澳 門 理 工 大 學
Universidade Politécnica de Macau
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Faculty of Applied Sciences
B.Sc. in Computing

Academic Year 2022/2023 2nd Semester

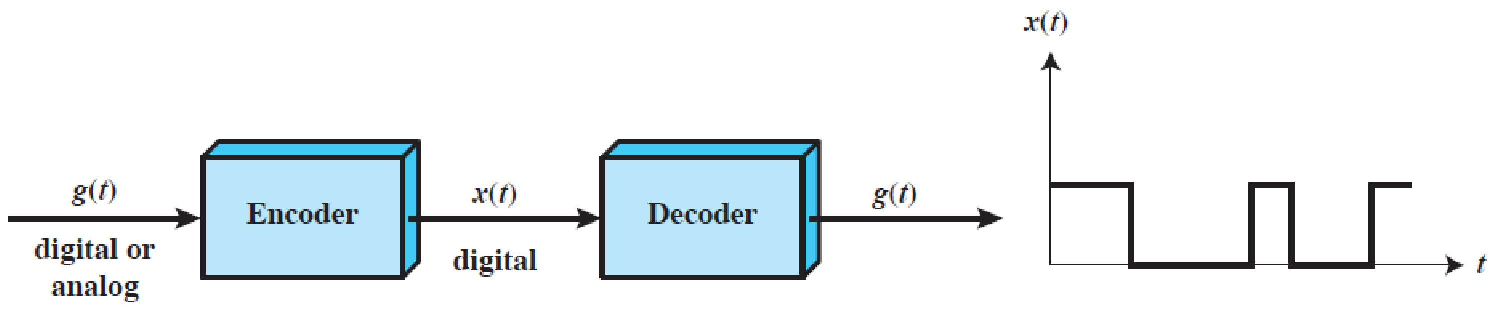
COMP123 – 121/122

Data Communications

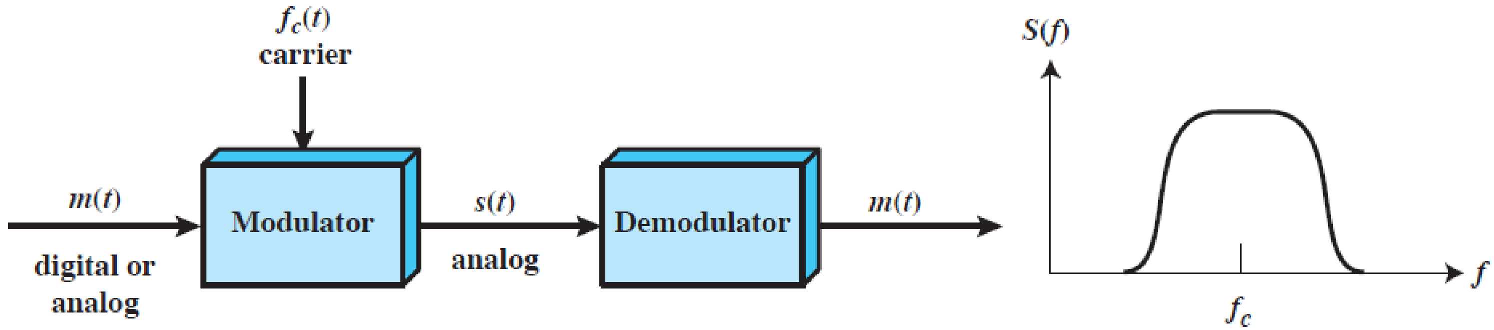
Data Encoding and Modulation

Signal Encoding Techniques

- Both analog and digital data can be encoded as either analog or digital signals.
- The particular encoding chosen depends on the specific requirements.
- Encoding techniques include NRZ, Manchester, AM, FM, PM, ASK, PSK, etc..



