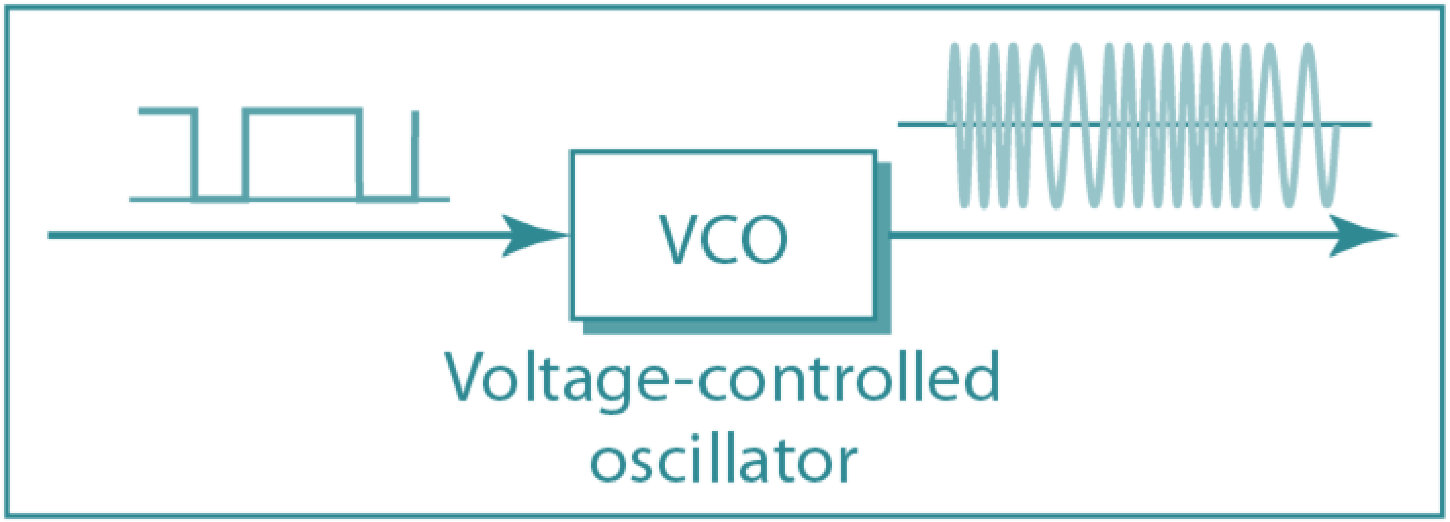


$$s(t) = \begin{cases} A\cos(2\pi f_1 t) & \text{binary 1} \\ A\cos(2\pi f_2 t) & \text{binary 0} \end{cases}$$

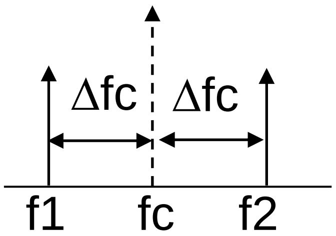
IMPLEMENTATION OF BINARY FSK



FREQUENCY SHIFT KEYING (FSK)

- Most common form: binary FSK (BFSK)
- The two binary data values represented by two different frequencies

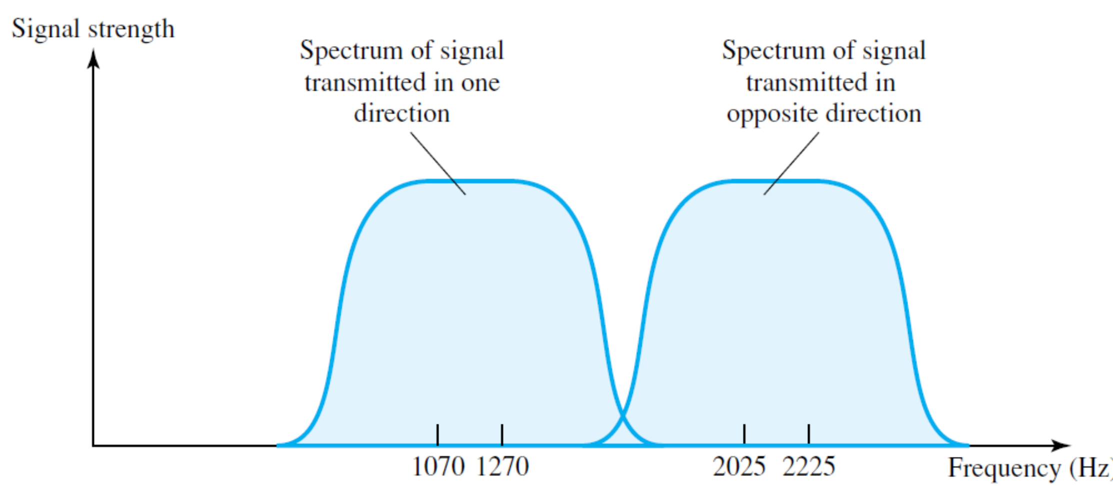
$$s(t) = \begin{cases} A\cos(2\pi f_1 t) & \text{binary } 0 \\ A\cos(2\pi f_2 t) & \text{binary } 1 \end{cases}$$



- Less susceptible to noise than ASK
  - Frequency can be detected correctly in the presence of noise better than amplitude
- Applications
  - Up to 1200bps on voice grade lines
  - Used at High frequency radio (3-30 MHz)
  - Higher frequencies on LANs using coaxial cables

FULL-DUPLEX FSK TRANSMISSION ON A VOICE-GRADE LINE

- Direction A: carrier centered on 1170 Hz
  - e.g. 1070 Hz represent 1
  - 1270 Hz represent 0
- Direction B: carrier centered on 2125 Hz
  - e.g. 2025 Hz represent 1
  - 2225 Hz represent 0



MULTIPLE FSK (MFSK)

- To improve BW utilization (efficiency)
- More than two frequencies used
- More susceptible to error
- An example of multi-level coding (M levels)
- Each signaling element conveys more than one bit (L bits, $L = log_2 M$)

MULTIPLE FSK (MFSK)

- The transmitted MFSK signal for one signal element time:

$$\textbf{MFSK} \qquad s_i(t) = A\cos 2\pi f_i t, \qquad 1 \le i \le M$$

$$f_i = f_c + (2i - 1 - M)f_d$$

f_c = the carrier frequency

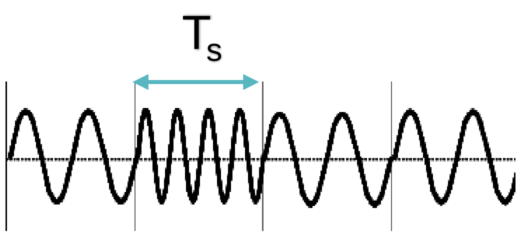
f_d = the difference frequency

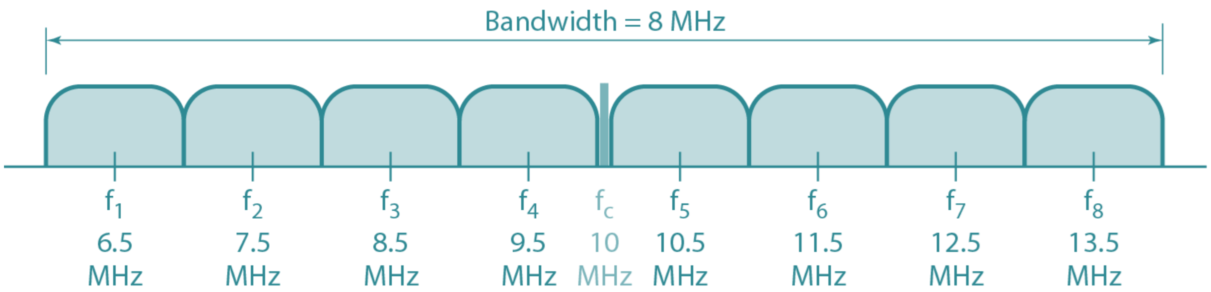
M = number of different signal elements $= 2^L$

L = number of bits per signal element

MULTIPLE FSK (MFSK)

- T =bit period (data rate =1/T)
- A signal element, a constant-frequency tone, encodes L bits
- T_s=LT output signal element period
- The minimum frequency separation required: $2f_d = 1/T_s$
- The total bandwidth required : $W_d = 2Mf_d$
- Max signaling rate D = 1/T_s = 2f_d
- Max data rate R = D L = 2f_d L





MFSK EXAMPLE

EXAMPLE With $f_c = 250$ kHz, $f_d = 25$ kHz, and $M = 8$ ($L = 3$ bits), we have the following frequency assignments for each of the eight possible 3-bit data combinations:

$$\begin{array}{llll} f_1 = 75\text{ kHz} & 000 & f_2 = 125\text{ kHz} & 001 \\ f_3 = 175\text{ kHz} & 010 & f_4 = 225\text{ kHz} & 011 \\ f_5 = 275\text{ kHz} & 100 & f_6 = 325\text{ kHz} & 101 \\ f_7 = 375\text{ kHz} & 110 & f_8 = 425\text{ kHz} & 111 \end{array}$$

