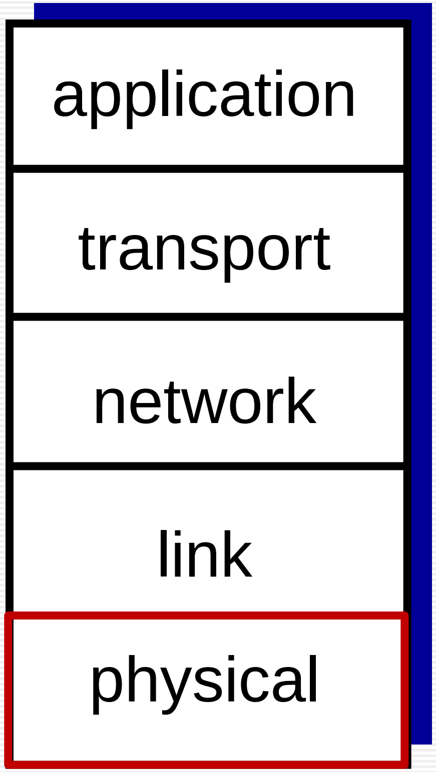
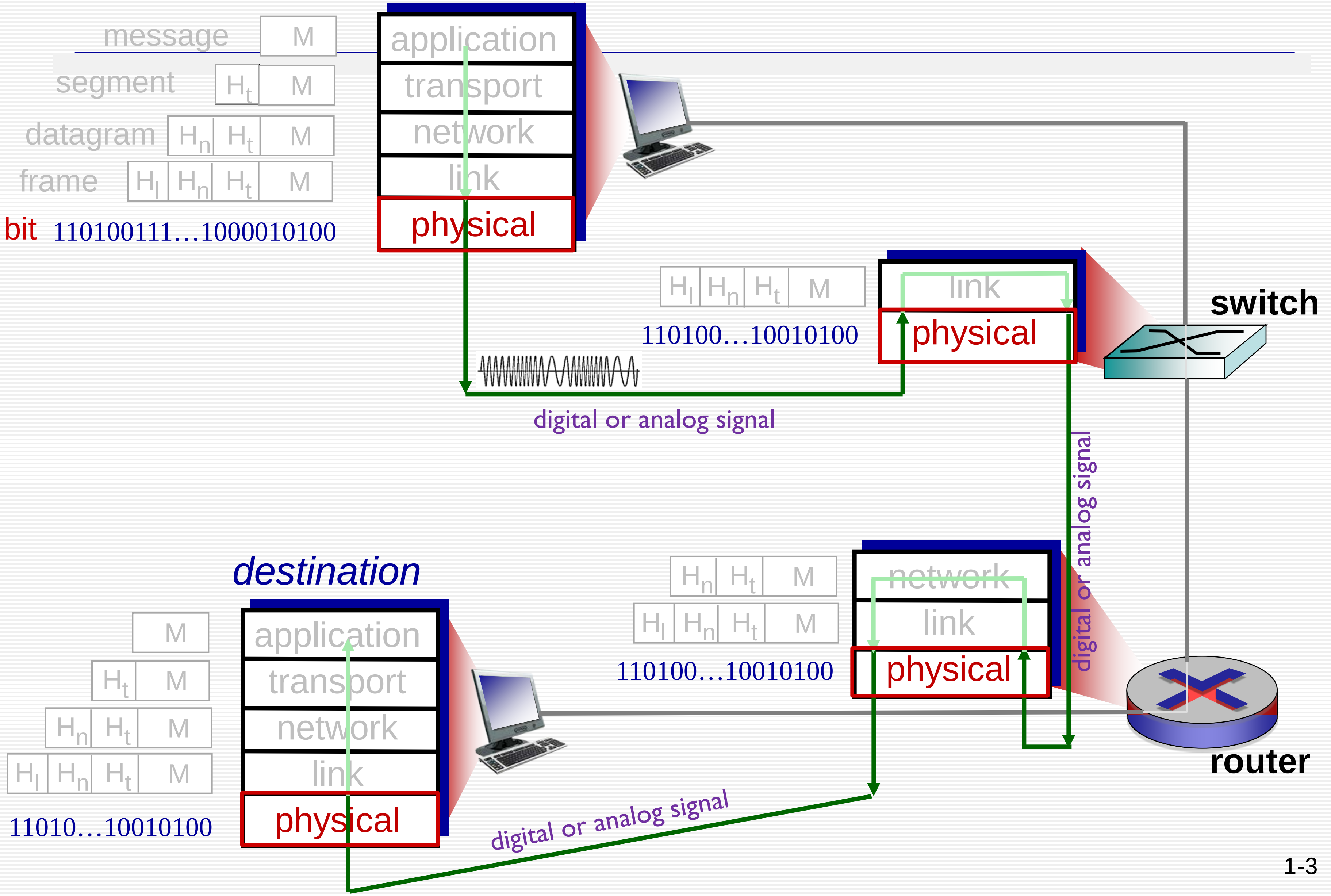
Review

Protocol stack

- *application:* supporting network applications
- *transport:* data transfer between applications (peer processes)
  - TCP, UDP
- *network:* routing of packets from source host to destination host
  - IP, routing protocols
- *link:* data transfer between neighboring network elements
  - Ethernet, 802.11 (WiFi), Cellular
- *physical:* signal representing bits on the medium (data encoding/decoding)

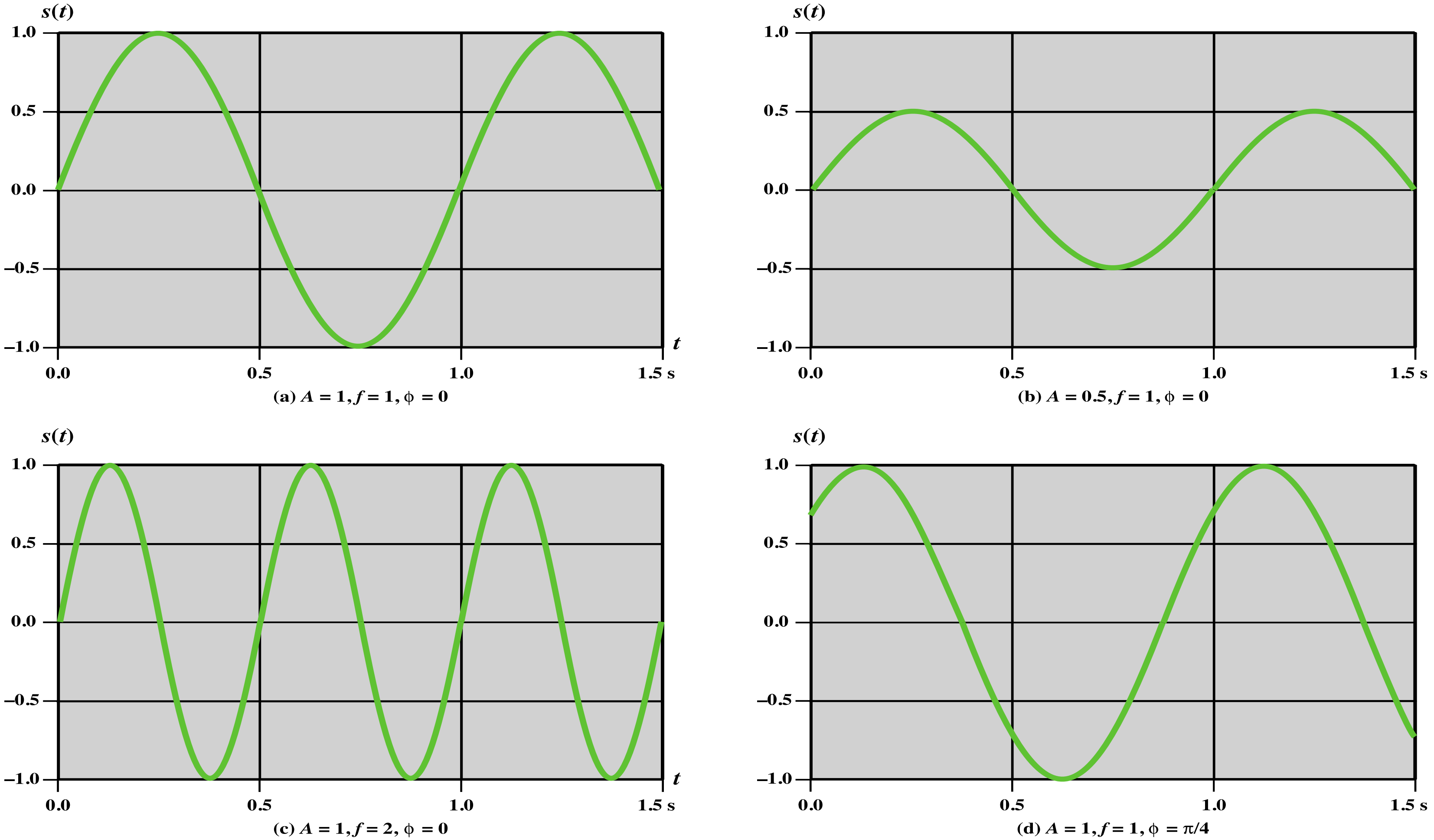



message
M
segment
H_t
M
datagram
H_n
H_t
M
frame
H_l
H_n
H_t
M
bit
110100111…1000010100
application
transport
network
link
physical
H_l
H_n
H_t
M
110100…10010100
link
physical
switch
digital or analog signal
digital or analog signal
destination
M
H_t
M
H_n
H_t
M
H_l
H_n
H_t
M
11010…10010100
application
transport
network
link
physical
H_n
H_t
M
H_l
H_n
H_t
M
110100…10010100
network
link
physical
router
digital or analog signal

Frequency
Spectrum
Bandwidth

Sinusoidal Signal

- Fundamental periodic signal
- Can be represented by three parameters (peak amplitude, frequency, phase)



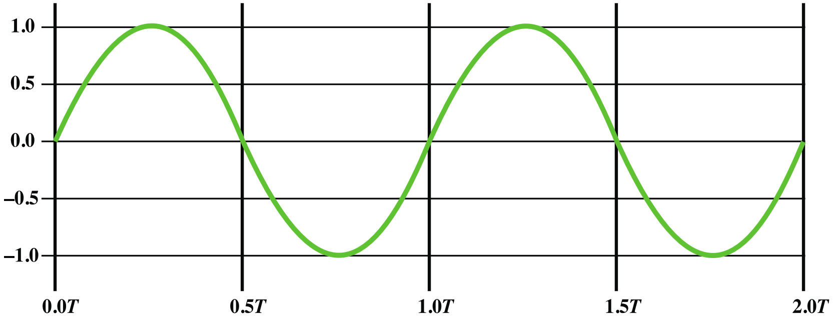
(a) $A = 1, f = 1, \phi = 0$

(b) $A = 0.5, f = 1, \phi = 0$

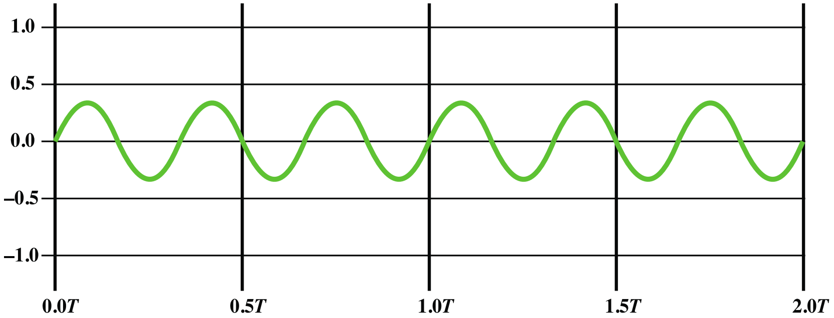
(c) $A = 1, f = 2, \phi = 0$

(d) $A = 1, f = 1, \phi = \pi/4$

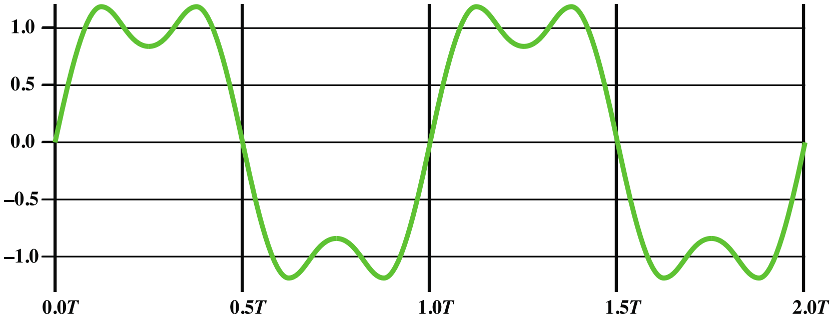
Figure 3.3 $s(t) = A \sin(2\pi f t + \phi)$