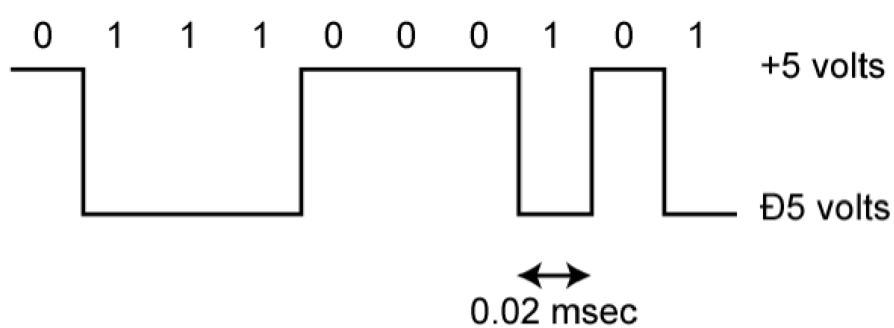
(a) Encoding onto a digital signal



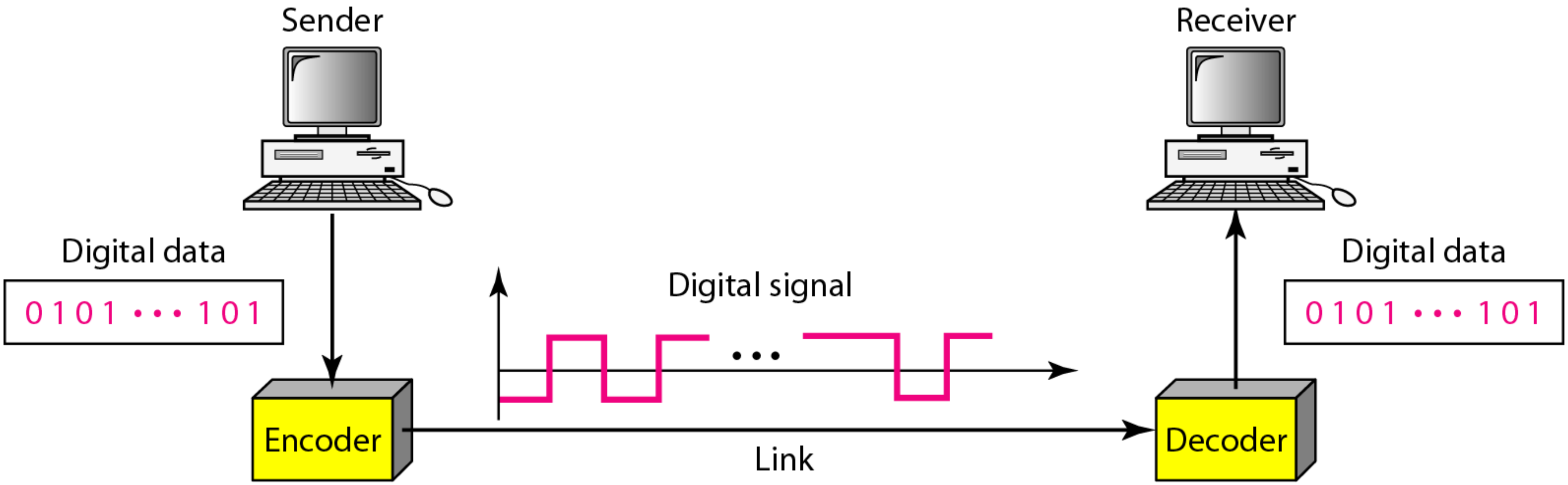
(b) Modulation onto an analog signal

Digital Data and Signals

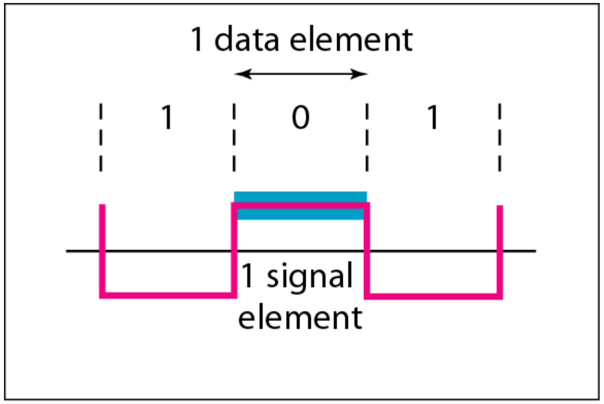
- The process of converting digital data to digital signals is called line coding.
- digital signal
  - discrete, discontinuous voltage pulses
  - each pulse is a signal element
  - binary data encoded into signal elements