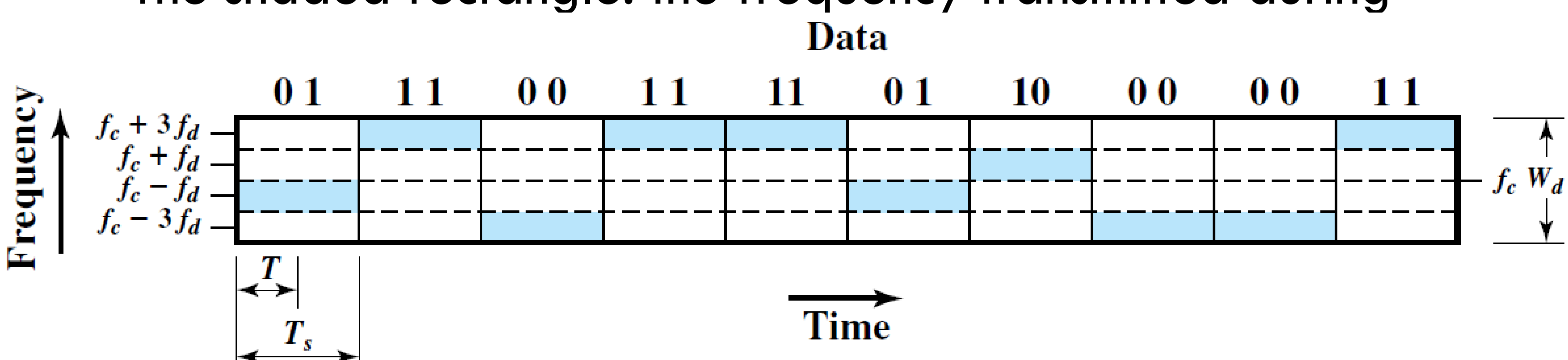
This scheme can support a data rate of $1/T = 2Lf_d = 150$ kbps.

4-FSK EXAMPLE

M = 4

L = Log_2 (M) = 2

- 20 bits is encoded 2 bits at a time
- Each of the four possible 2-bit combinations transmitted as a different frequency
- Frequency transmitted (*y*-axis) as a function of time (*x*-axis)
- Columns: a time unit in which a single 2-bit signal element is transmitted
- The shaded rectangle: the frequency transmitted during



PHASE SHIFT KEYING (PSK)

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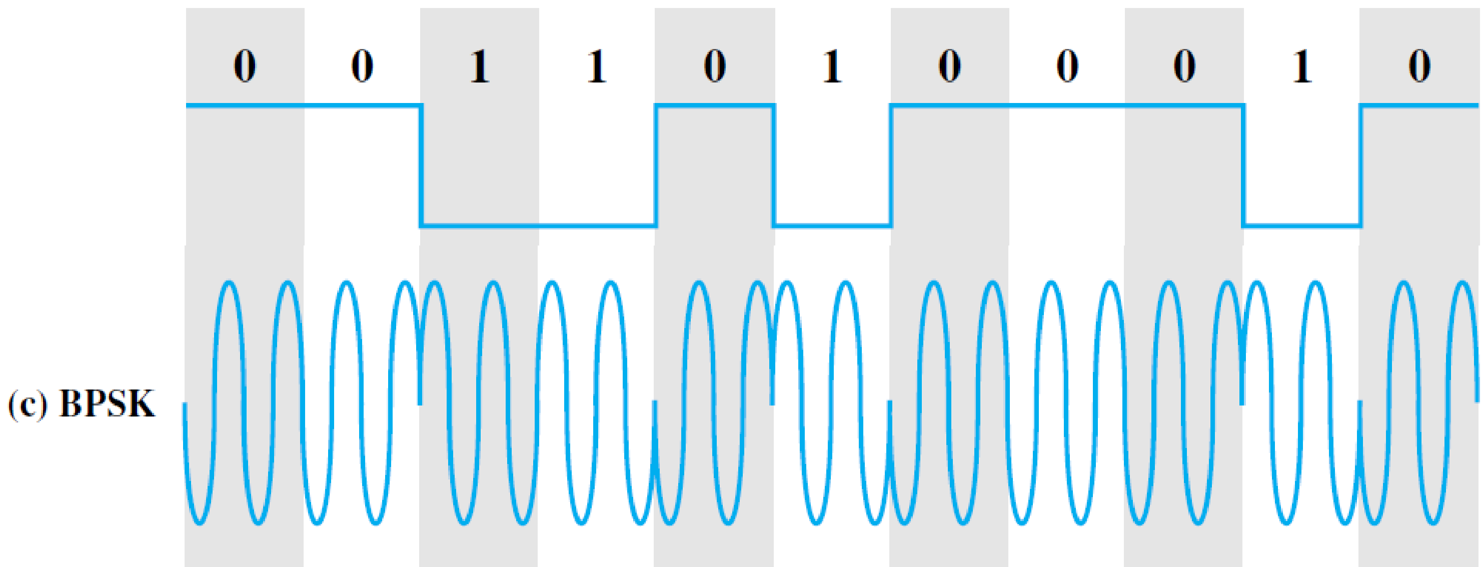
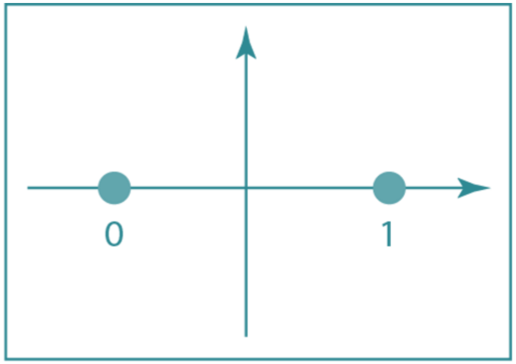


BPSK

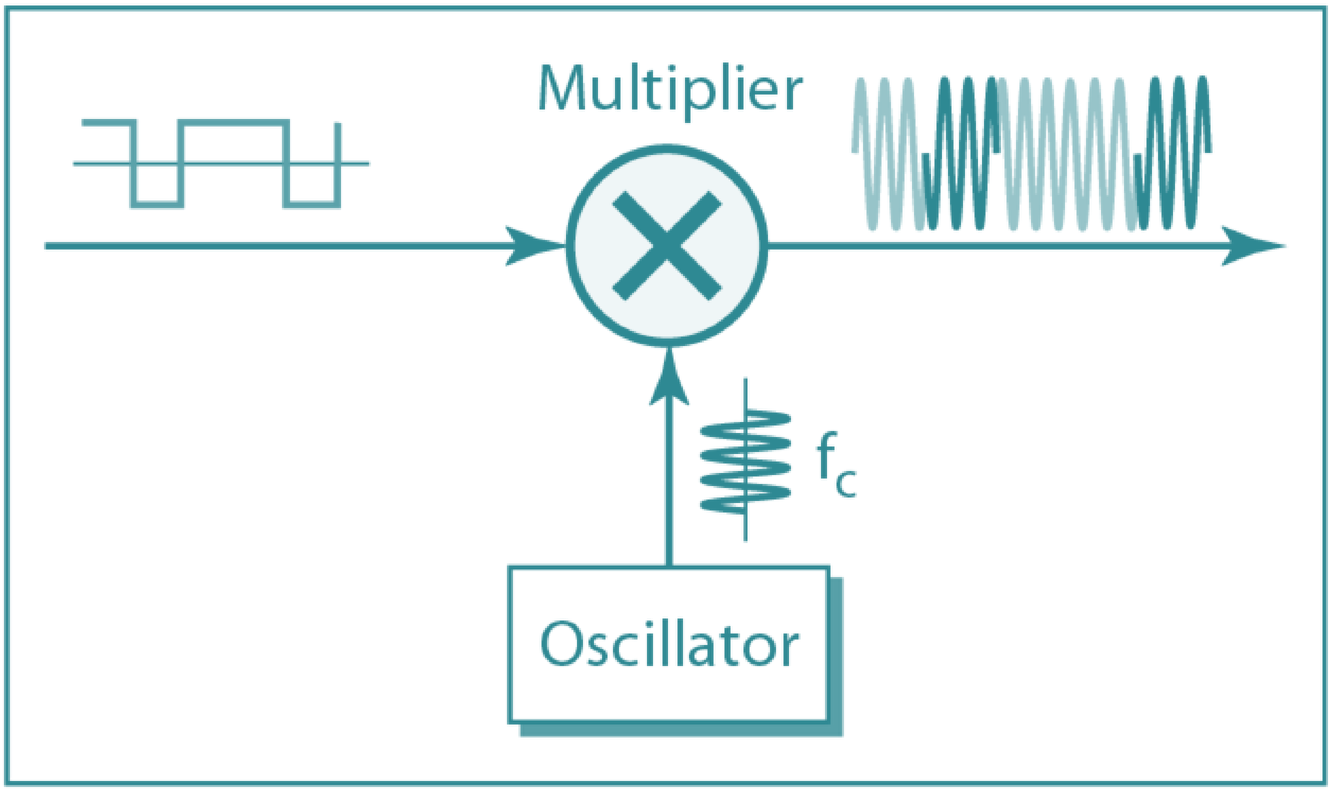
$$s(t) = \begin{cases} A\cos(2\pi f_c t) \\ A\cos(2\pi f_c t + \pi) \end{cases} = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ -A\cos(2\pi f_c t) & \text{binary } 0 \end{cases}$$