(a) $\sin(2\pi ft)$

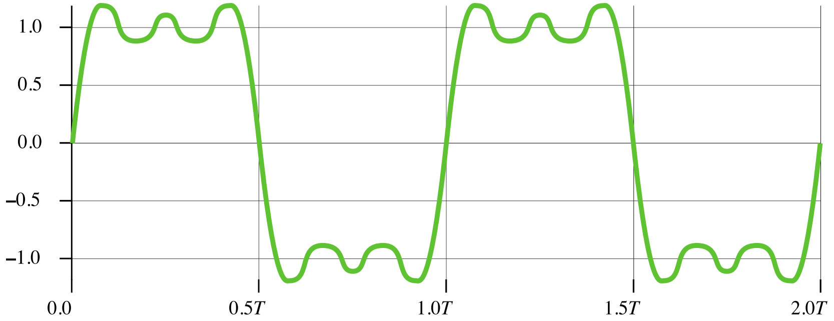


(b) $(1/3)\sin(2\pi(3f)t)$

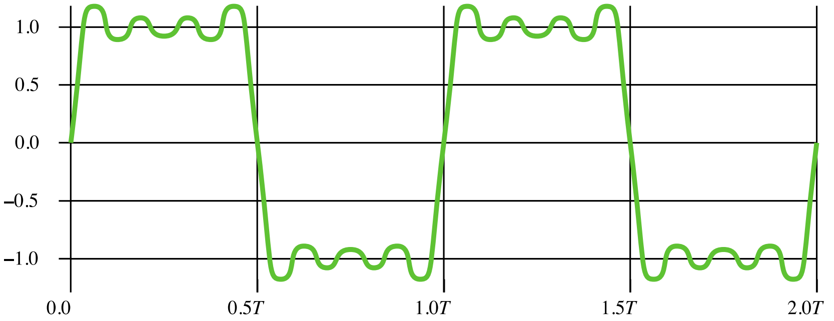


(c) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t)]$

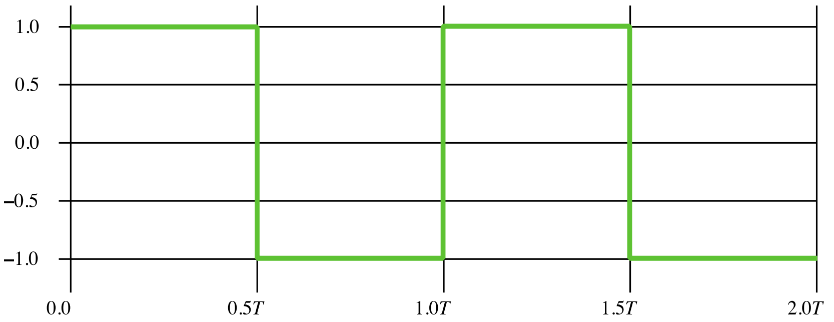
Figure 3.4 Addition of Frequency Components ($T = 1/f$)



(a) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t)]$



(b) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t) + (1/7)\sin(2\pi(7f)t)]$



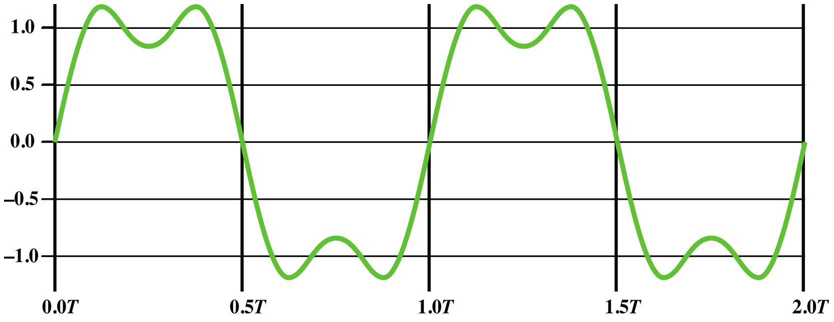
(c) $(4/\pi)\,\sum(1/k)\sin(2\pi(kf)t)$, for k odd

Figure 3.7 Frequency Components of Square Wave ($T = 1/f$)

Frequency Domain Concepts

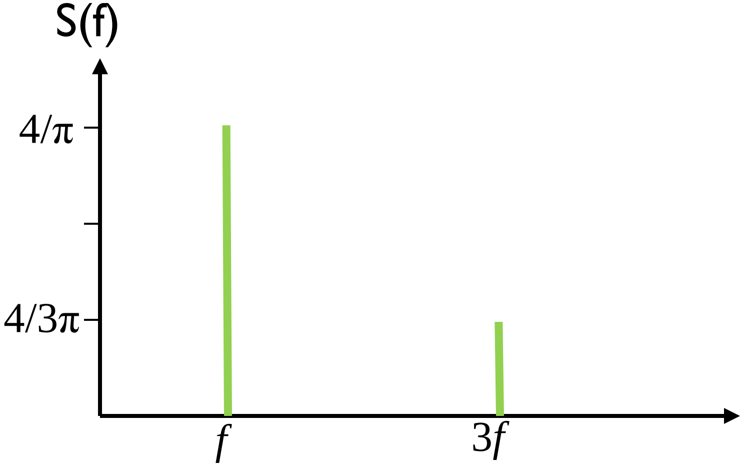
- Signals are made up of many frequencies
- Components are sine waves
- Fourier analysis can show that any signal is made up of components at various frequencies, in which each component is a sinusoid
- Can plot frequency domain functions

Periodic Signal



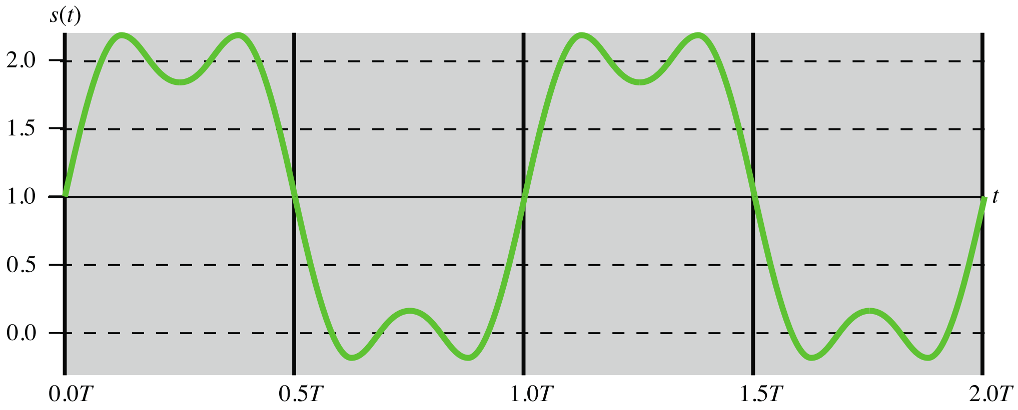
(c) (4/π) [sin (2πft) + (1/3) sin (2π(3f)t)]

time domain

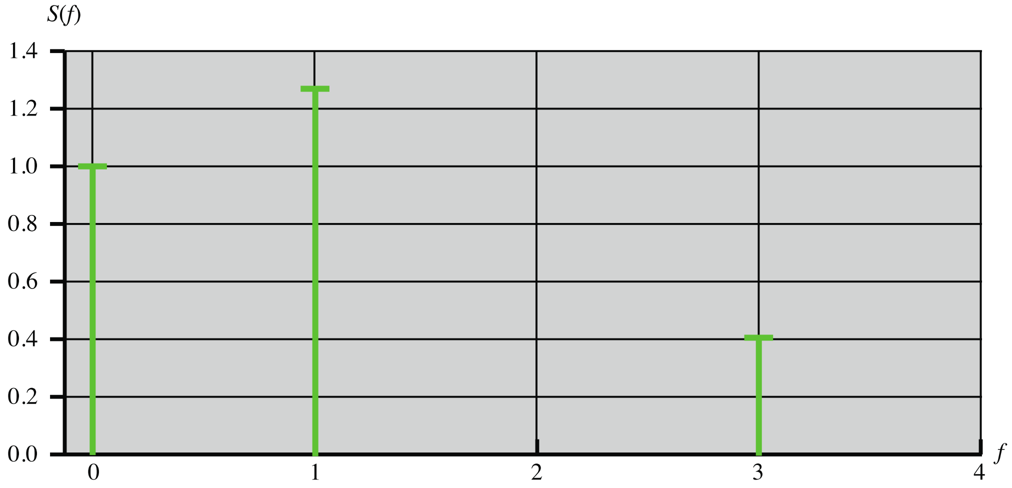


frequency domain

Signal with dc component



(a) $s(t) = 1 + (4/\pi)\,[\sin(2\pi f t) + (1/3)\sin(2\pi(3f)t)]$

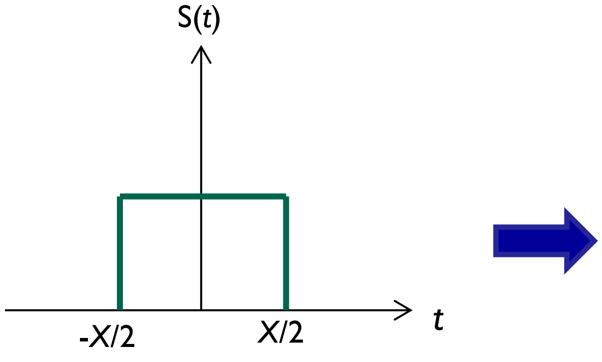


(b) S(*f*)

Figure 3.6 Signal with dc Component

Non-periodic Signal

- Even non-periodic signals can be characterized in the frequency domain using a continuous spectrum of frequency components



Time-Domain Representation

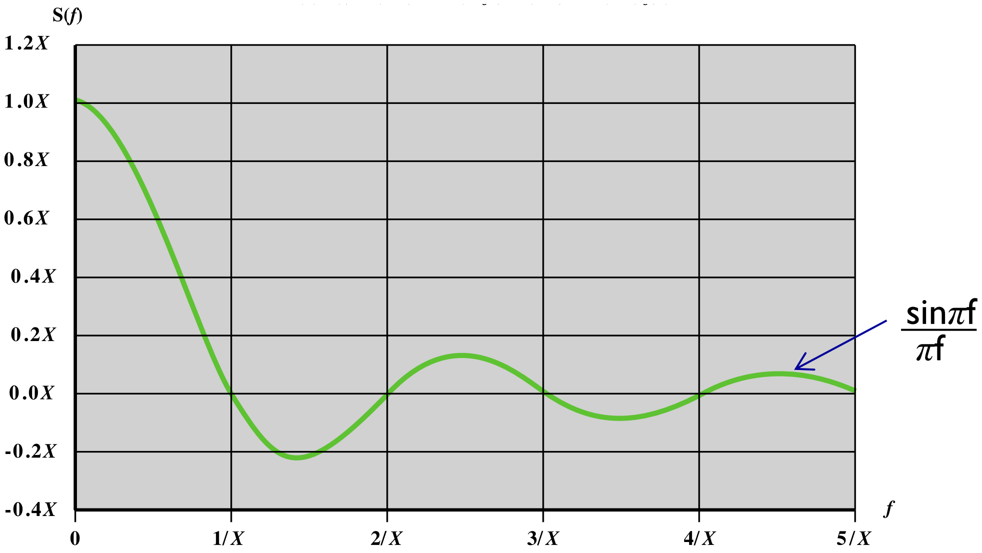
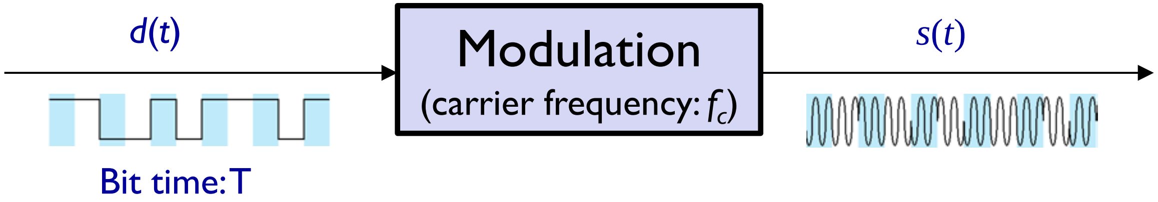


Figure 3.5 Frequency-Domain Representations

Modulation

Time domain



$d(t)$

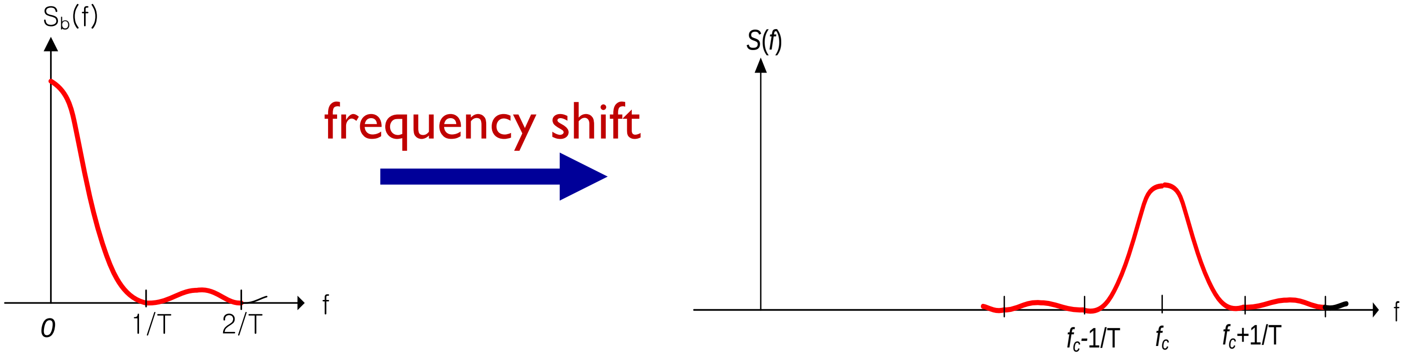
Modulation

(carrier frequency: f_c)