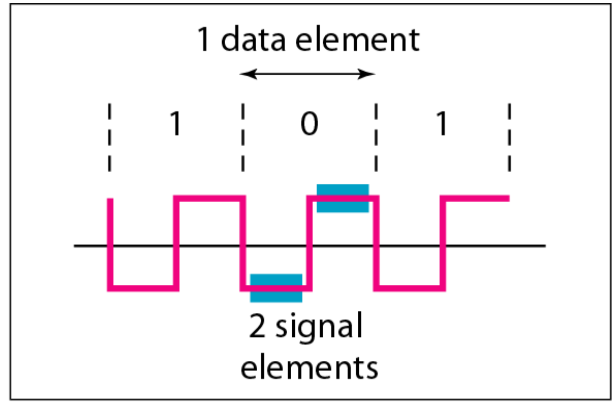
Line Coding and Decoding



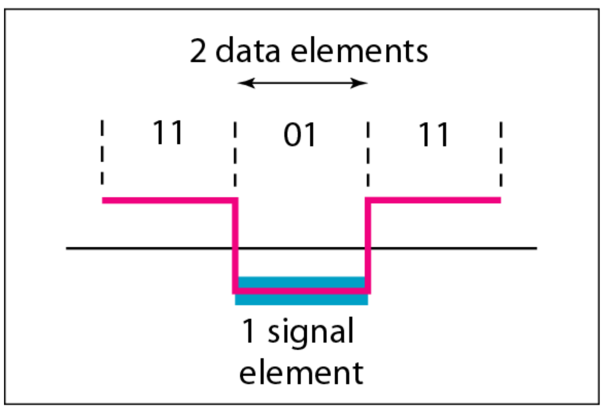
Signal Element versus Data Element



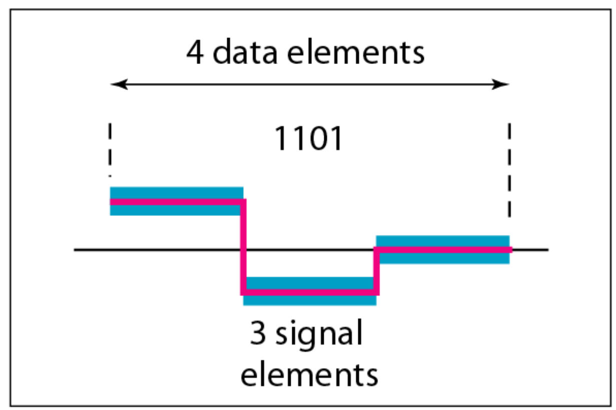
a. One data element per one signal element ($r = 1$)