$$s_d(t) = A\, d(t)\cos(2\pi f_c t)$$

d(t) = +1 for '1' data and -1 for '0' data



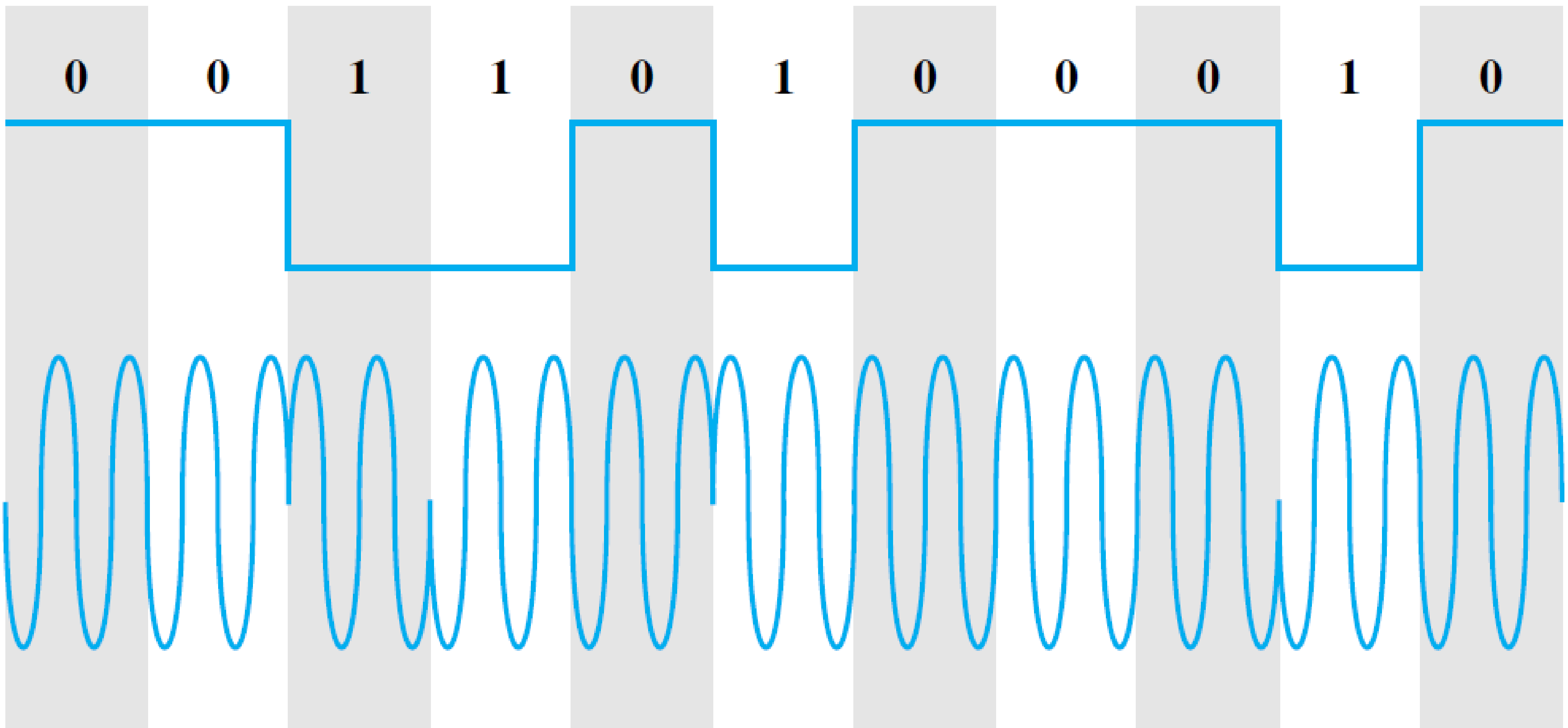
IMPLEMENTATION OF BINARY PSK



DIFFERENTIAL PHASE SHIFT KEYING (DPSK)

- Phase shifted relative to the previous signal element, rather than some reference signal
- 0: Do not reverse phase
- 1: Reverse phase (as with NRZI, invert on 1)
- Advantage:
  - No need for a reference oscillator at RX to determine absolute phase

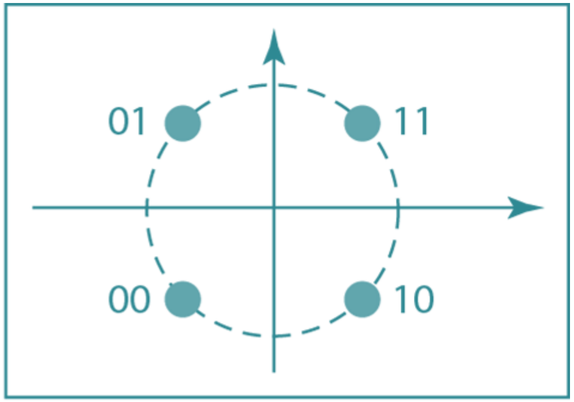
DIFFERENTIAL PHASE SHIFT KEYING (DPSK)



FOUR-LEVEL PSK (QPSK)

- 4 different phases spaced at π/2 (90°)

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



$$
\cos(2\pi f_c t + n\frac{\pi}{4}) = \pm\frac{1}{\sqrt{2}}\cos(2\pi f_c t) \mp \frac{1}{\sqrt{2}}\sin(2\pi f_c t)
$$

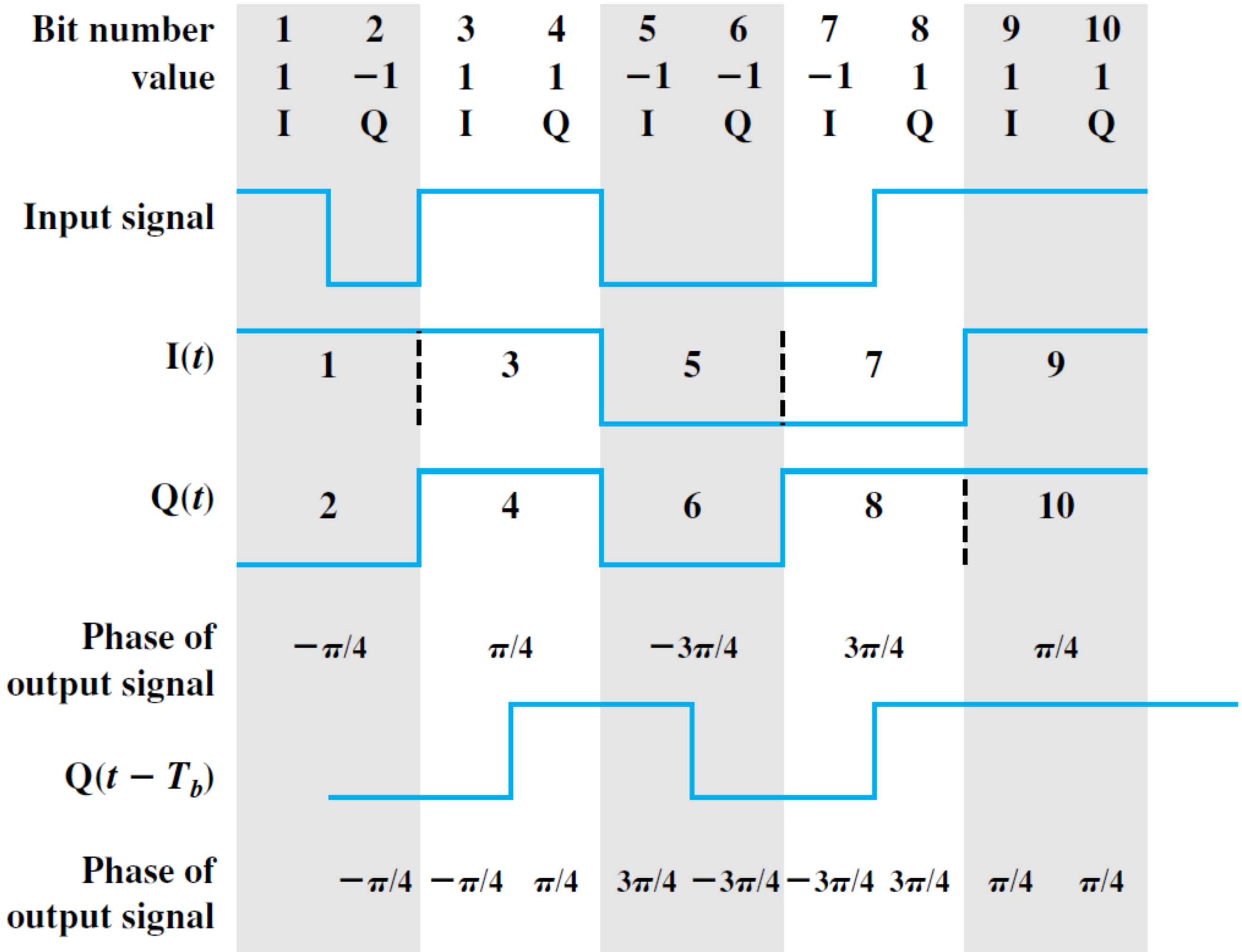
$$
s(t) = \mathrm{I}(t)\frac{1}{\sqrt{2}}\cos(2\pi f_c t) - \mathrm{Q}(t)\frac{1}{\sqrt{2}}\sin(2\pi f_c t)
$$