$s(t)$

Bit time: T

Frequency domain

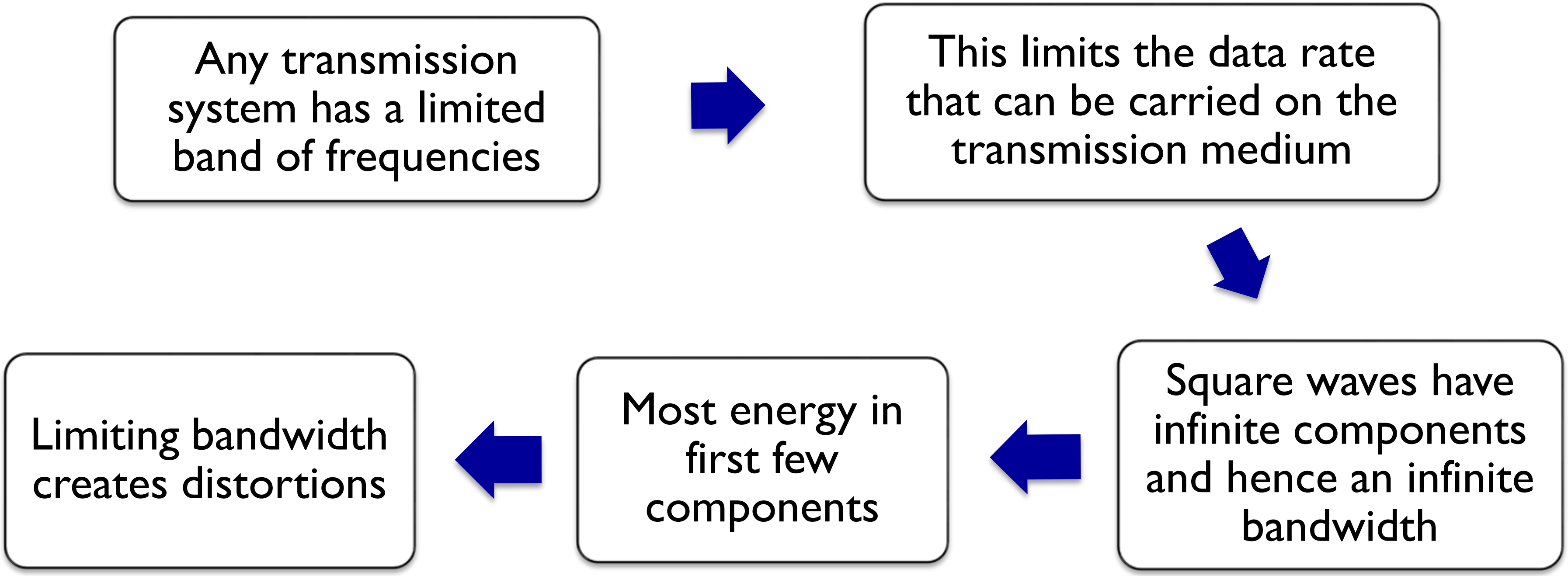


frequency shift

Terminology

- Signal Spectrum
  - Range of frequencies that the signal contains
- Absolute bandwidth
  - Width of the spectrum
- Effective bandwidth
  - Band of frequencies which contains most of the energy of the signal
- DC component
  - When the signal contains zero frequency
  - The mean value of waveform
  - A waveform without dc component is known as a dc-balanced waveform

Data Rate and Bandwidth



Any transmission system has a limited band of frequencies

This limits the data rate that can be carried on the transmission medium

Square waves have infinite components and hence an infinite bandwidth

Most energy in first few components

Limiting bandwidth creates distortions

- **There is a direct relationship between data rate and bandwidth**
- Shannon Capacity:

$$\boxed{C=B \log_2 (1+SNR)}$$

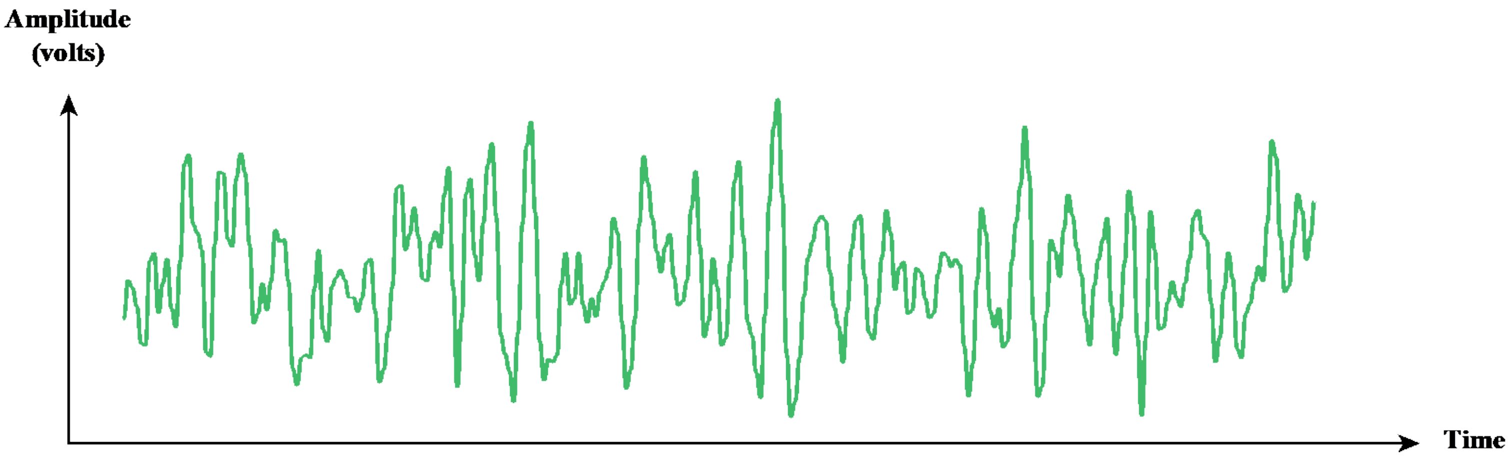
Maximum rate

Bandwidth

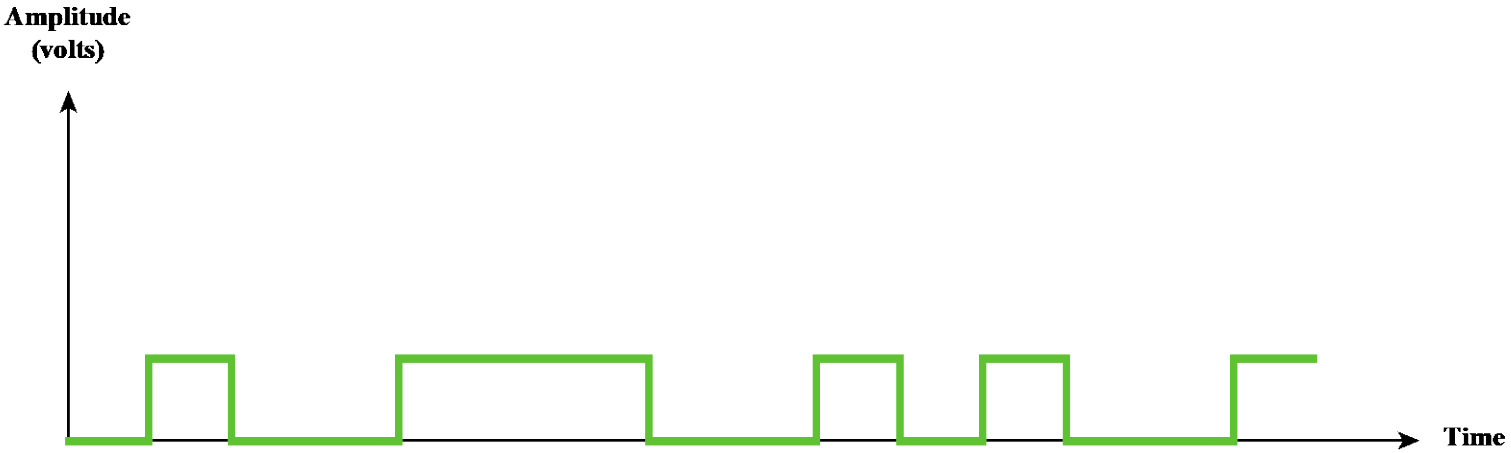
Ratio of signal power to noise power

Chapter 5

Signal Encoding Techniques



(a) Analog



(b) Digital

Figure 3.1 Analog and Digital Waveforms

Encoding Technique

- Digital Data → Digital Signal
- Digital Data → Analog Signal
- Analog Data
  - → Digital Data → Digital Signal
  - → Digital Data → Analog Signal
- Analog Data → Analog Signal

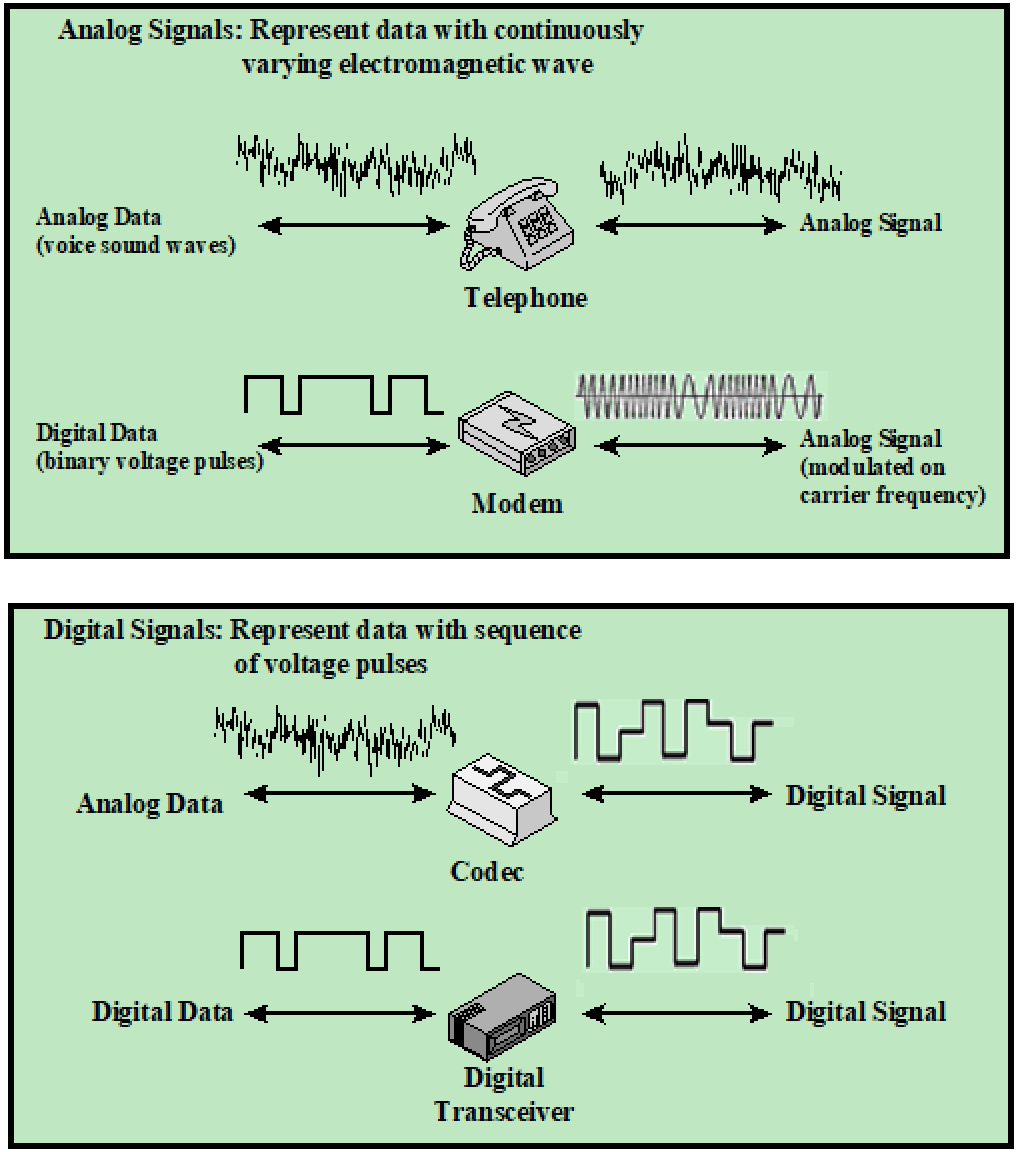


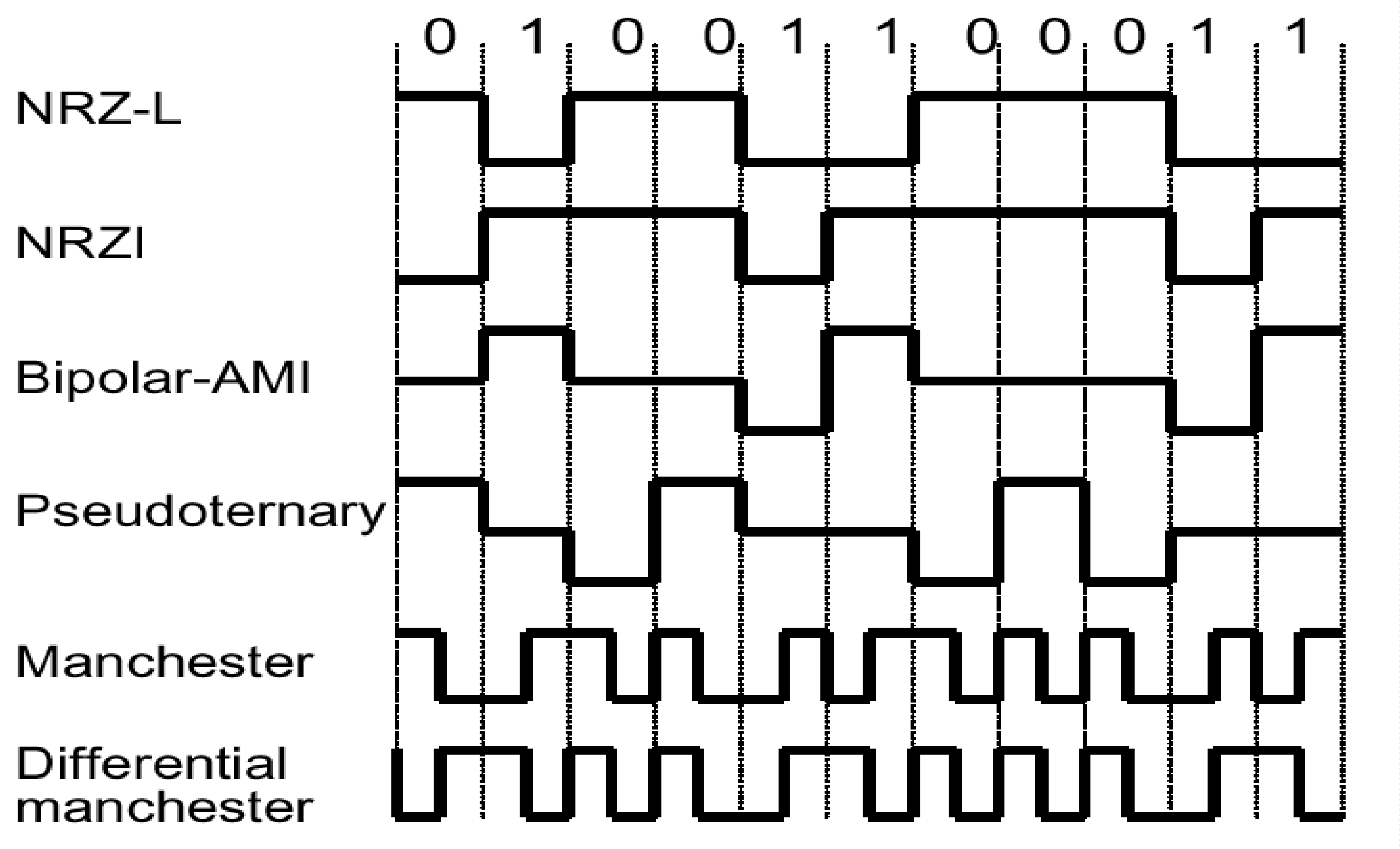
Figure 3.13 Analog and Digital Signaling of Analog and Digital Data