b. One data element per two signal elements $\left(r = \frac{1}{2}\right)$

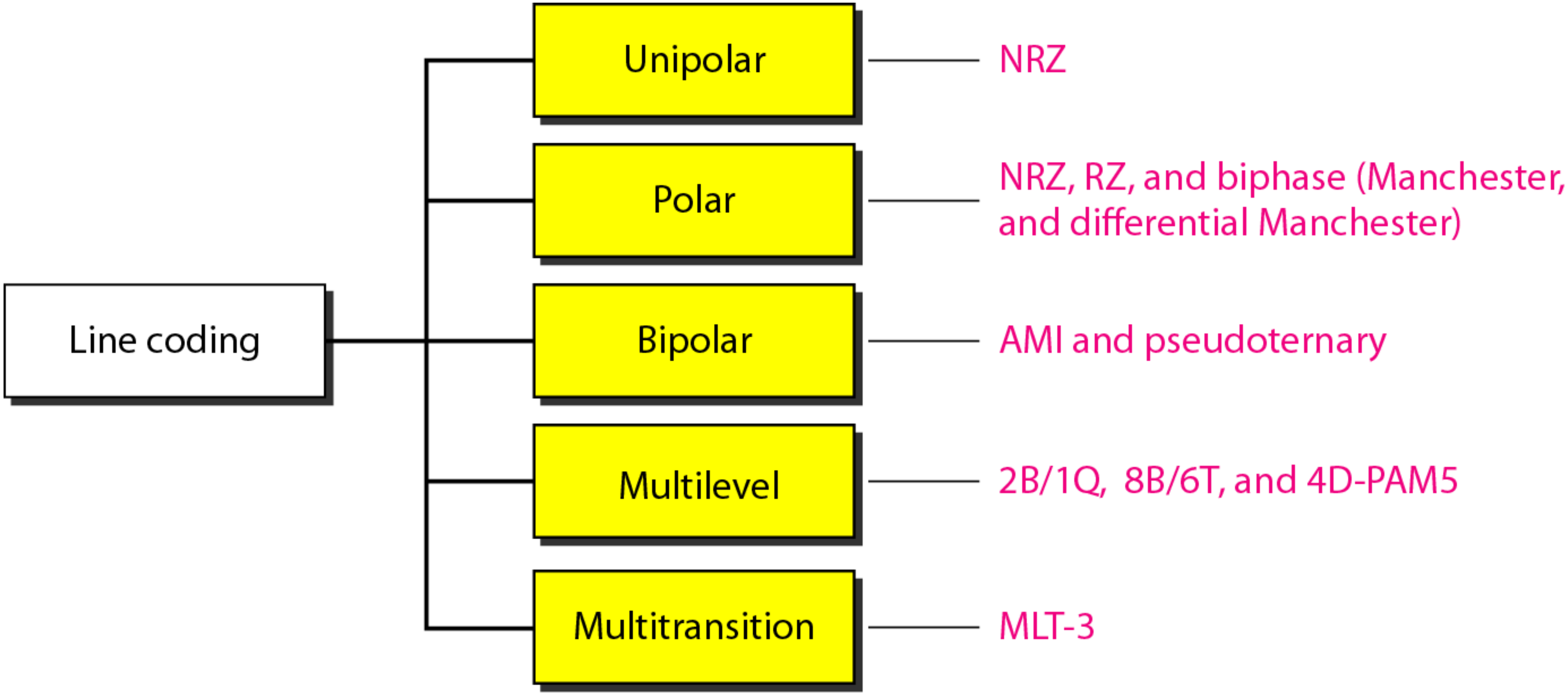


c. Two data elements per one signal element ($r = 2$)



d. Four data elements per three signal elements $\left(r = \frac{4}{3}\right)$

Line Coding Schemes



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 of data (R) transmission in bits per second
- **duration or length of a bit** – time taken for transmitter to emit the bit (1/R)
- **modulation rate** – rate at which the signal level changes, measured in baud = signal elements per second.

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

need to know:

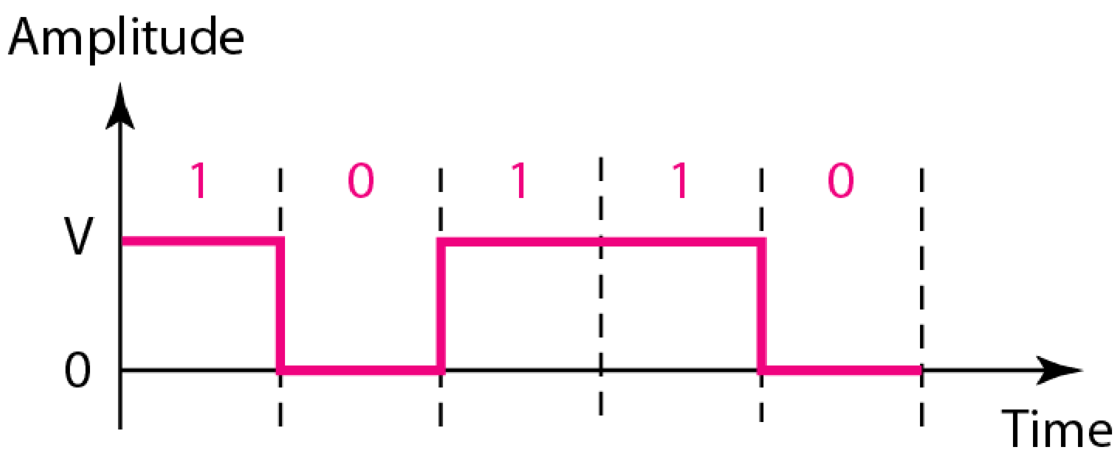
- timing of bits - when they start and end
- signal levels

factors affecting signal interpretation:

- signal to noise ratio (SNR)
- data rate
- bandwidth
- encoding scheme

Unipolar Scheme – NRZ (Non-Return-to-Zero)

- Positive voltage defines bit 1 and the zero voltage defines bit 0
- The signal does not return to zero at the middle of the bit