OFFSET QPSK (OQPSK)

- Orthogonal QPSK
- A delay of one bit time is introduced in the Q stream

$$s(t) = \frac{1}{\sqrt{2}} I(t) \cos 2\pi f_c t - \frac{1}{\sqrt{2}} Q(t - T_b) \sin 2\pi f_c t$$

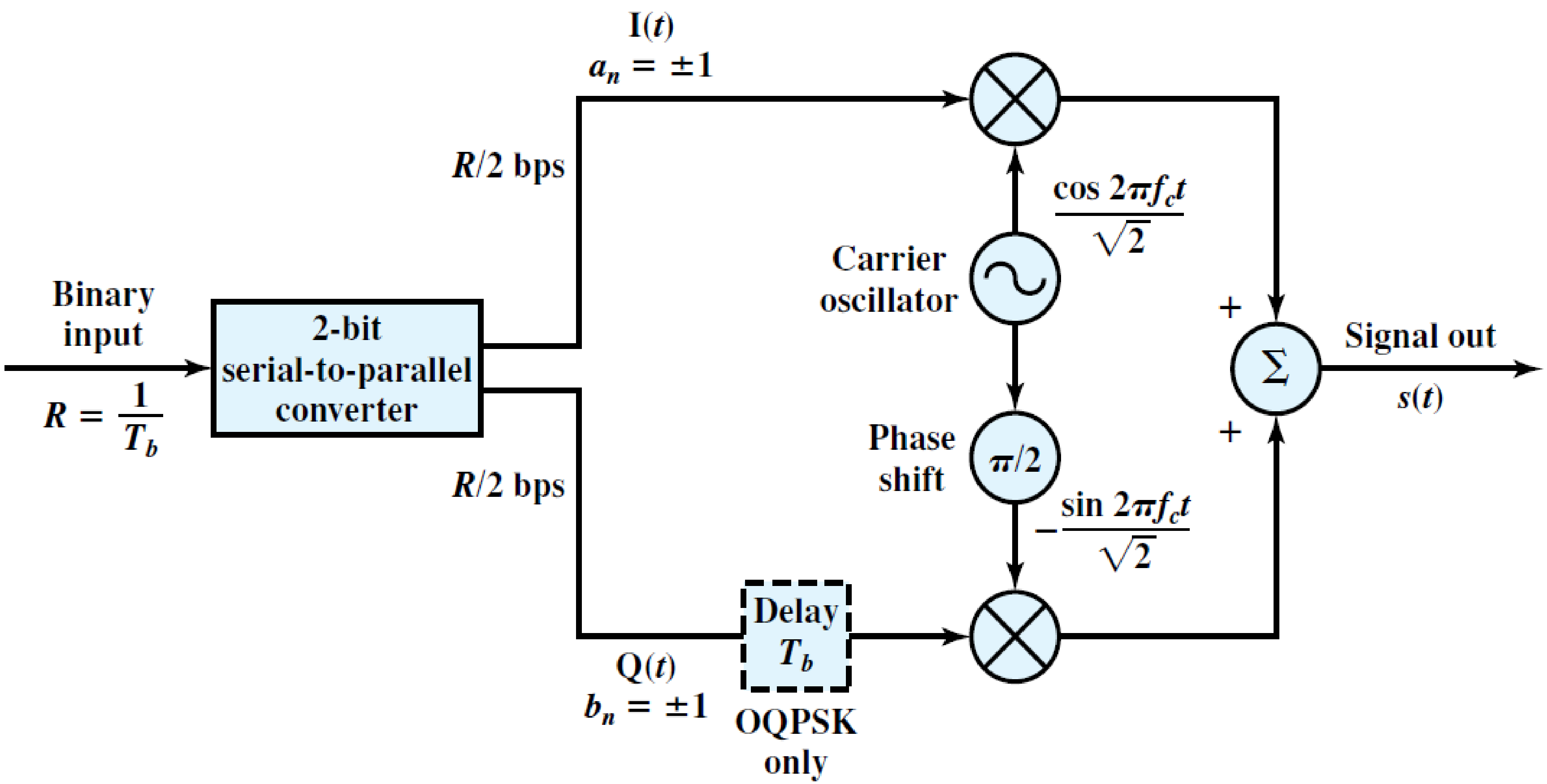
QPSK AND OQPSK WAVEFORMS



QPSK VS. OQPSK

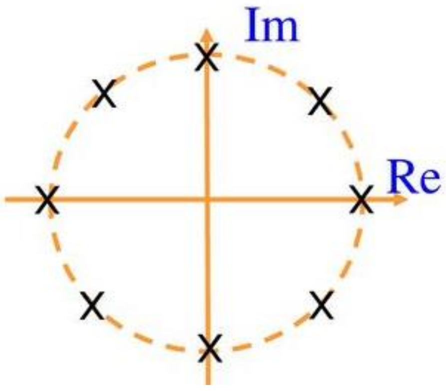
- QPSK: From one symbol time to the next, a phase change of as much as 180° is possible
- OQPSK: The phase change in the combined signal never exceeds 90°
- Spectral characteristics and bit error performance are the same
- Advantage of OQPSK over QPSK:
  - Physical limitations on phase modulators
  - Easier to control the spreading of the signal bandwidth due to nonlinear components

QPSK AND OQPSK MODULATORS



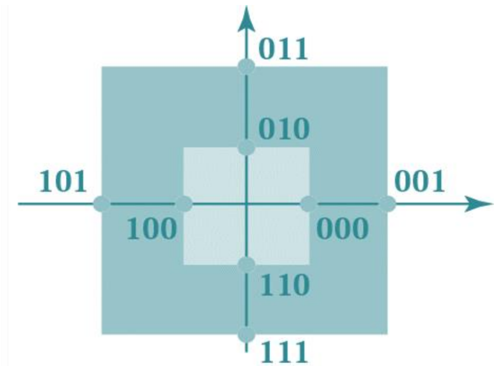
MULTI-LEVEL PSK (MPSK)

- Multilevel signaling
- More efficient use of bandwidth
  - Higher data rate for the same signaling rate
- Each signal element represents $\log_2 M = L$ bits

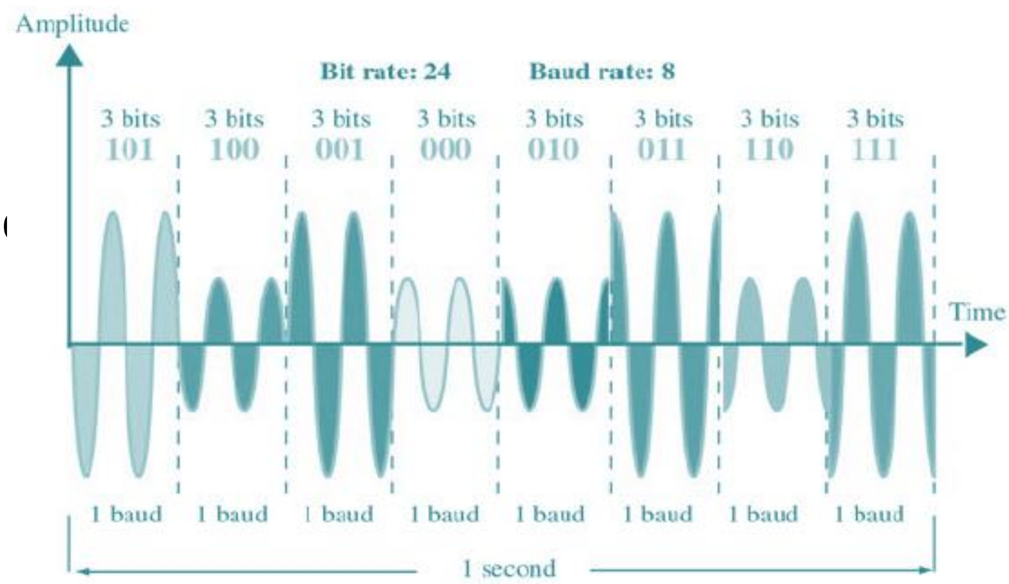


QUADRATURE AMPLITUDE MODULATION (QAM)