Digital Data ⟶ Digital Signals (1)

- A digital signal is a sequence of discrete, discontinuous voltage pulses.
- Each pulse is a signal element.
- Encoding Scheme: mapping a digital data into signal element
- Binary data is transmitted by encoding each data bit into signal elements.

Digital Data ⟶ Digital Signals (2)

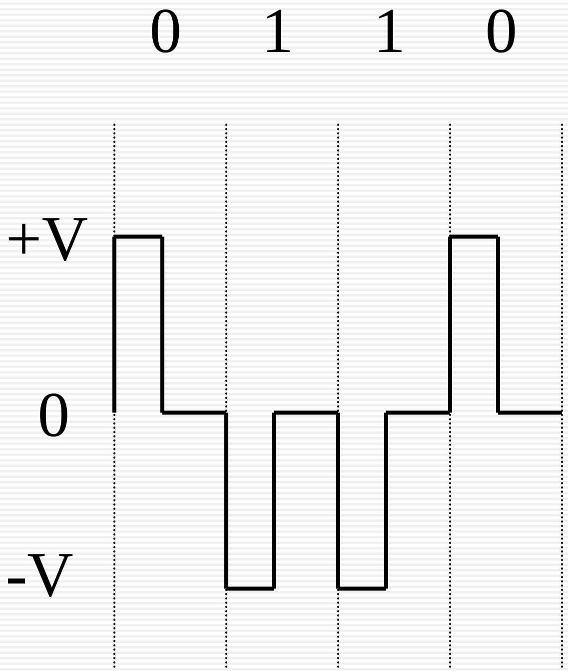
- Various encoding schemes



Digital Data ⟶ Digital Signals (3)

RZ(Return to Zero)

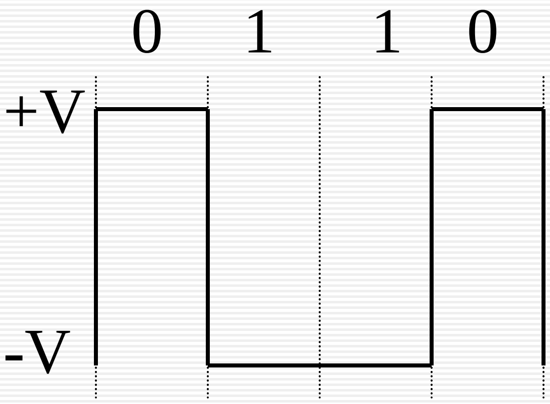
- 0: positive pulse
- 1: negative pulse
- Signal returns to zero after each encoded bit



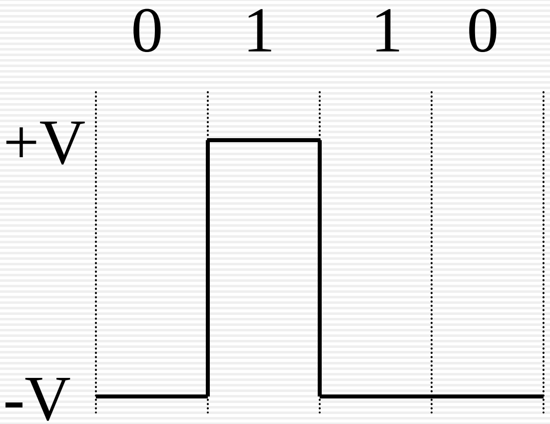
Digital Data ⟶ Digital Signals (4)

NRZ(Nonreturn to Zero)

- Voltage level is constant during bit interval (no return to a zero voltage level)
- NRZ-L(NRZ Level)
  - 0: positive voltage
  - 1: negative voltage
- NRZ-I(NRZ Inverted)
  - a form of differential encoding
  - 0: no transition
  - 1: transition at the beginning of bit interval
- NRZ strengths
  - simple, and efficiently use bandwidth
- NRZ limitations
  - presence of dc component
  - lack of synchronization capability



NRZ-L



NRZ-I

Digital Data → Digital Signals (5)

Multilevel Binary

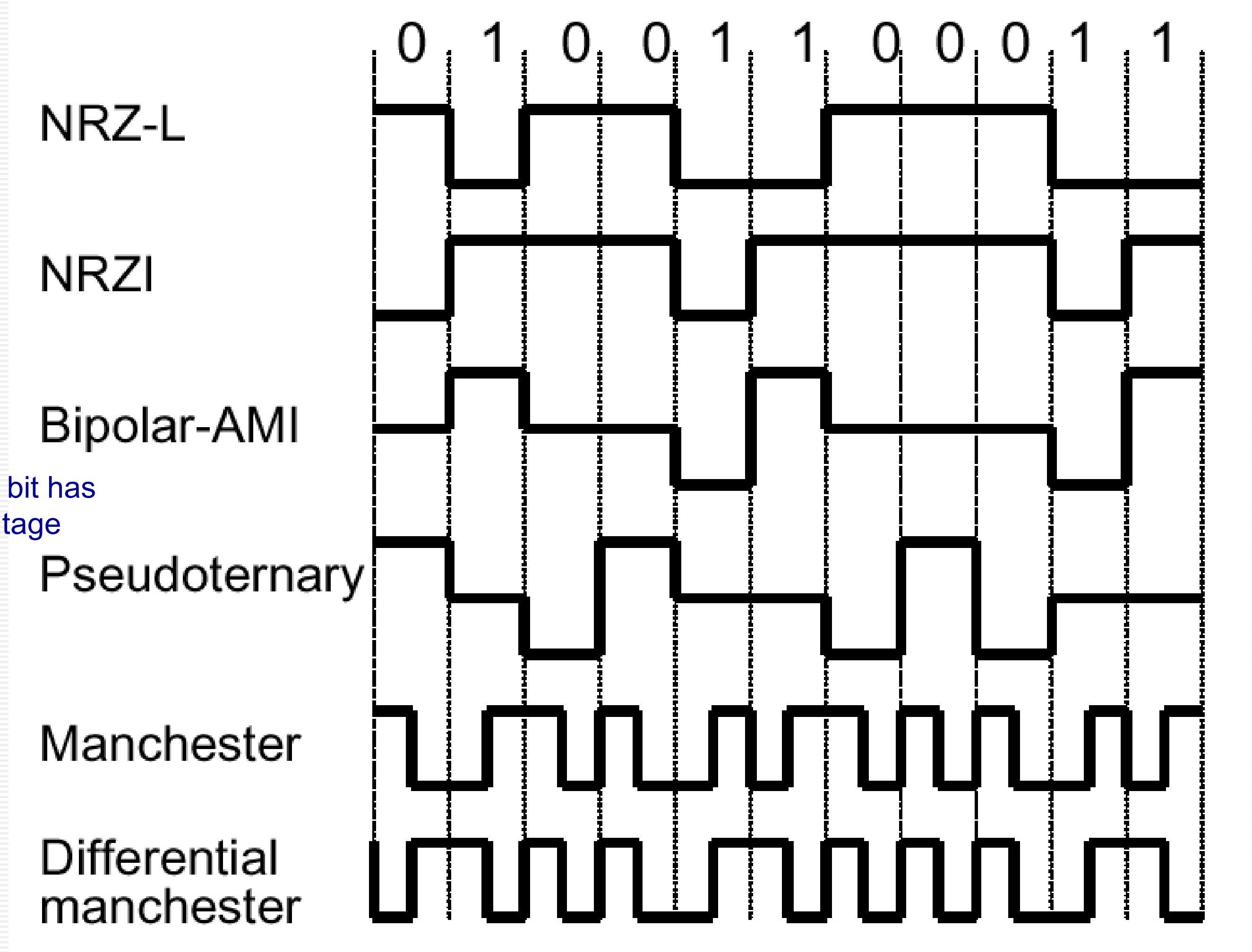
- Bipolar-AMI(Alternate Mark Inversion)
  - three voltage levels(positive, zero, negative)
  - 0: zero voltage
  - 1: alternately by positive and negative voltages
  - better synchronization than NRZ
  - no dc component
  - error detection capability
- Pseudoternary
  - Same as bipolar-AMI, except representation of 0 and 1 is interchanged

Digital Data → Digital Signals (6)

Biphase

- Always a transition at the middle of each bit interval
- Manchester
  - 0: high to low transition
  - 1: low to high transition
- Differential Manchester
  - 0: transition at the beginning of bit interval
  - 1: no transition
- Synchronization and error detection capability, and no dc component

Digital Data ⟶ Digital Signals (7)



most recent
preceding 1 bit has
negative voltage

Digital Data →Digital Signals (8)

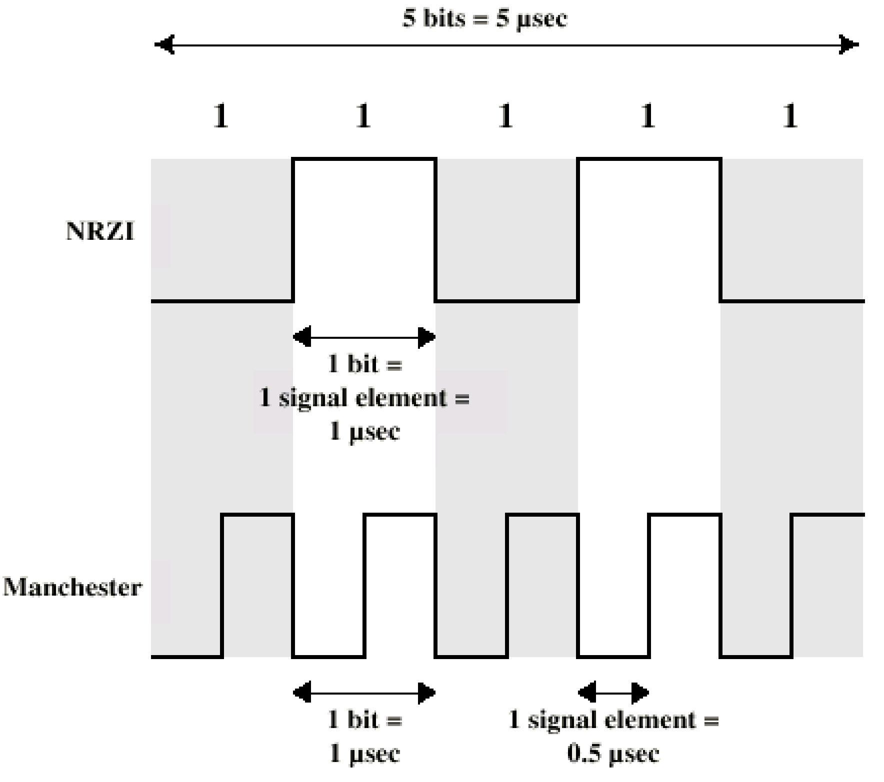
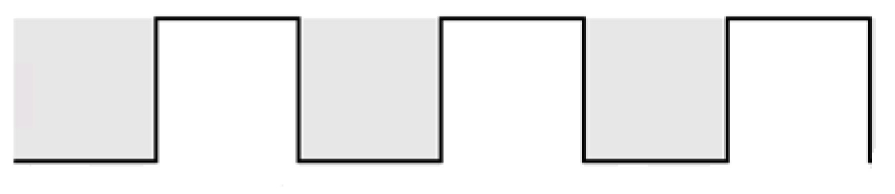


Figure 5.5 A Stream of Binary Ones at 1 Mbps

Digital Data ⟶ Digital Signals (9)



NRZI: 6 bits

Manchester: 3 bits ⇒ lower data rate

Digital Data → Digital Signals (10)

Scrambling Techniques

- For long-distance communications
- No dc component, good synchronization, and error detection capability, without reduction in data rate
- B8ZS(Bipolar with 8-Zeros Substitution)
  - Based on bipolar-AMI
  - 8 consecutive zeros are encoded as either 000+-0-+ or 000-+0+- so that two code violations always occur

Digital Data ⟶ Digital Signals (11)