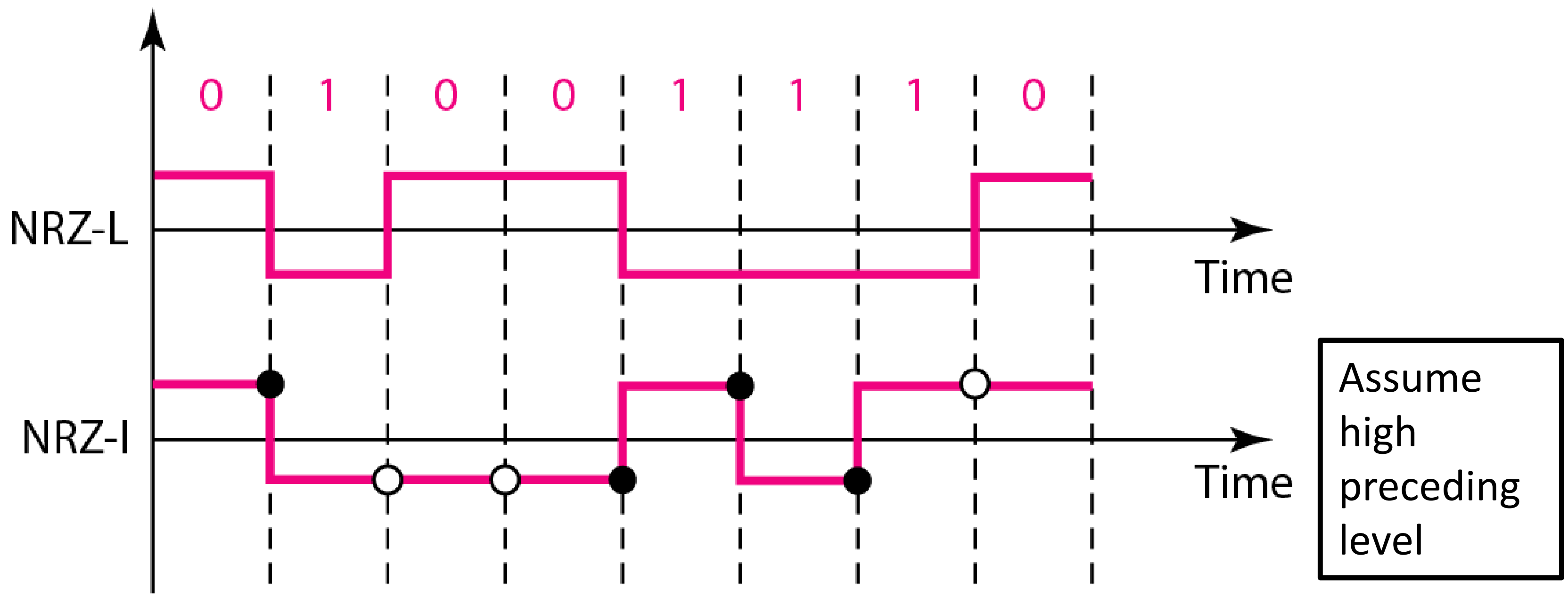
Nonreturn to Zero-Level (NRZ-L)

- easiest way to transmit digital signals is to use two different voltages for 0 and 1 bits
- voltage constant during bit interval
  - no transition (no return to zero voltage)
  - 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 (NRZ-I)

- Non-return to zero, invert on ones
- constant voltage pulse for duration of bit
- data encoded as presence or absence of signal transition at beginning of bit time
  - transition (low to high or high to low) denotes binary 1
  - no transition denotes binary 0
- example of <u>differential encoding</u>
  - data represented by <u>changes</u> 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