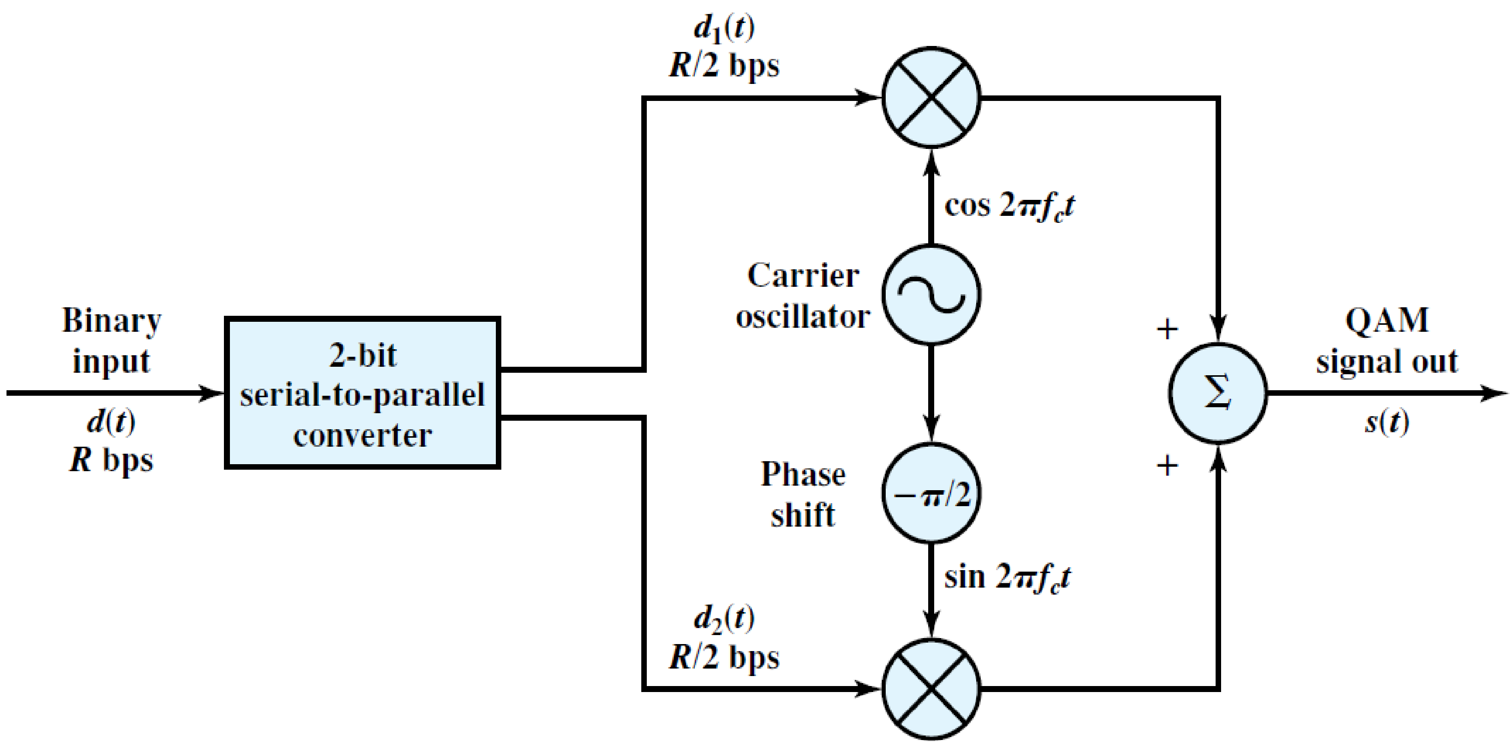
- An extension of the QPSK
- Combines both ASK and PSK
- Example:
  - ASK with 2 levels
  - PSK with 4 levels
  - 4 x 2 = 8-QAM
- M = 8, L = 3
- Bandwidth savings
- Susceptibility to nois
- Used on
  - ADSL
  - Wireless system



8-QAM
2 amplitudes, 4 phases



QUADRATURE AMPLITUDE MODULATION



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

PERFORMANCE OF D-A ENCODING SCHEMES (WITHOUT NOISE)

Transmission bandwidth B_T

Bandwidth (or spectral) Efficiency:

$$BE = \frac{R}{B_T}$$

For **ASK** and **PSK:**

- D: signaling, modulation, baud rate

  r : filtering coefficient; $0 < r < 1$

$$B_T = (1+r)D$$

- With binary encoding (not multilevel): D = R

$$B_T = (1+r)R$$

- Bandwidth Efficiency, BE:

$$BE_{BASK,BPSK} = \frac{R}{B_T} = \frac{1}{1+r}$$

PERFORMANCE OF D-A ENCODING SCHEMES (WITHOUT NOISE)

For **MPSK:** M phases, L bits/signal element $L = \log_2(M)$

- B_T directly related to the signaling rate, D $B_T = (1+r)D$

- With M-level encoding:

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

$$B_T = \frac{(1+r)R}{L} = \frac{(1+r)R}{\log_2^M}$$

- Bandwidth Efficiency, BE:

$$BE_{MPSK} = \frac{R}{B_T} = \frac{L}{1+r}$$

For multilevel, L ≥ 2 and r ≤ 1, so BE ≥ 1

PERFORMANCE OF D-A ENCODING SCHEMES (WITHOUT NOISE)

For **MFSK:** M Frequencies, L bits/signal element

$$L = \log_2(M)$$

$$B_T = (1+r)\ [\textit{width} \text{ of signal } \textit{spectrum}]$$
$$= (1+r)[M(2fd)]$$

At maximum signaling rate: $D = 1/T_s = 2f_d$

$$B_T = (1+r)MD = \frac{(1+r)MR}{L} = (\frac{(1+r)M}{log_2 M})R$$

Bandwidth Efficiency, BE:

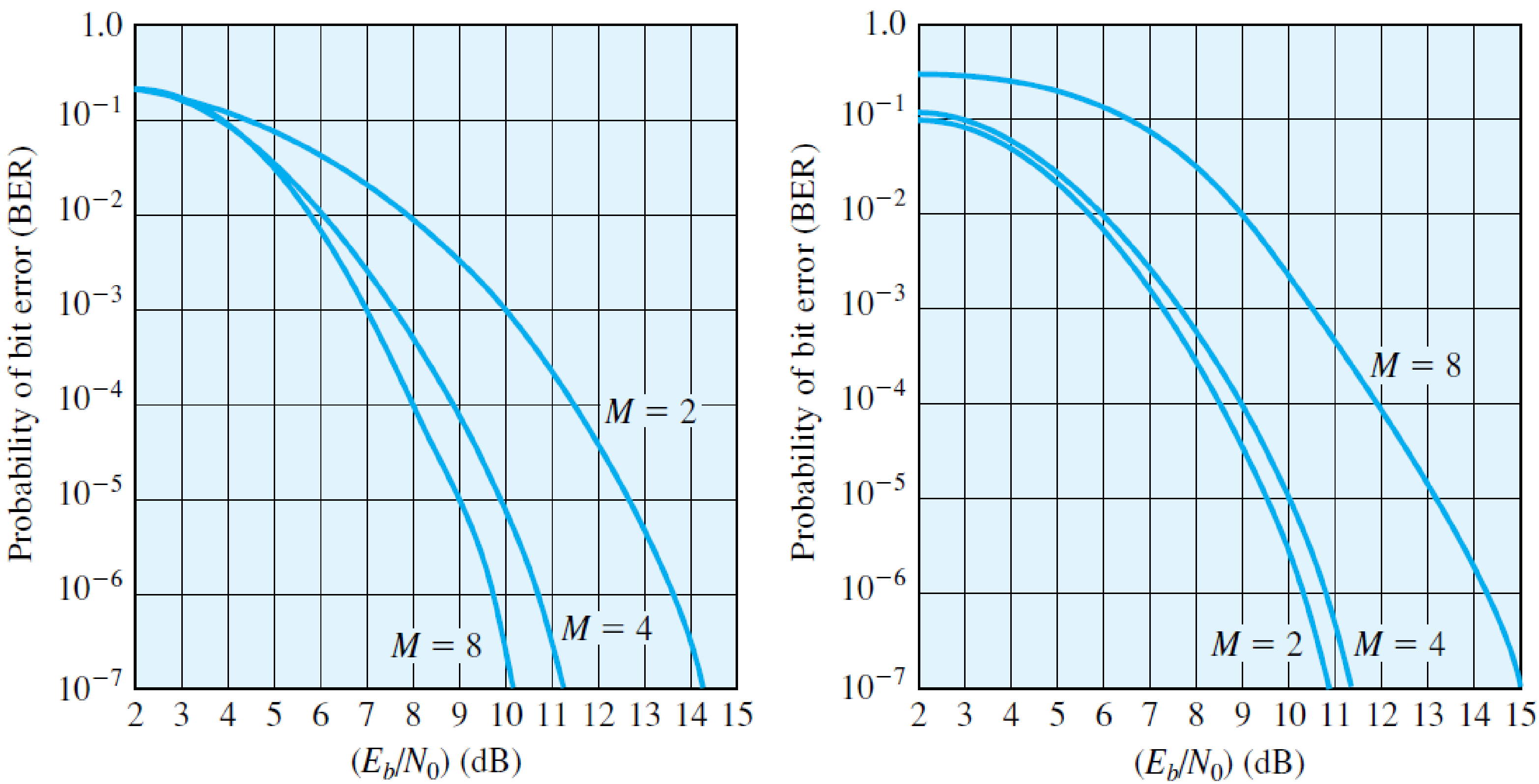
$$BE_{MFSK} = \frac{R}{B_T} = \frac{L}{(1+r)M}$$

BANDWIDTH EFFICIENCY FOR VARIOUS DIGITAL-TO-ANALOG ENCODING SCHEMES

$$BE = \frac{R}{B_T}$$

	$r = 0$	$r = 0.5$	$r = 1$
ASK	1.0	0.67	0.5
FSK	0.5	0.33	0.25
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 D-A ENCODING SCHEMES BIT ERROR RATE



(a) Multilevel FSK (MFSK)

(b) Multilevel PSK (MPSK)