- HDB3(High-Density Bipolar 3-Zeros)
  - 4 zeros are encoded as either 000-, 000+, +00+, or -00-
  - Substitution rule :
    - the 4th bit is always a code violation,
    - successive violations are of alternate polarity
      (not to introduce dc component)

Polarity of preceding pulse	Number of ones since last substitution	
	odd	even
-	000-	+00+
+	000+	-00-

last substitution

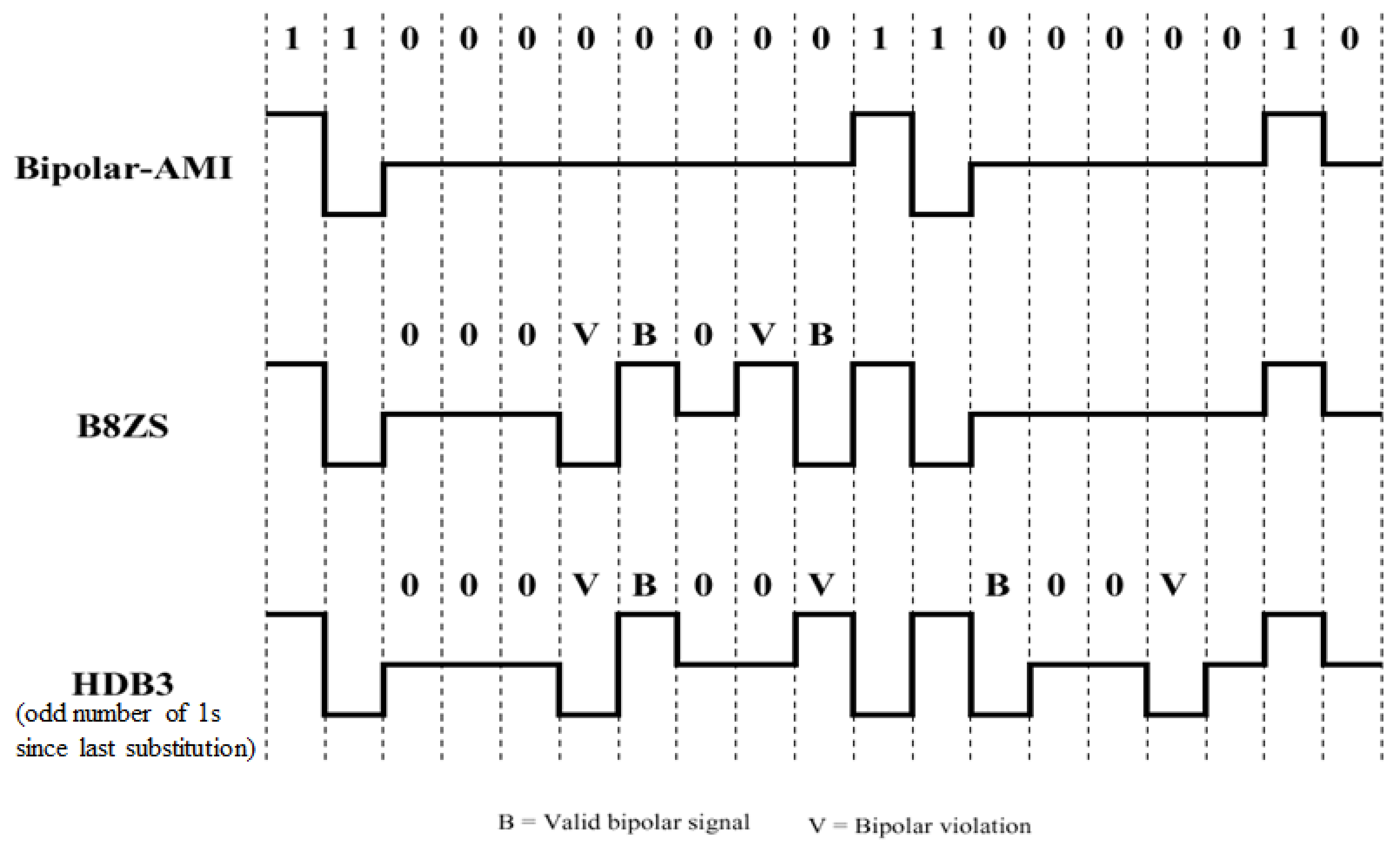
Polarity of preceding pulse

Example:

+ 000 - 00 + 00 - 000-

- 00+000 - + 0 - +00+

Digital Data ⟶ Digital Signals (12)



B = Valid bipolar signal V = Bipolar violation

Digital Data ⟶ Digital Signals (13)

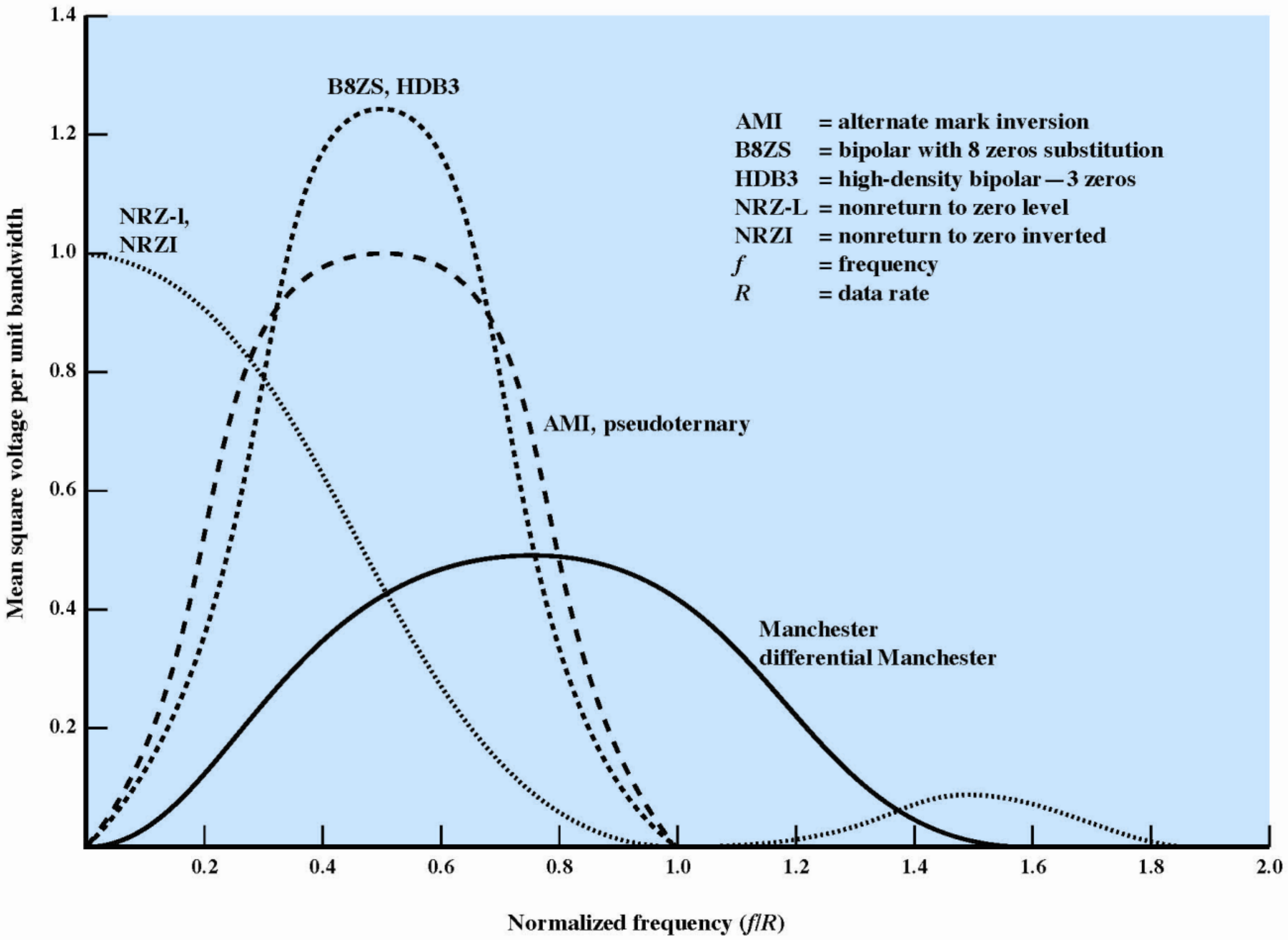


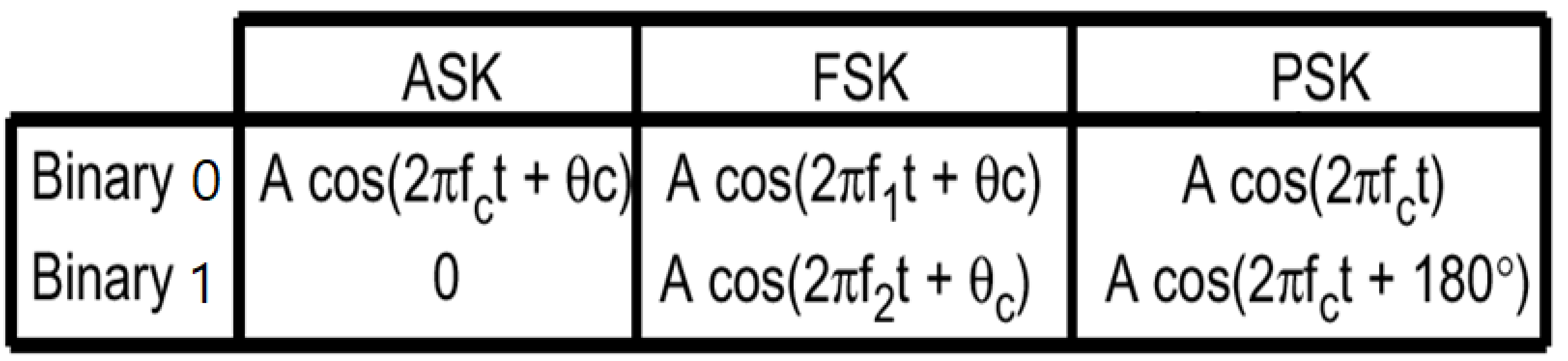
Figure 5.3 Spectral Density of Various Signal Encoding Schemes

Digital Data ⟶ Digital Signals (14)

- Evaluation factors for encoding schemes
  - Signal spectrum
    - less bandwidth, no dc component
    - shape of spectrum(better to center in the middle of bandwidth)
  - Self-clocking capability
    - It is desired for synchronization
  - Error detection capability
  - Signal interference and noise immunity
  - Cost and complexity

Digital Data → Analog Signals (1)

- Encoding is by modulation of a continuous sinusoidal carrier signal. $A\cos(2\pi f_c+\theta_c)$
- This involves alteration of some characteristics of the carrier signal-amplitude, frequency, or phase.
- Various encoding techniques: ASK, FSK, PSK, ...



	ASK	FSK	PSK
Binary 0	$A\cos(2\pi f_c t + \theta c)$	$A\cos(2\pi f_1 t + \theta c)$	$A\cos(2\pi f_c t)$
Binary 1	0	$A\cos(2\pi f_2 t + \theta_c)$	$A\cos(2\pi f_c t + 180°)$

Digital Data ⟶ Analog Signals (2)

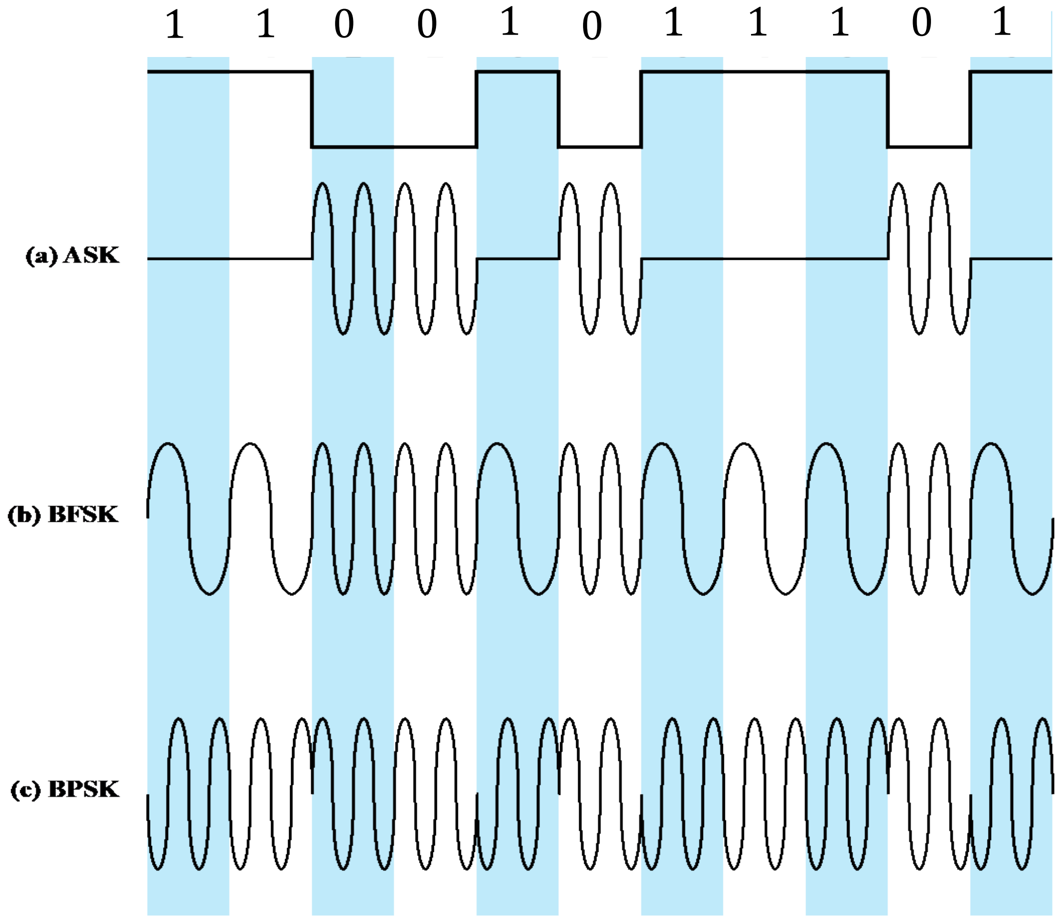


Figure 5.7 Modulation of Analog Signals for Digital Data

Digital Data ⟶ Analog Signals (3)