Comparison of NRZ-L and NRZ-I



○ No inversion: Next bit is 0 ● Inversion: Next bit is 1

NRZ Pros & Cons

Pros

- easy to engineer
- make efficient use of bandwidth

➢ used for magnetic recording

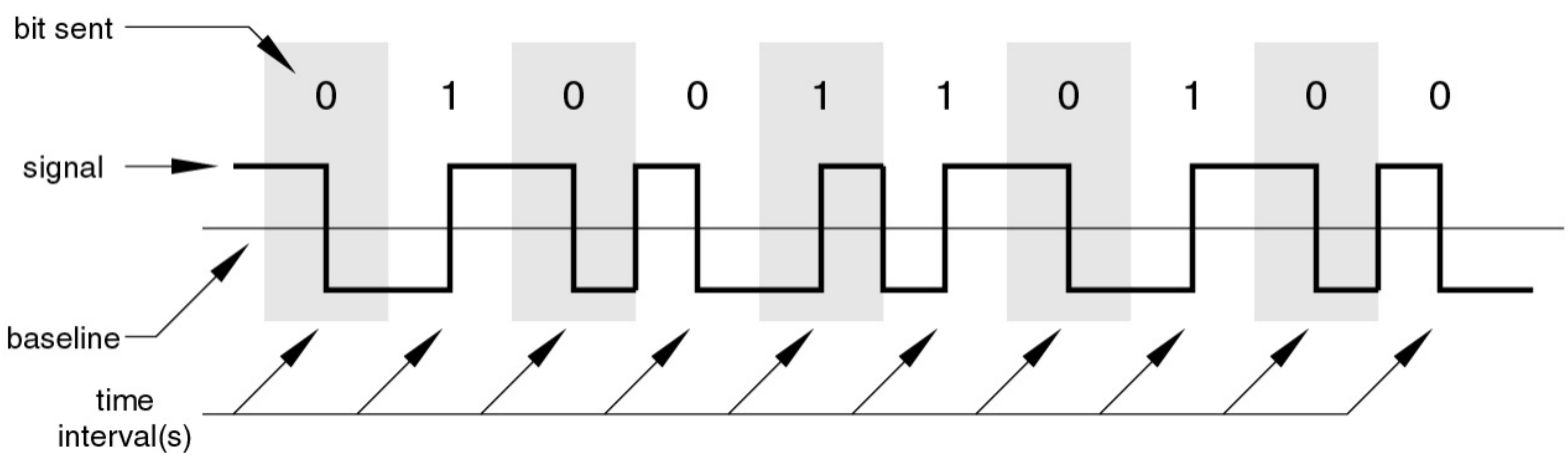
Cons

- presence of a dc component
- lack of synchronization capability

➢ not often used for signal transmission

Manchester Encoding

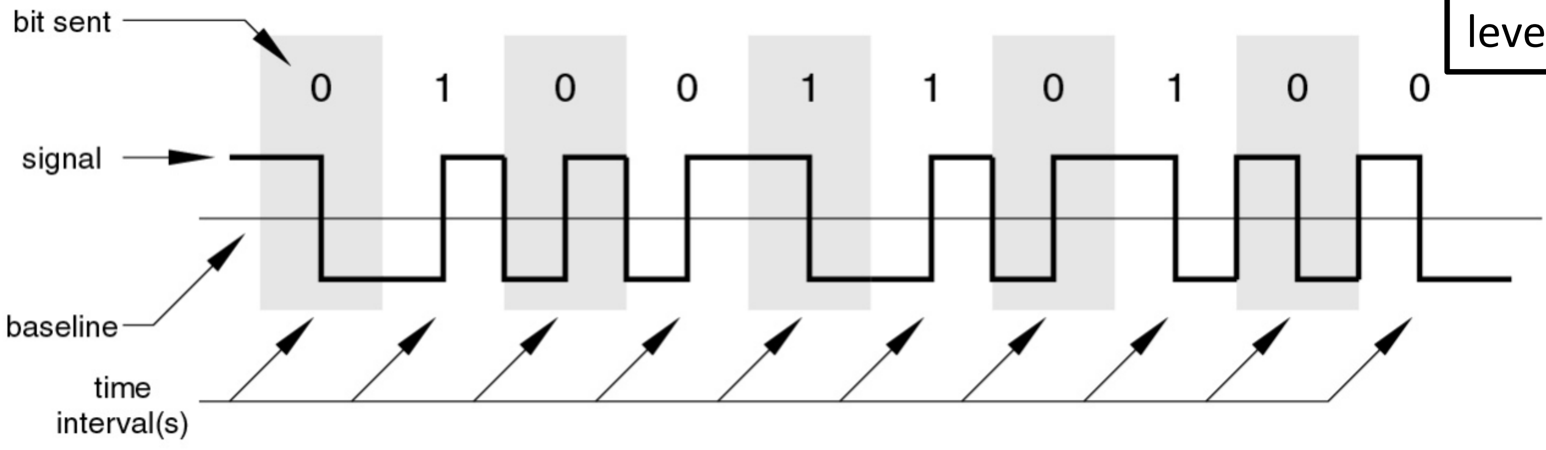
- transition in middle of each bit period
- midbit transition serves as clock and data
- low to high transition represents a 1
- high to low transition represents a 0
- used by IEEE 802.3