ANALOG DATA, DIGITAL SIGNAL

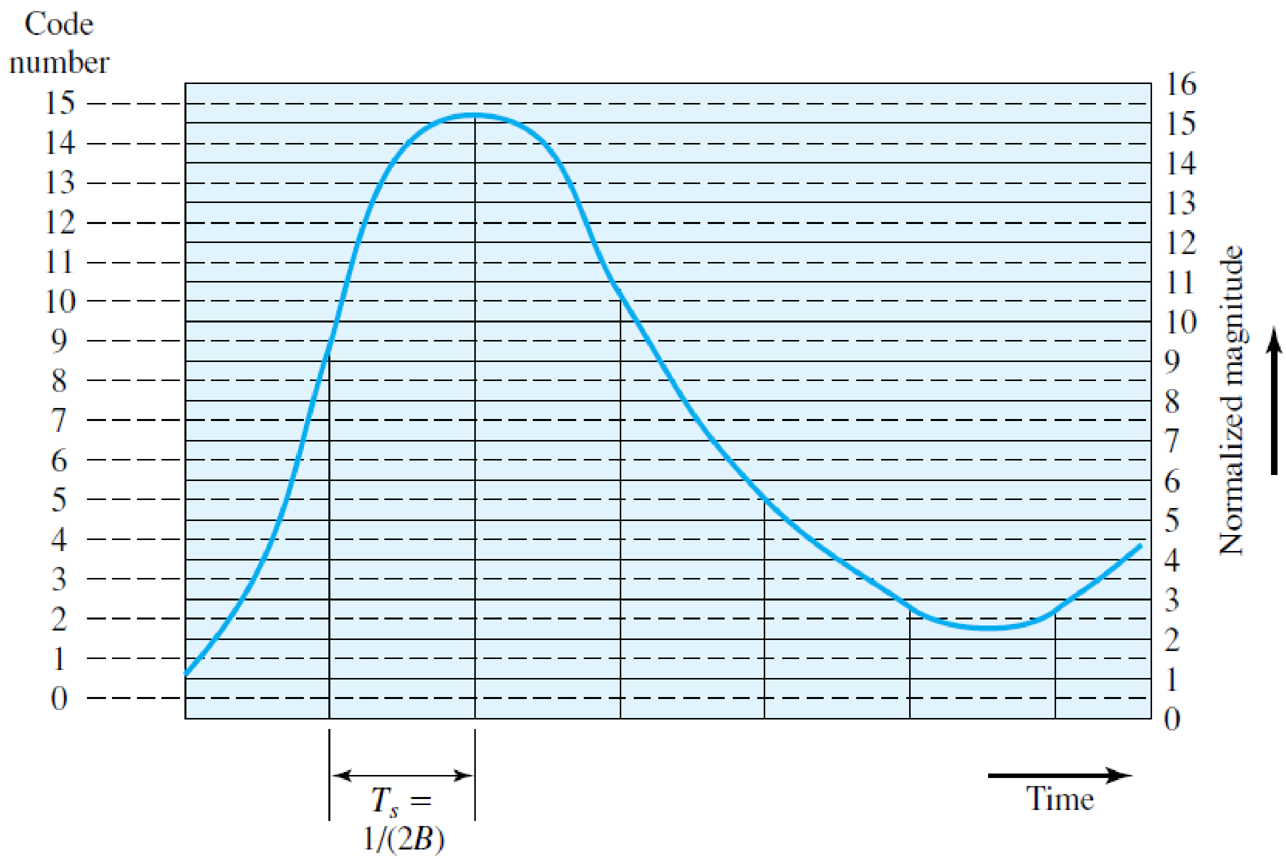
ANALOG DATA, DIGITAL SIGNAL

- Analog data are digitized to use digital transmission facilities
- codec (coder-decoder)
  - The device used for converting analog data into digital form for transmission
  - Recovering the original analog data from the digital

ANALOG DATA TO DIGITAL SIGNAL TECHNIQUES

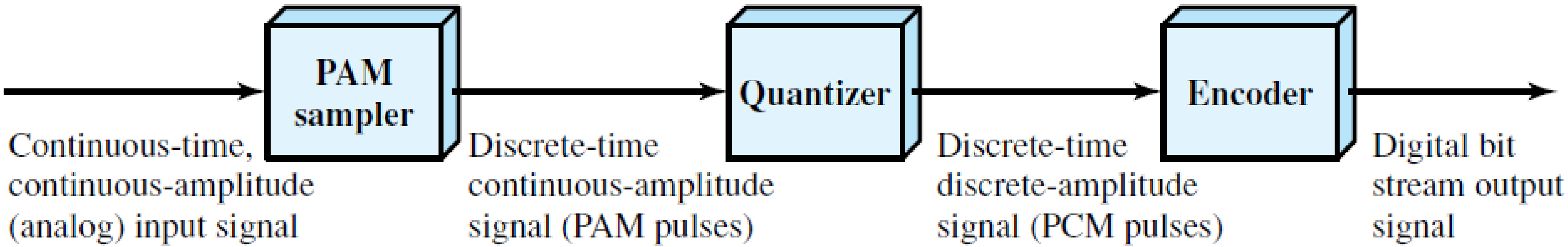
- Pulse Code Modulation (PCM)
  - Sampling the analog data
  - Quantizing the samples
- Analog samples
  - pulse amplitude modulation (PAM)
- To convert to digital, each of these analog samples must be assigned a binary code

PCM



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

PCM BLOCK DIAGRAM



- Input: Continuous-time continuous-amplitude (analog) signal
- Output: Digital signal consists of blocks of *n* bits
- Each *n*-bit number: Amplitude of a PCM pulse
- n bit system gives M = 2^n levels

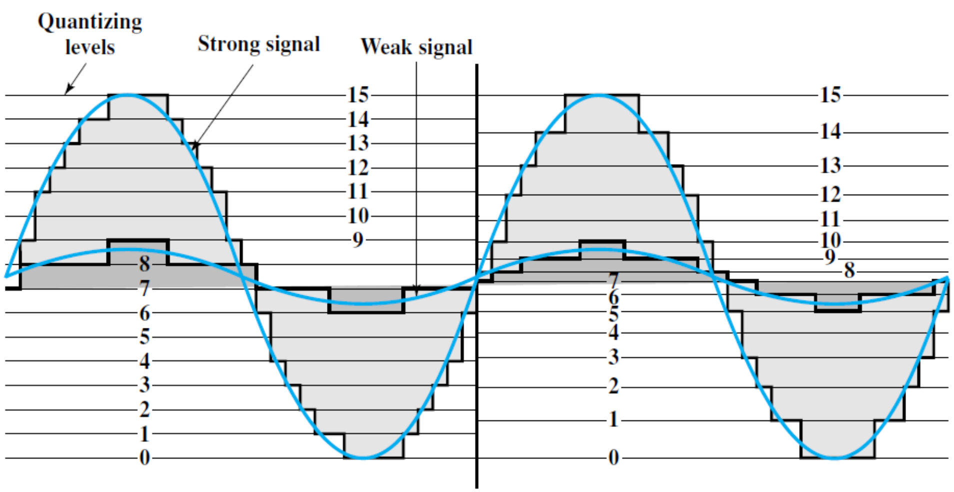
QUANTIZING NOISE

- Reproducing the analog signal violates the terms of the sampling theorem
- By quantizing the PAM pulse, the original signal cannot be recovered exactly
- Quantizing error / Quantizing noise
- Signal-to-noise ratio for quantizing noise

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

NONLINEAR ENCODING

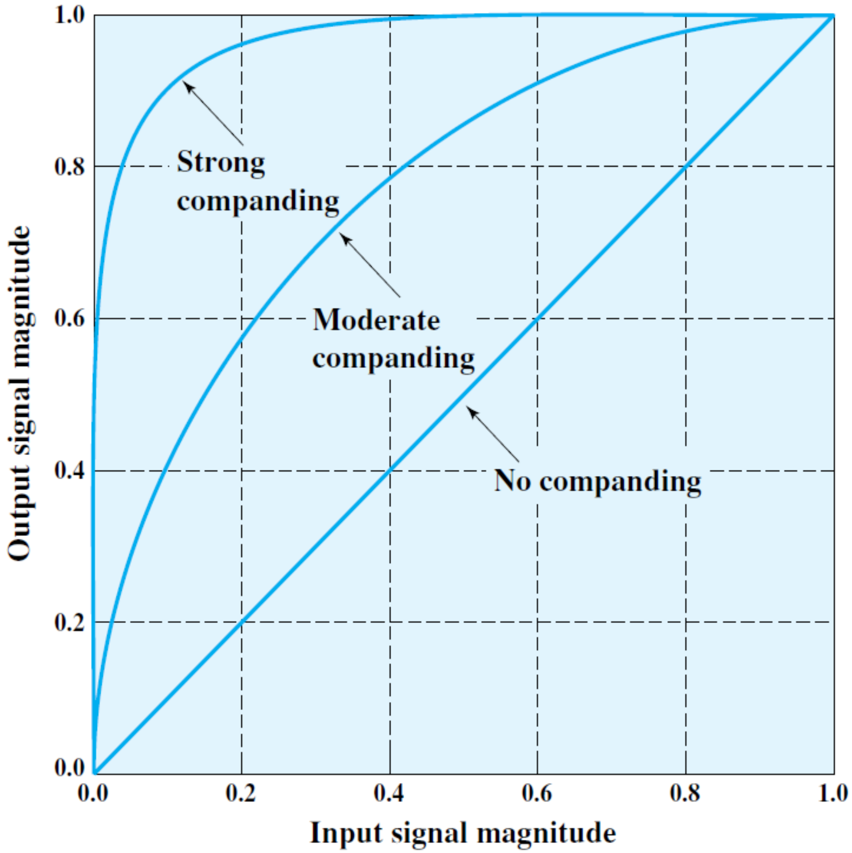
- Linear Coding
  - Equally spaced quantization levels
  - Same mean absolute error for each sample
  - More distortion of lower amplitude values
- Nonlinear coding
  - Greater number of quantizing steps for signals of low amplitude
  - Reduction in overall signal distortion