- QPSK(Quadrature PSK) modulation

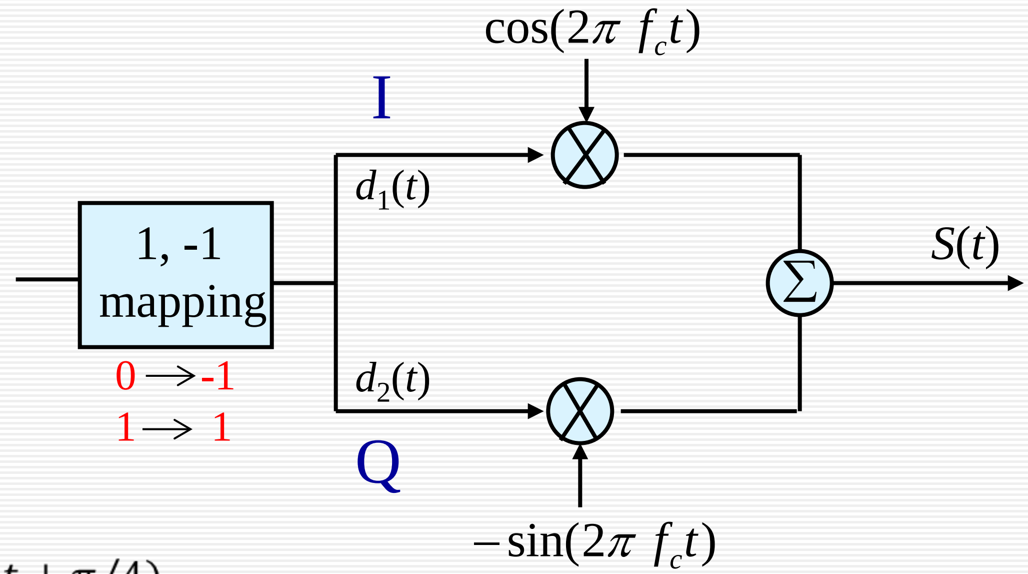
Bit phase IQ

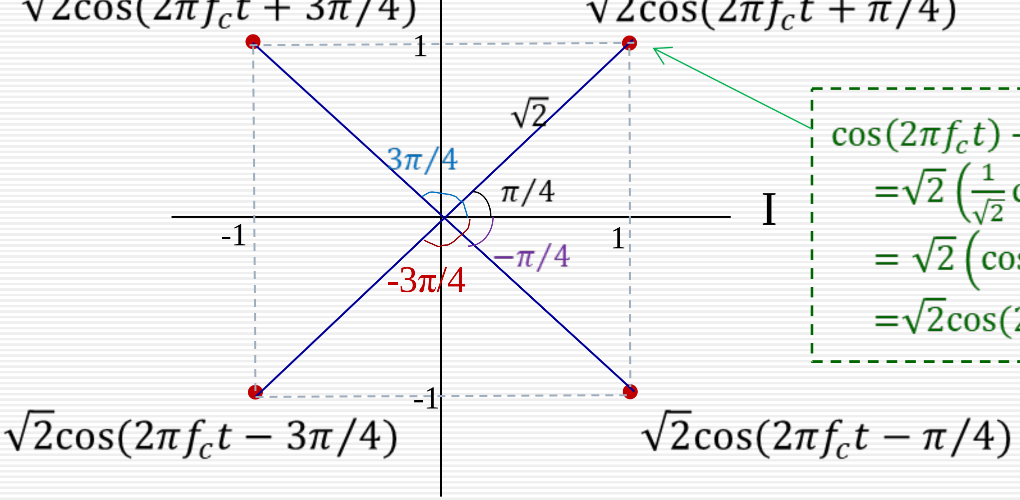
1 1: $\pi/4$ (+1+j)

0 1: $3\pi/4$ (-1+j)

0 0: $-3\pi/4$ (-1-j)

1 0: $-\pi/4$ (+1-j)





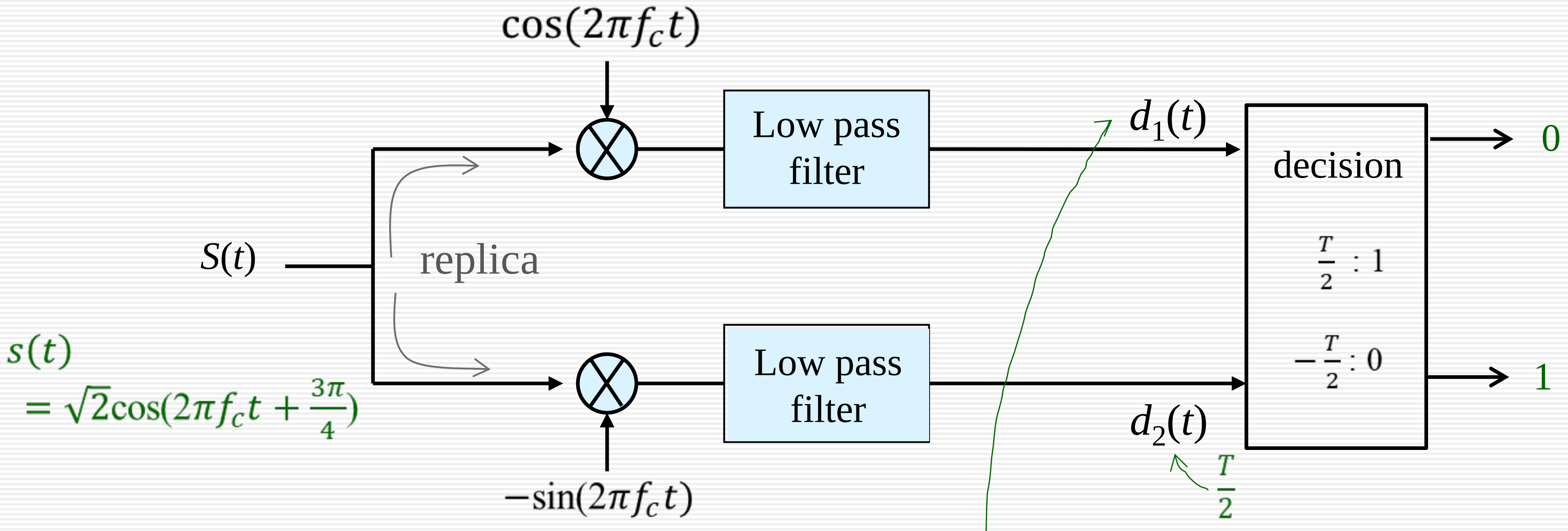
$$\begin{aligned}
&\cos(2\pi f_c t) - \sin(2\pi f_c t)\\
&=\sqrt{2}\left(\tfrac{1}{\sqrt{2}}\cos(2\pi f_c t) - \tfrac{1}{\sqrt{2}}\sin(2\pi f_c t)\right)\\
&= \sqrt{2}\left(\cos\left(\tfrac{\pi}{4}\right)\cos(2\pi f_c t) - \sin(\tfrac{\pi}{4})\sin(2\pi f_c t)\right)\\
&=\sqrt{2}\cos(2\pi f_c t + \tfrac{\pi}{4})
\end{aligned}$$

$\cos(A+B) = \cos A\cos B - \sin A\sin B$

$\sin(A+B) = \sin A\cos B + \cos A\sin B$

Digital Data → Analog Signals (4)

- QPSK demodulation



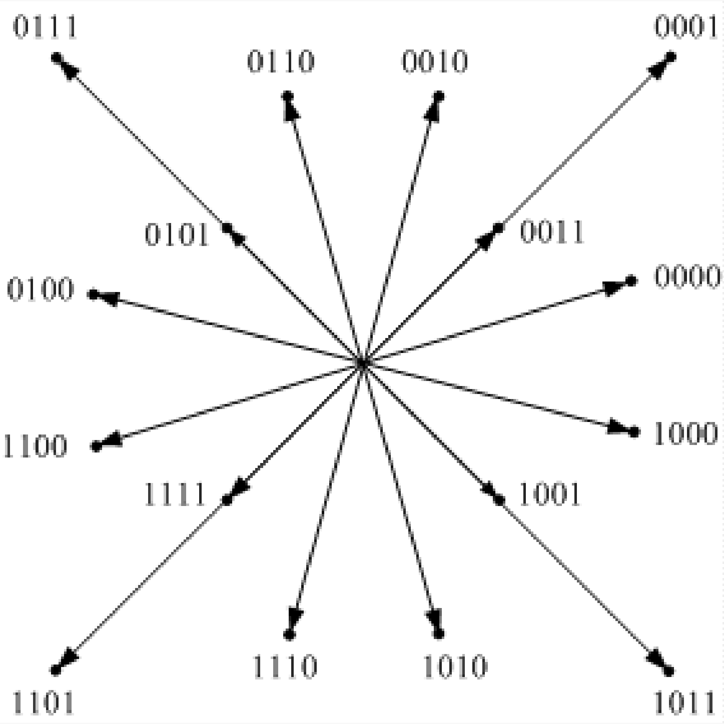
$$s(t) = \sqrt{2}\cos(2\pi f_c t + \frac{3\pi}{4})$$

$$\int_0^T s(t)\cos(2\pi f_c t)dt = \int_0^T \sqrt{2}\cos(2\pi f_c t + \frac{3\pi}{4})\cos(2\pi f_c t)dt$$
$$= \sqrt{2}\int_0^T \cos(2\pi f_c t)\, cos\frac{3\pi}{4}\cos(2\pi f_c t)dt - \sqrt{2}\int_0^T \sin(2\pi f_c t)\, sin\frac{3\pi}{4}\cos(2\pi f_c t)\, dt$$
$$=- \int_0^T \cos(2\pi f_c t)\cos(2\pi f_c t)dt - \int_0^T \sin(2\pi f_c t)\cos(2\pi f_c t)\, dt$$
$$=- \frac{1}{2}\int_0^T (\cos(4\pi f_c t) + cos0)dt - \frac{1}{2}\int_0^T (\sin(4\pi f_c t) + sin0)dt$$
$$=- \frac{1}{2}\int_0^T \cos(4\pi f_c t)\, dt \;- \frac{1}{2}\int_0^T 1\, dt - \int_0^T \sin(4\pi f_c t)\, dt = -\frac{T}{2}$$

$\cos(A+B) = \cos A\cos B - \sin A\sin B$
$\cos(A-B) = cosAcosB + sinAsinB$
$\sin(A+B) = \sin A\cos B + \cos A\sin B$
$\sin(A-B) = sinAcosB - cosAsinB$

Digital Data ⟶ Analog Signals (5)

Constellation Pattern



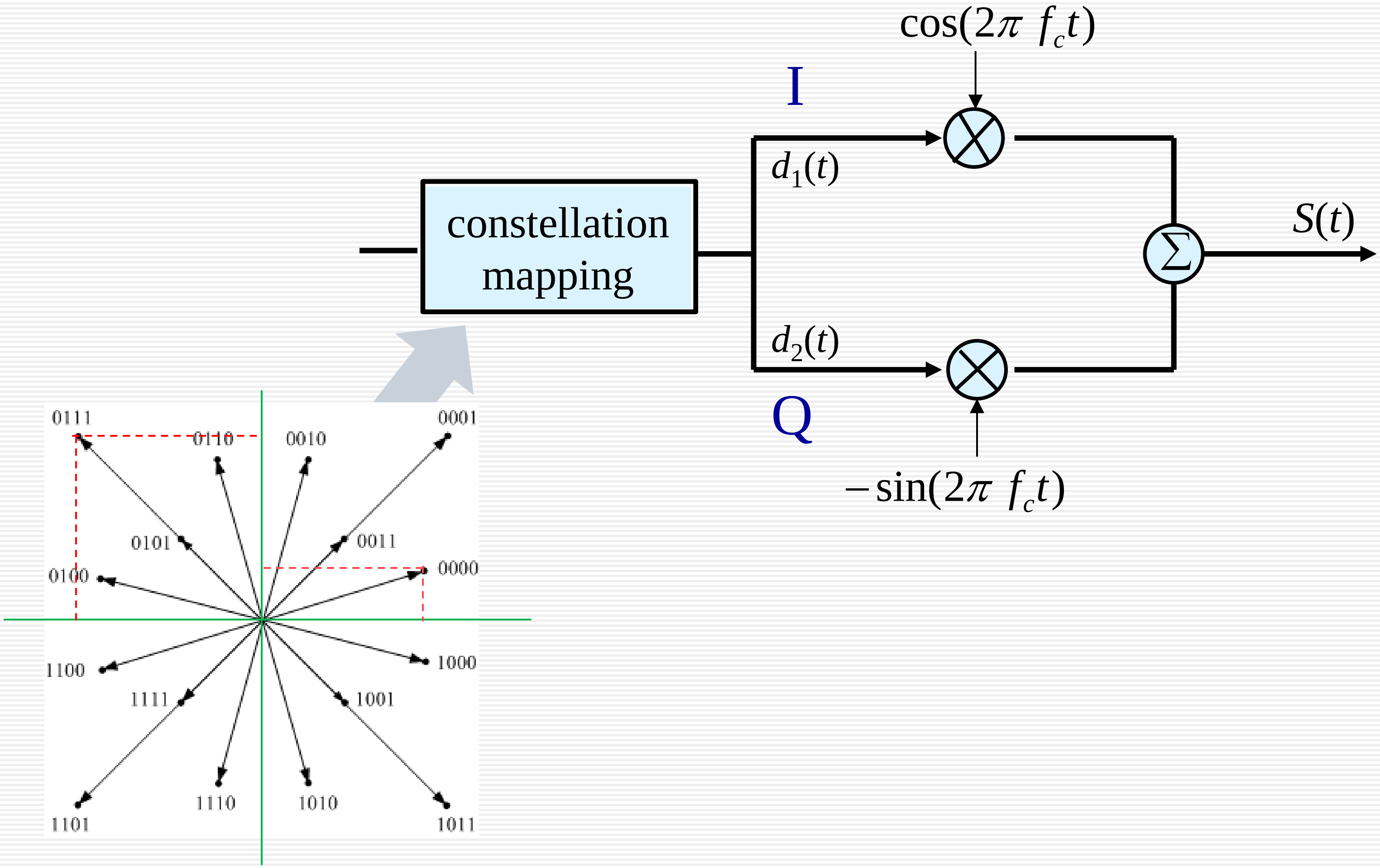
- PSK using 12 angles and three amplitudes - 9,600 bps modem (2,400 baud)