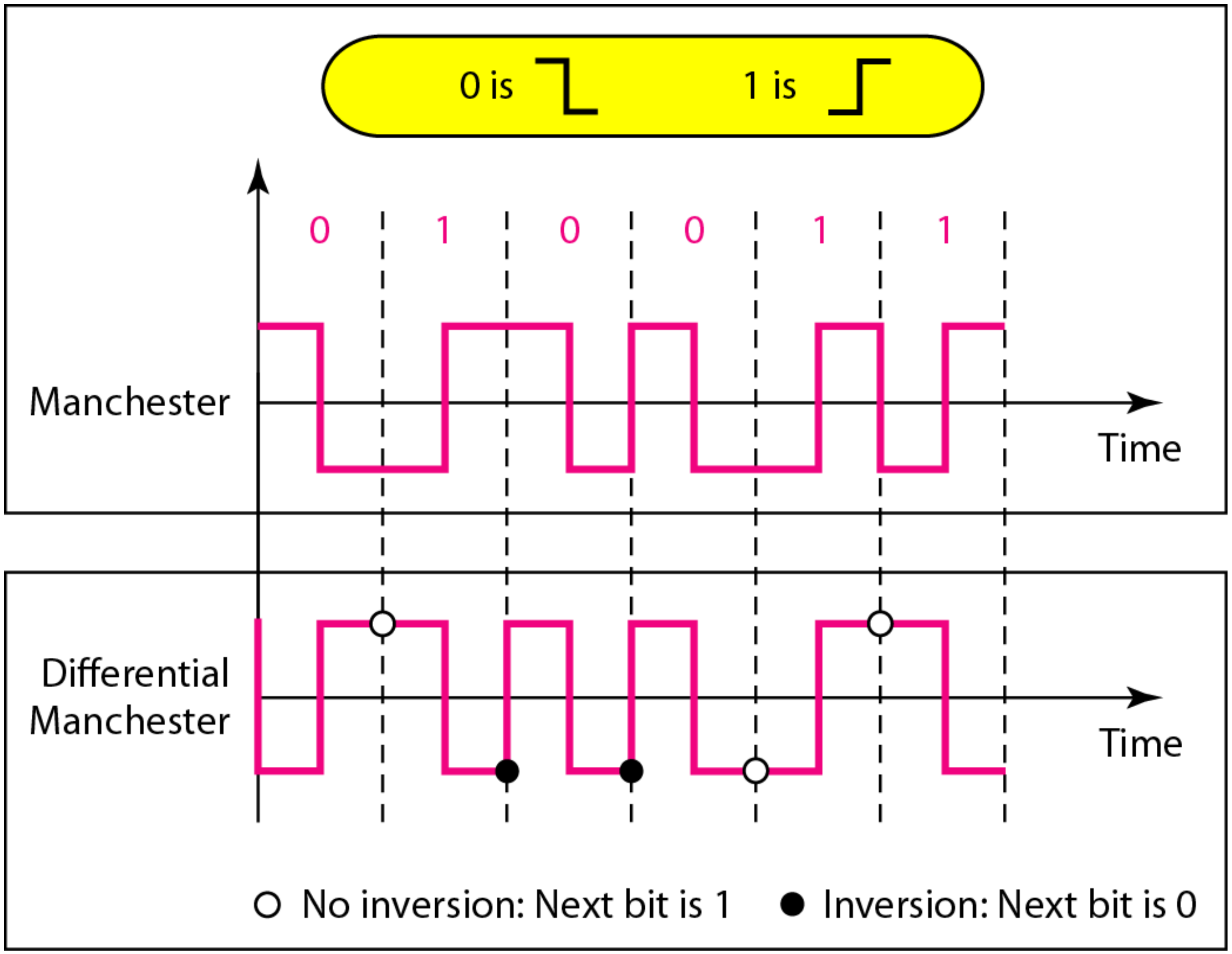
Differential Manchester Encoding

- midbit transition is only used for clocking
- transition at start of bit period representing 0
- no transition at start of bit period representing 1
  - this is a differential encoding scheme
- used by IEEE 802.5

Assume low preceding level



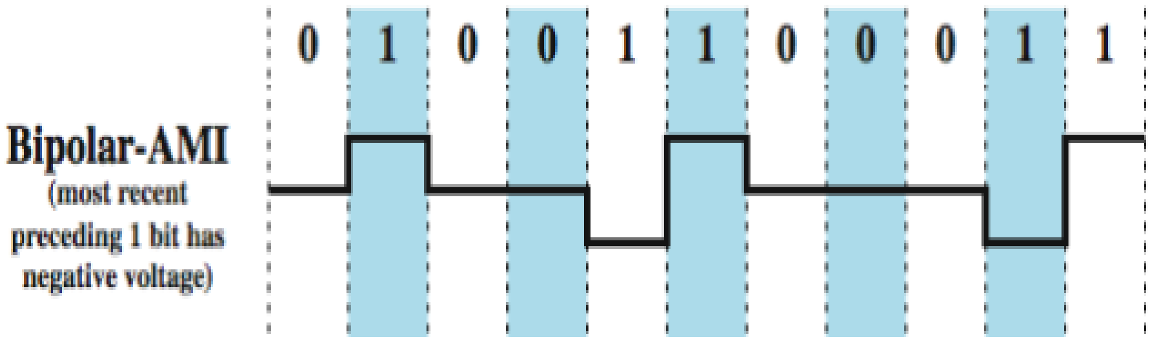
Comparison of Manchester and Differential Manchester Encoding



Assume high preceding level

Alternative Mark Inversion (AMI)