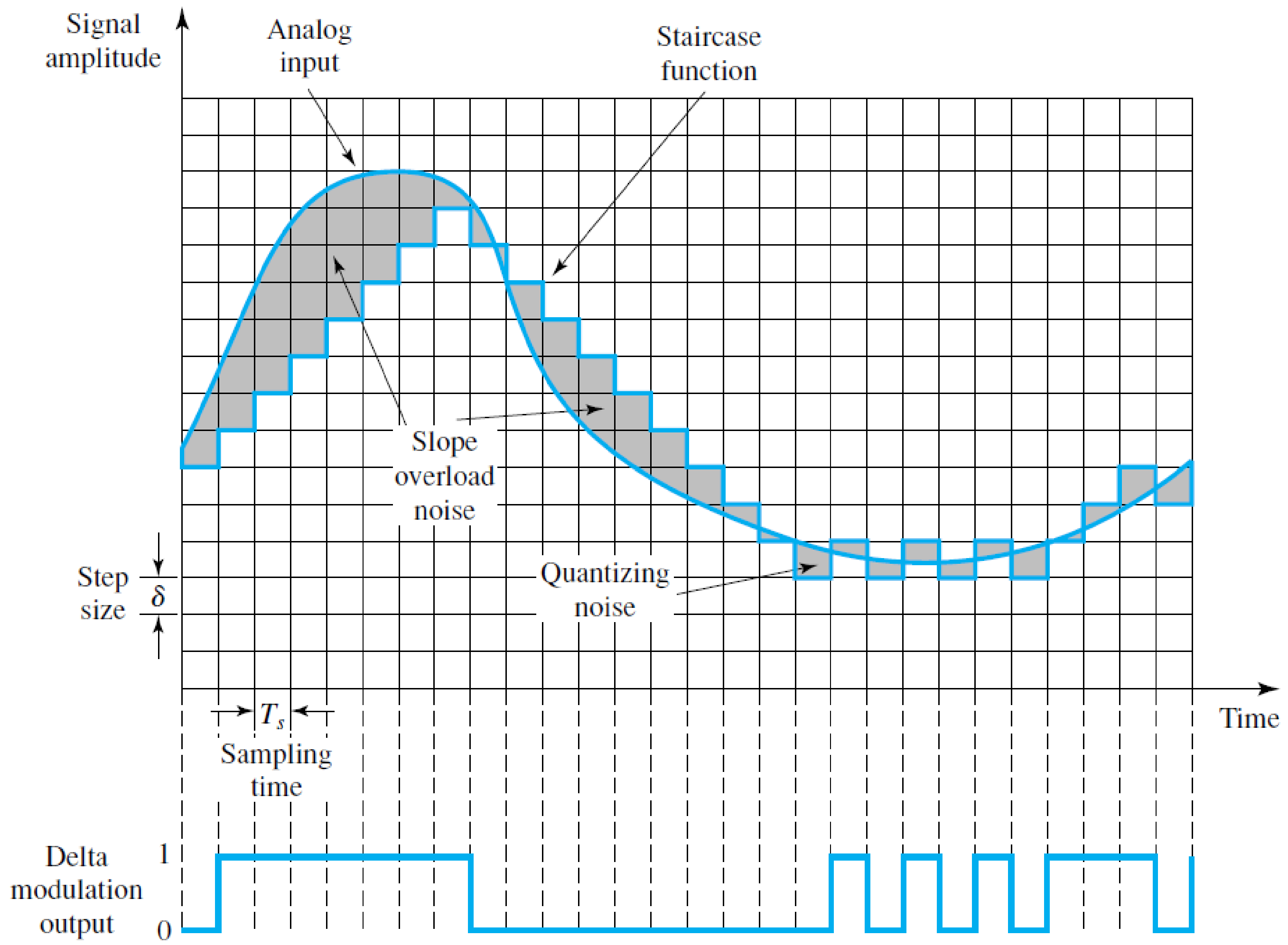
(a) Without nonlinear encoding (b) With nonlinear encoding

COMPANDING (COMPRESSING-EXPANDING)

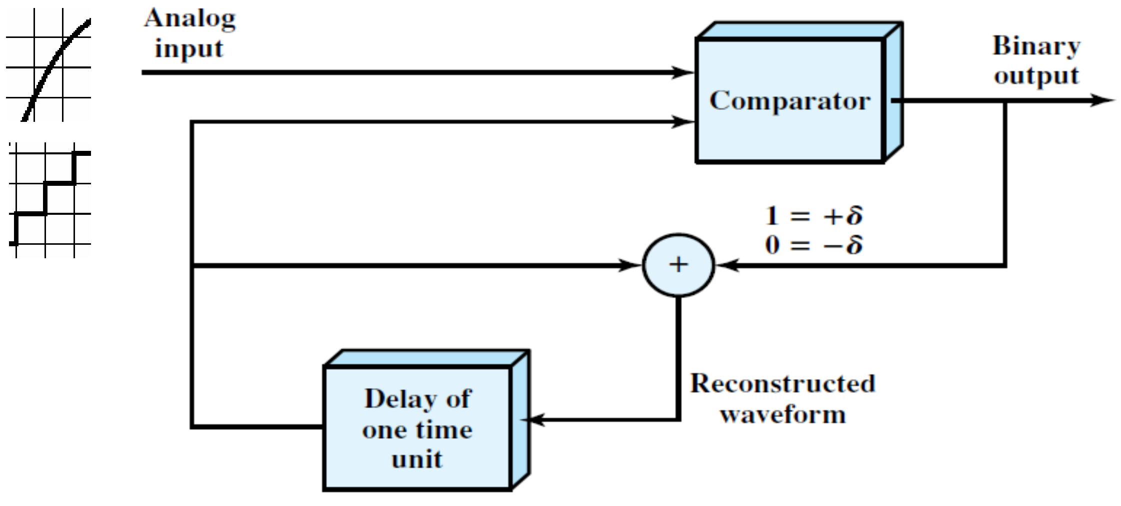
- More gain to weak signals than to strong signals on input
- More levels available for lower-level signals
- Significant improvement in the PCM SNR ratio



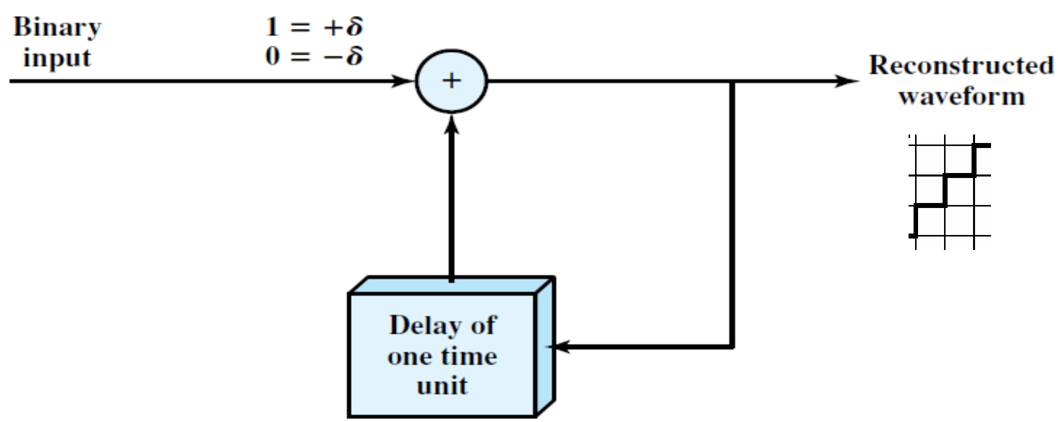
DELTA MODULATION (DM)