Digital Data ⟶ Analog Signals (6)

- Modulation Rate
  - Data rate (in bps) = modulation rate (in baud) x the number of bits per signal element
- Constellation Pattern
  - The patterns showing legal combinations of amplitude and phase
- Example (2400 baud)
  - 64 points constellation ⇒ 14,400 bps modem
  - 128 points constellation ⇒ 16,800 bps modem

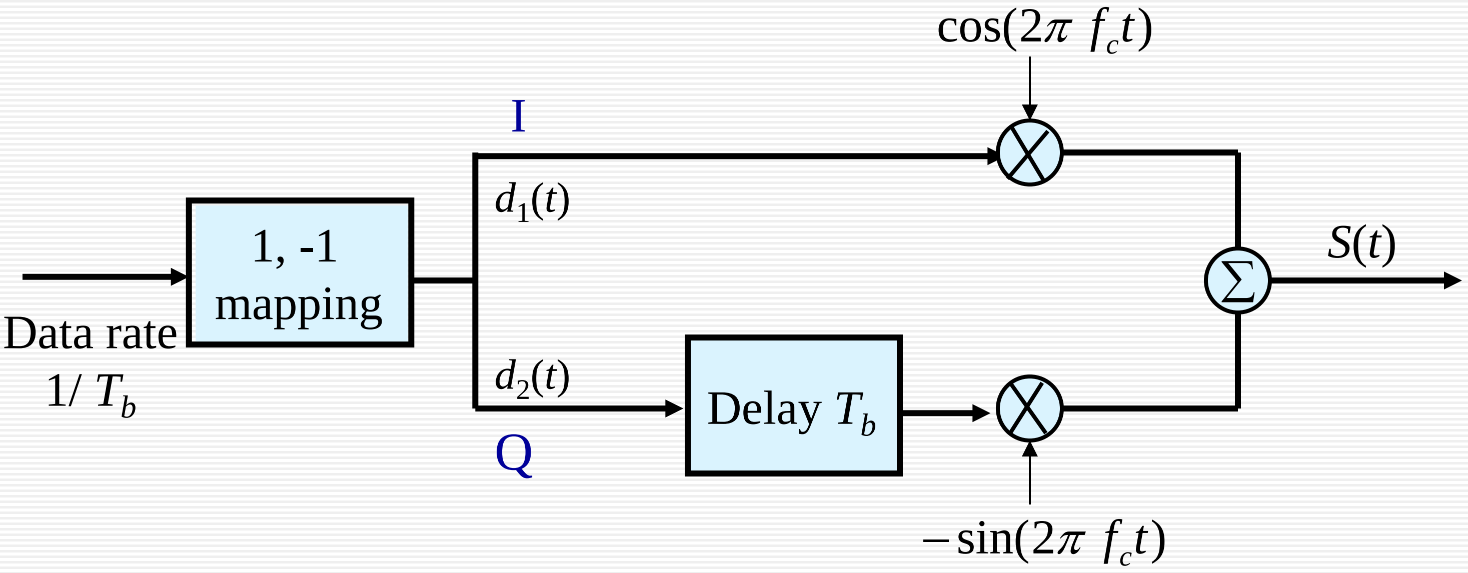
Digital Data → Analog Signals (7)

- QAM modulator

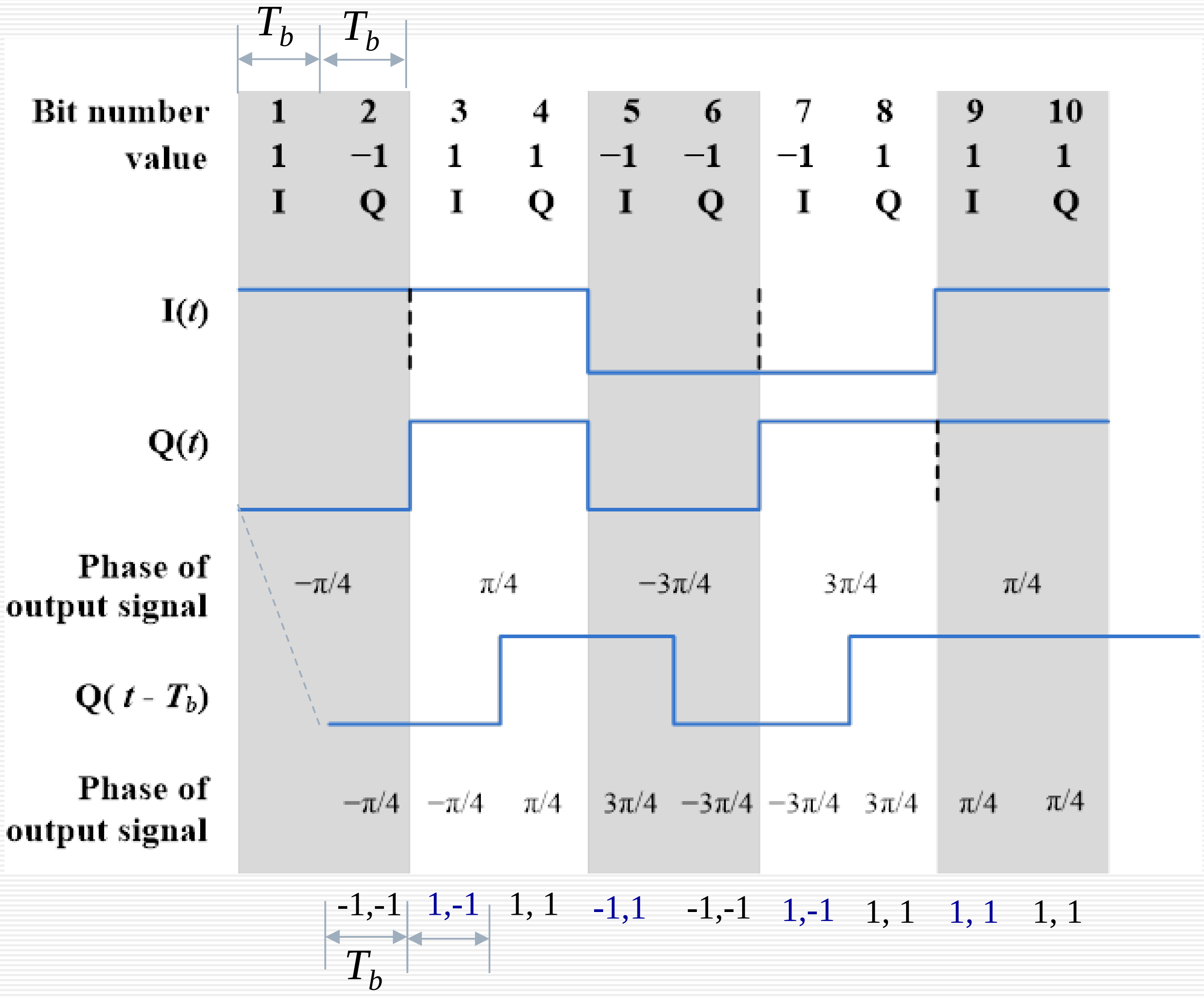


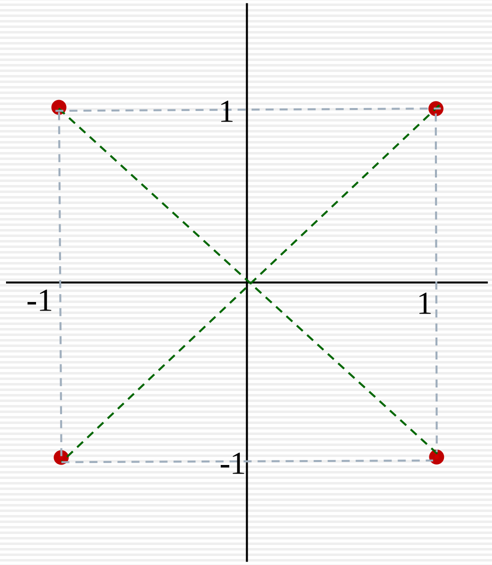
Digital Data $\rightarrow$ Analog Signals (8)

- Offset-QPSK modulation



Offset-QPSK


T_b
T_b
Bit number 1 2 3 4 5 6 7 8 9 10
value 1 −1 1 1 −1 −1 −1 1 1 1
I Q I Q I Q I Q I Q
I(t)
Q(t)
Phase of output signal
−π/4 π/4 −3π/4 3π/4 π/4
Q(t - T_b)
Phase of output signal
−π/4 −π/4 π/4 3π/4 −3π/4 −3π/4 3π/4 π/4 π/4
-1,-1 1,-1 1, 1 -1,1 -1,-1 1,-1 1, 1 1, 1 1, 1
T_b


1
-1
1
-1

Digital data transmission terminology

Term	Description
Data element	bits (binary one or zero)
Data rate	bits per second(bps) 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
Signaling rate or modulation rate	signal elements per second (baud) rate at which signal elements are transmitted

Analog Data → Digital Data (1)

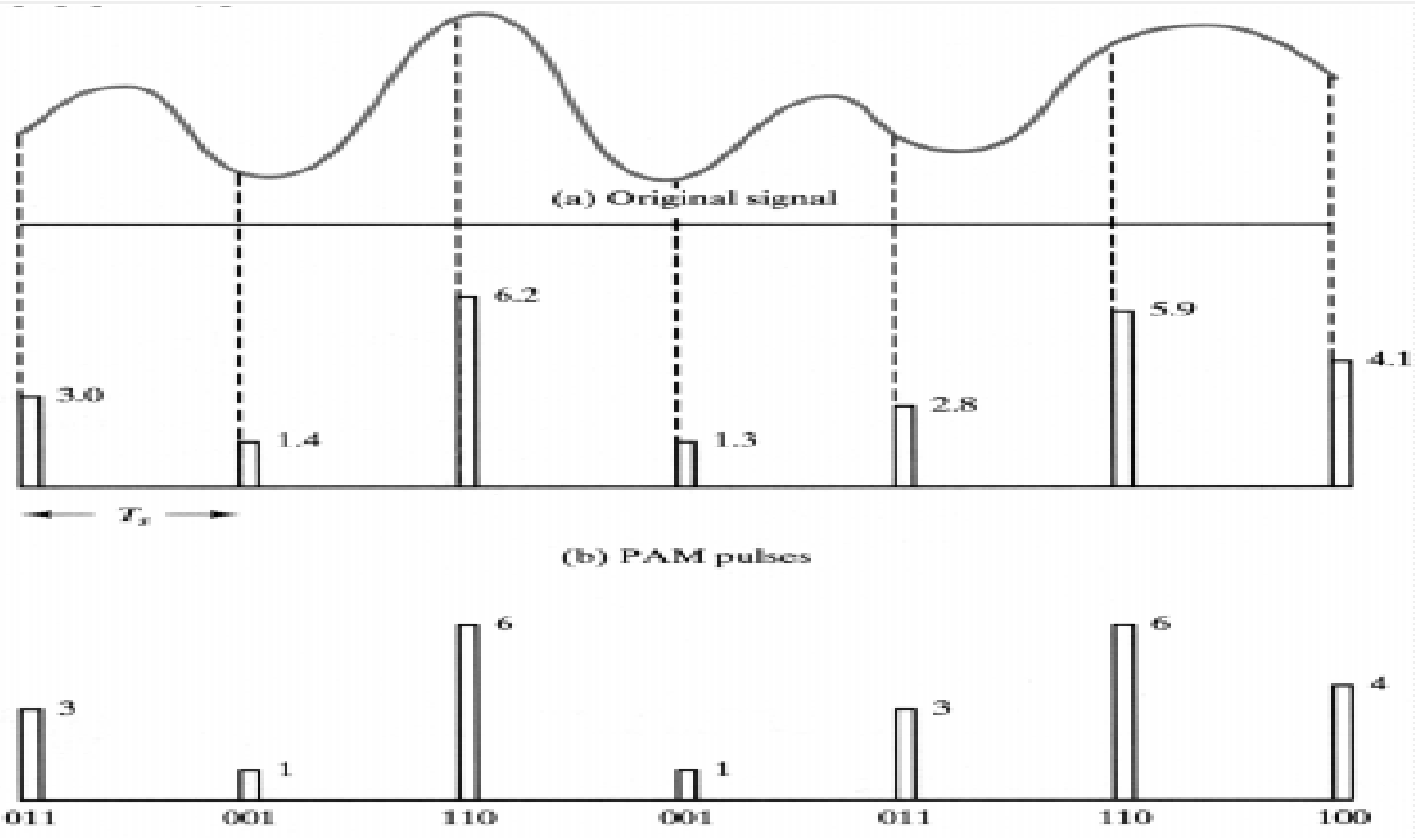
Digitization

- Conversion of analog data into digital data
    - Digital data can then be transmitted using NRZ-L
    - Digital data can then be transmitted using code other than NRZ-L
    - Digital data can converted to analog signal
- Analog to digital conversion done using a codec
- Pulse code modulation
- Delta modulation

Analog Data → Digital Data (2)

- PCM(Pulse Code Modulation)
  - Based on the Nyquist’s Sampling Theorem
- Nyquist’s sampling Theorem
  - If a signal is sampled at regular intervals at a rate higher than twice the highest signal frequency, the samples contain all the information of the original signal
  - example (voice)
    - sampling rate = 8000 sampling/sec (1 sampling/125μs)
    - 1 sample = 8 bits
    - 64kbps

Analog Data ⟶ Digital Data (3)



(a) Original signal

(b) PAM pulses

(c) PCM pulses

011001110001011110100

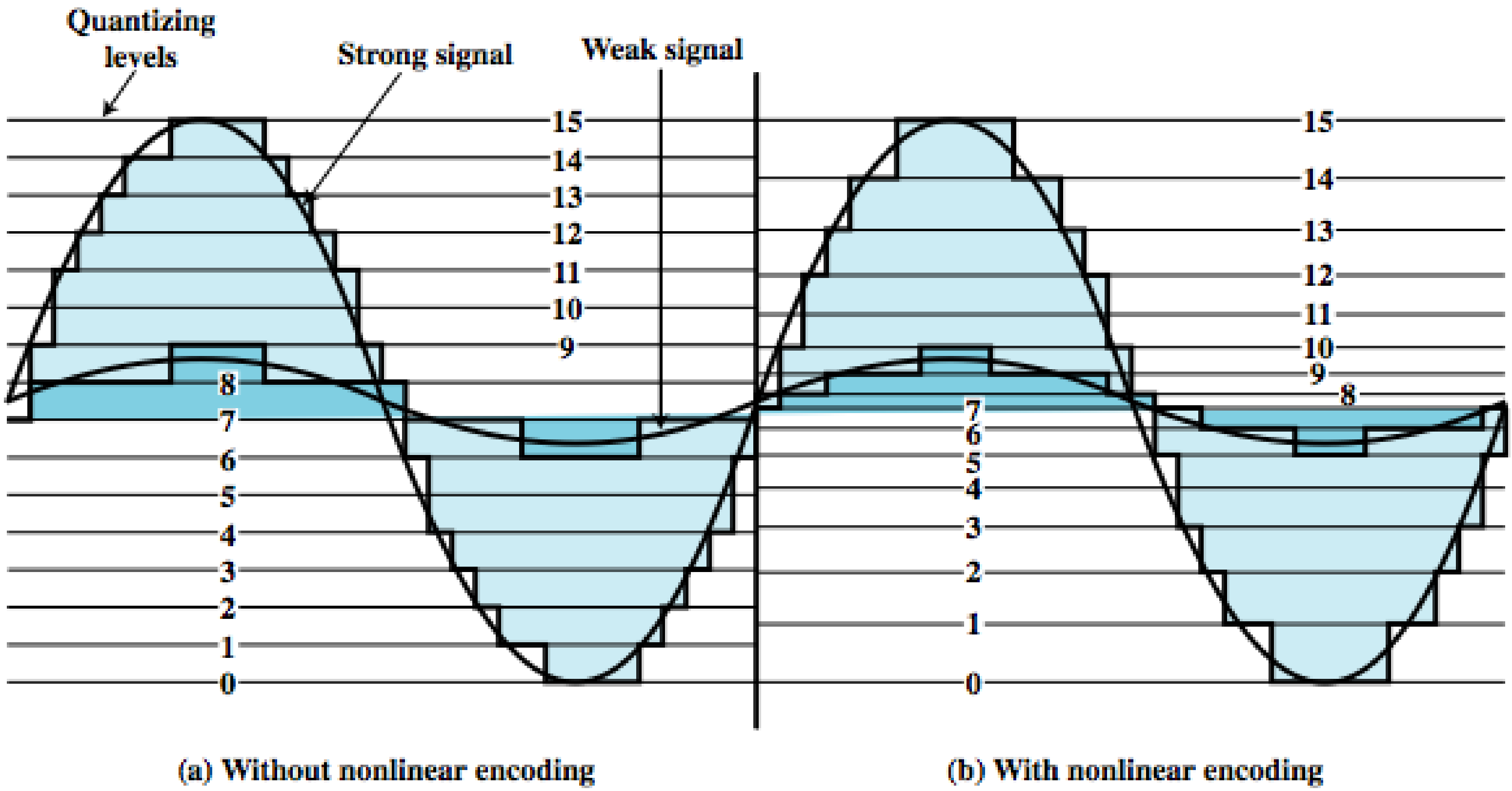
(d) PCM output

Analog Data → Digital Data (4)

- Analog-to-Digital Conversion

- PCM
  - To reduce the information loss due to quantization
    - a large *n*, where *n* is the number of bits per sample
    - nonlinear coding or companding+linear coding

Analog Data → Digital Data (5)



Effect of nonlinear coding

Companding (compressing-expanding)

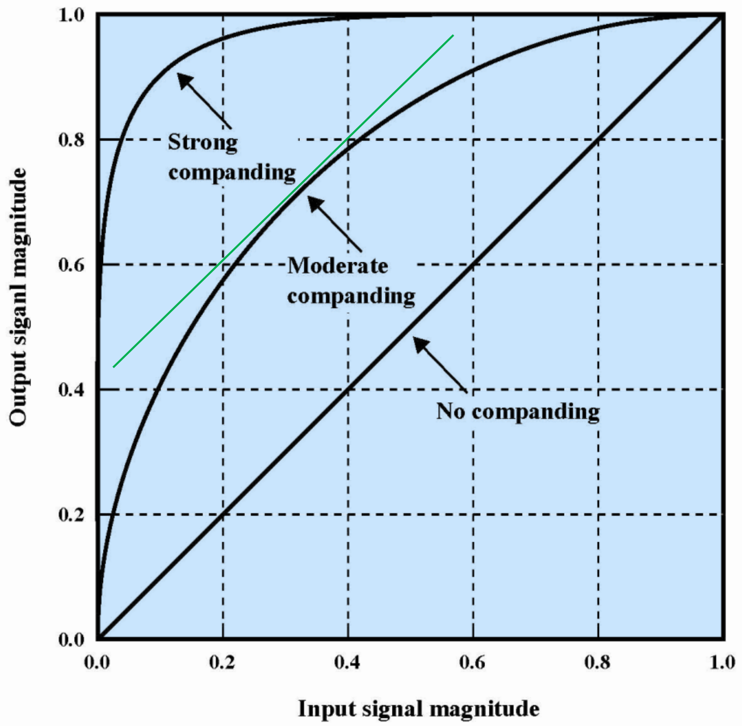


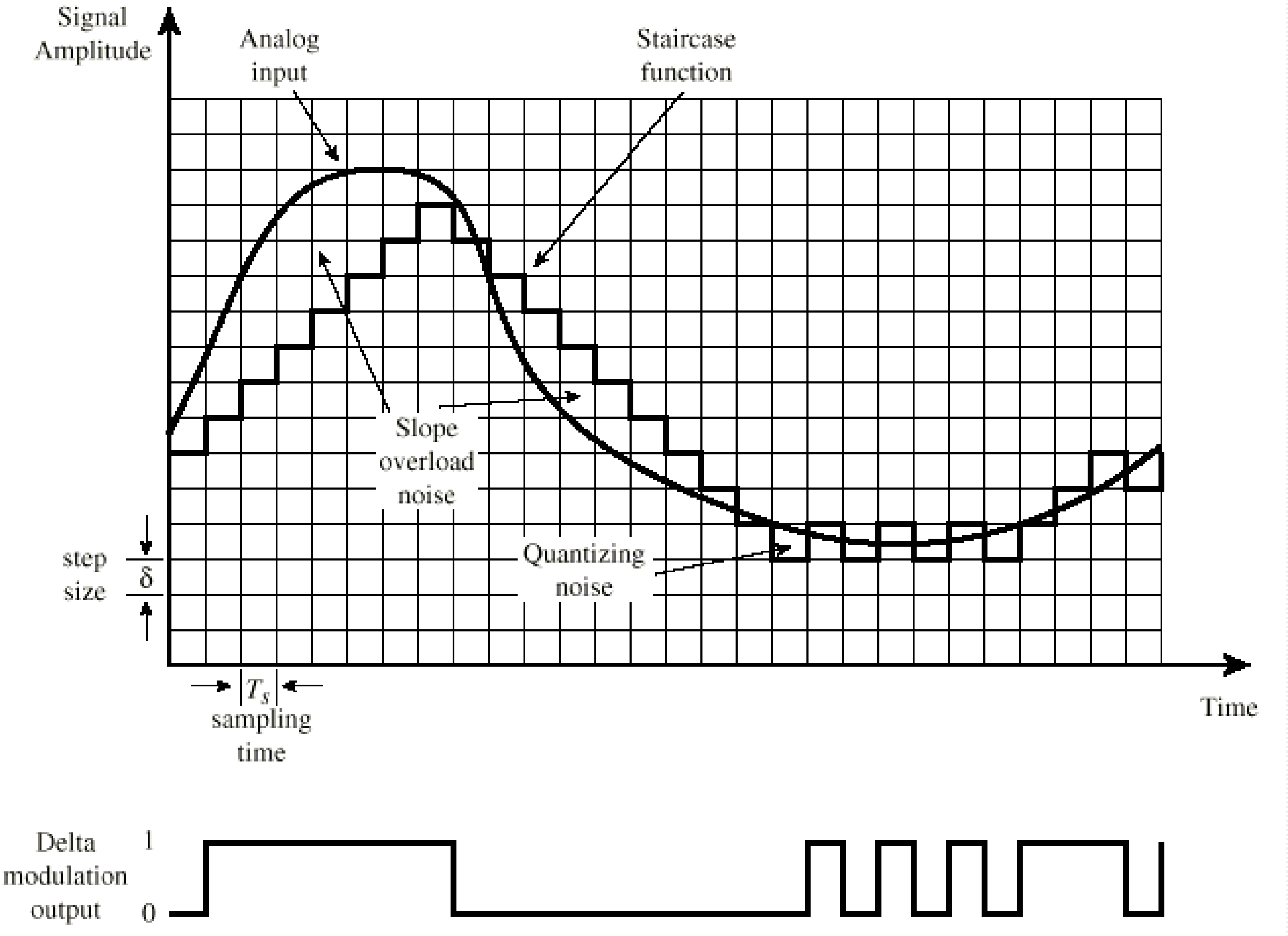
Figure 5.19 Typical Companding Functions

Analog Data ⟶ Digital Data (6)

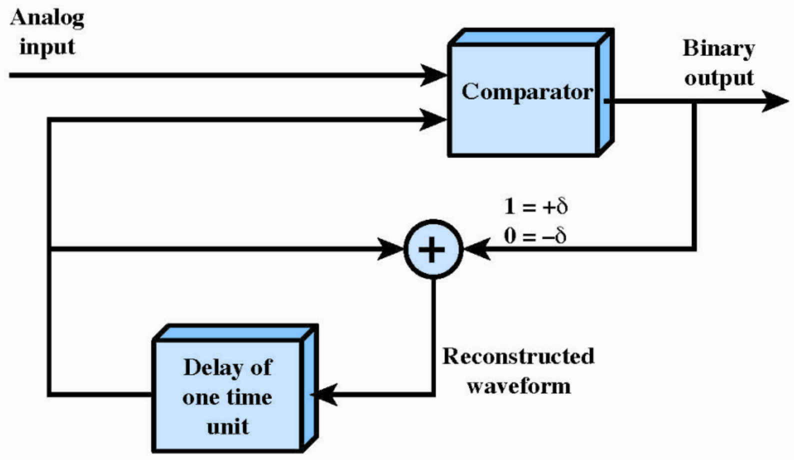
DM(Delta Modulation)

- This uses *n*=1
  - Higher sampling rate than PCM(Nyquist’s rate) is needed, but each sample uses only 1 bit instead of *n.*
- Analog input is approximated by a staircase function
  - Move up or down by δ at each sampling time
- binary digital signal is produced;
  - “0” stands for change of -δ
  - “1” for change of +δ.
- Implementation much simpler than PCM.

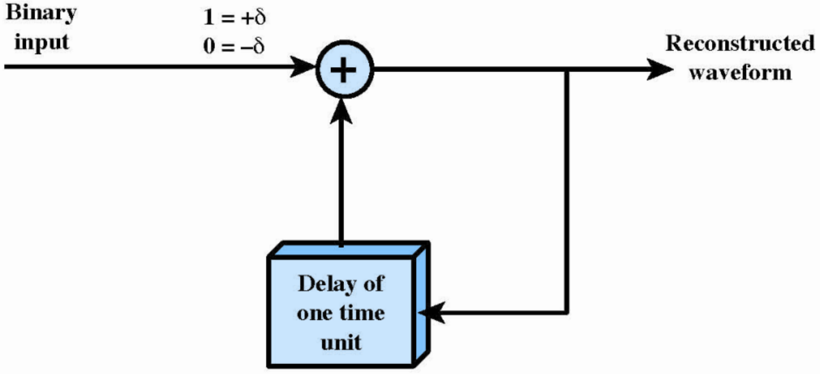
Delta Modulation Example



Delta Modulation



(a) Transmission



(b) Reception