DM TRANSCEIVER



(a) Transmission

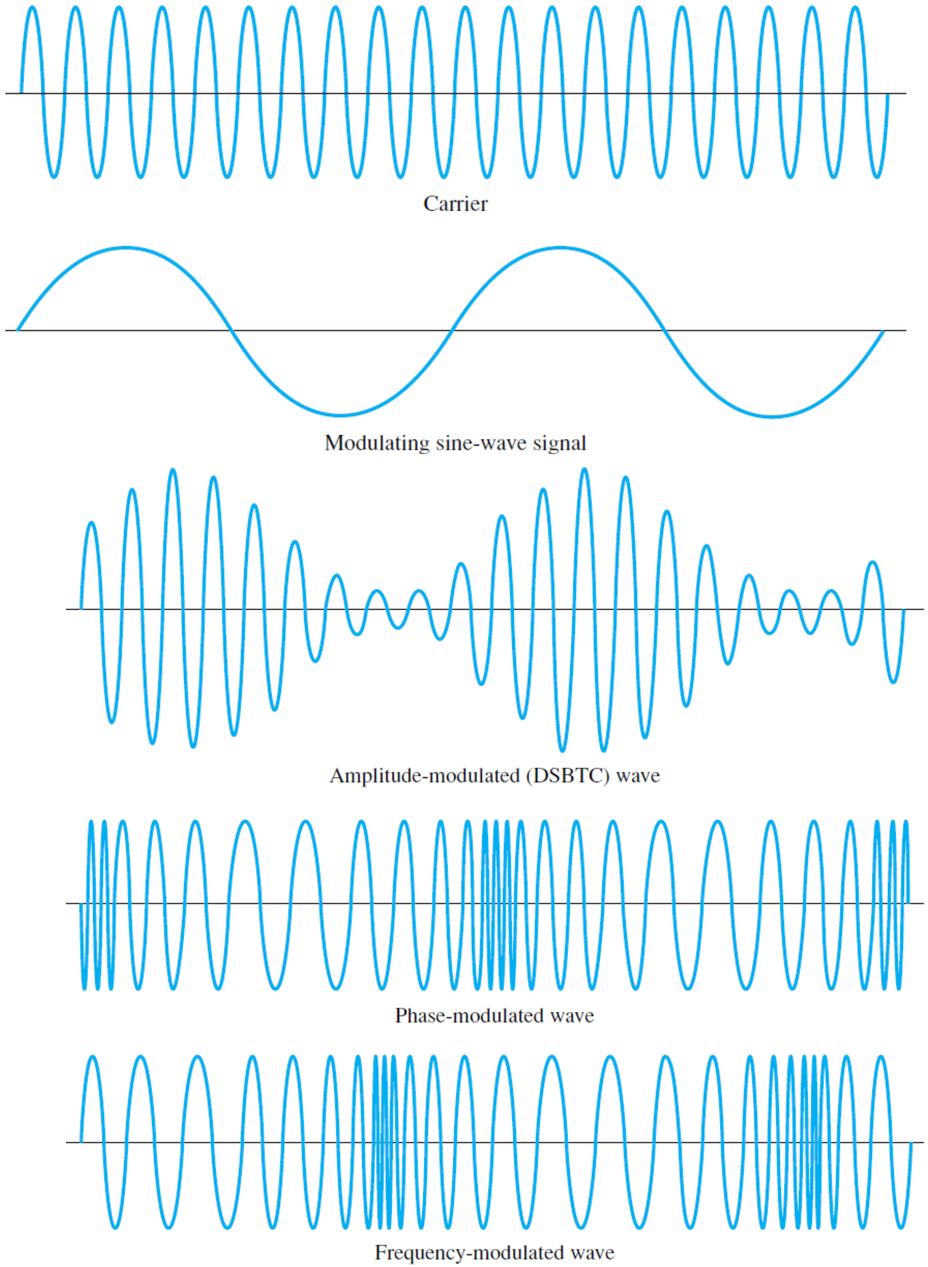


(b) Reception

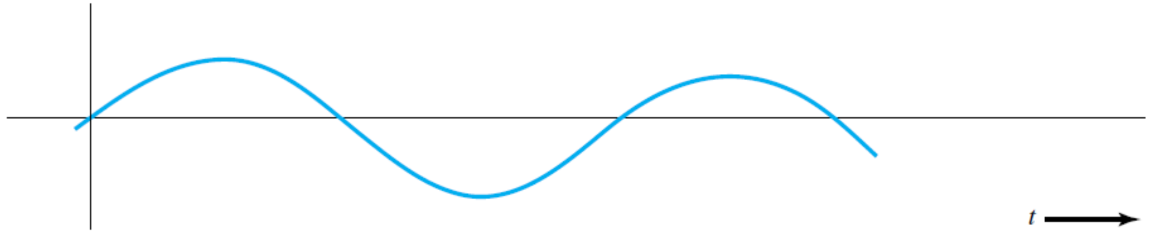
ANALOG DATA, ANALOG SIGNAL

ANALOG DATA, ANALOG SIGNAL

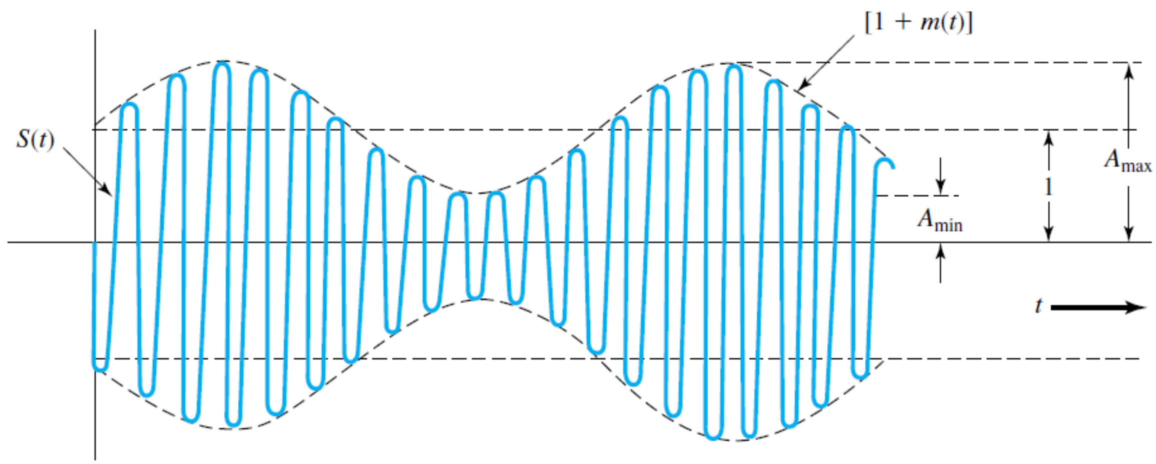
- Analog data modulated by a carrier signal
- Producing analog signal in a different frequency band
- Can be utilized on an analog transmission system
- FDM
- Basic techniques
  - Amplitude modulation (AM)
  - Frequency modulation (FM)
  - Phase modulation (PM)


Carrier
Modulating sine-wave signal
Amplitude-modulated (DSBTC) wave
Phase-modulated wave
Frequency-modulated wave

AMPLITUDE MODULATION



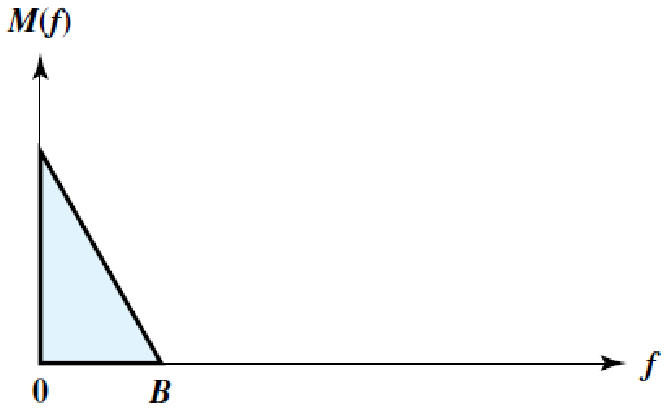
(a) Sinusoidal modulating wave



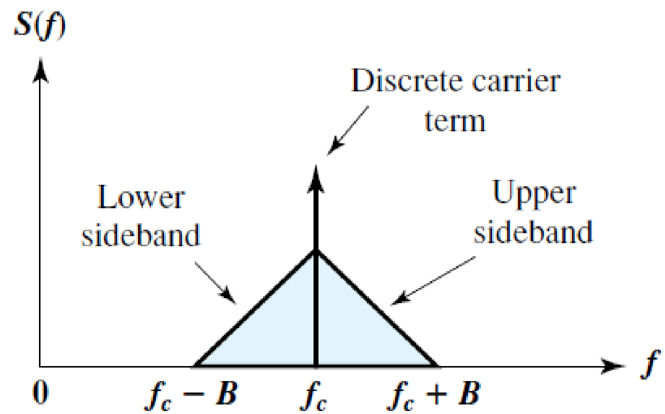
(b) Resulting AM signal

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

SPECTRUM OF AN AM SIGNAL



(a) Spectrum of modulating signal



(b) Spectrum of AM signal with carrier at f_c

$$B_T = 2B$$

PHASE MODULATION (PM)

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

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

Carson's rule:

$$B_T = 2(\beta + 1)B$$

$$n_p A_m$$

FREQUENCY MODULATION (FM)

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

$$2\pi f_i(t) = \frac{d}{dt}[2\pi f_c t + \phi(t)]$$

$$f_i(t) = f_c + \frac{1}{2\pi}\phi'(t)$$

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

$$\Delta F = \frac{1}{2\pi} n_f A_m \text{ Hz}$$

$$\frac{\Delta F}{B} = \frac{n_f A_m}{2\pi B}$$

$$B_T = 2(\beta + 1)B$$

$$B_T = 2\Delta F + 2B$$