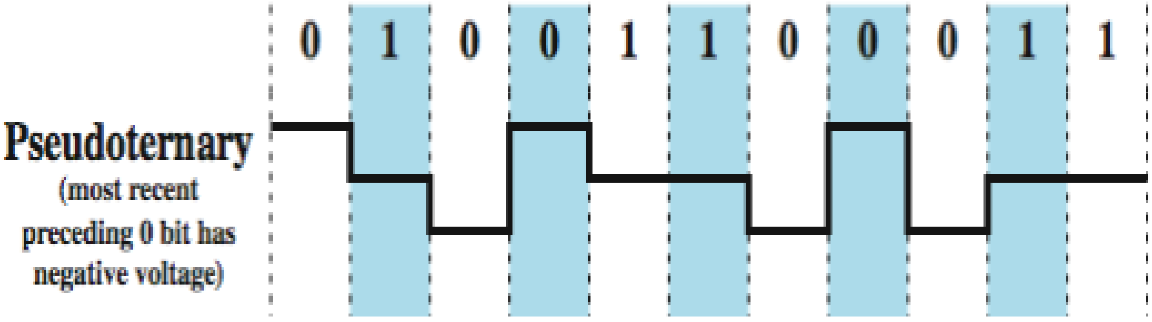
- A neutral zero voltage represents binary 0
- Binary 1s are represented by alternating positive and negative voltages
- Commonly used for long distance communication



Assume the previous 1 is with low level.

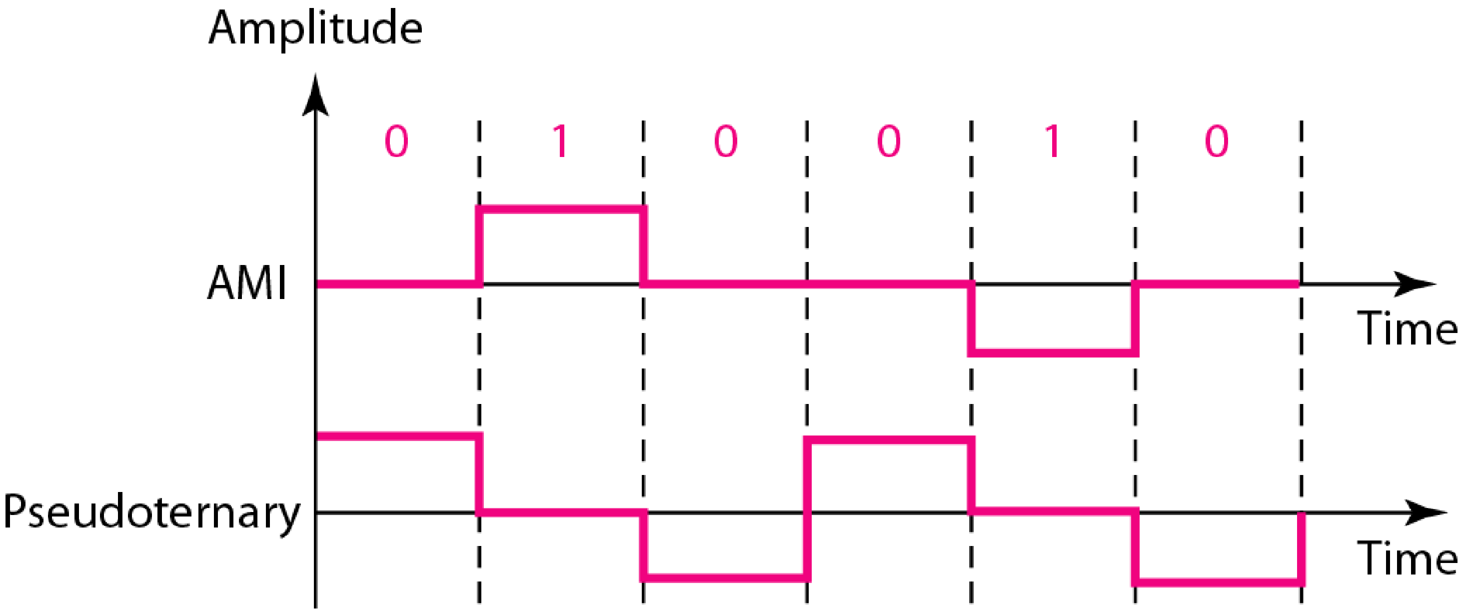
Pseudoternary

- A variation of AMI
- A neutral zero voltage represents binary 1
- Binary 0s are represented by <u>alternating</u> positive and negative voltages



Assume the previous 0 is with low level.

Comparison of AMI and Pseudoternary



Assume the previous 1 is with low level.

Assume the previous 0 is with low level.

Biphase Pros and Cons

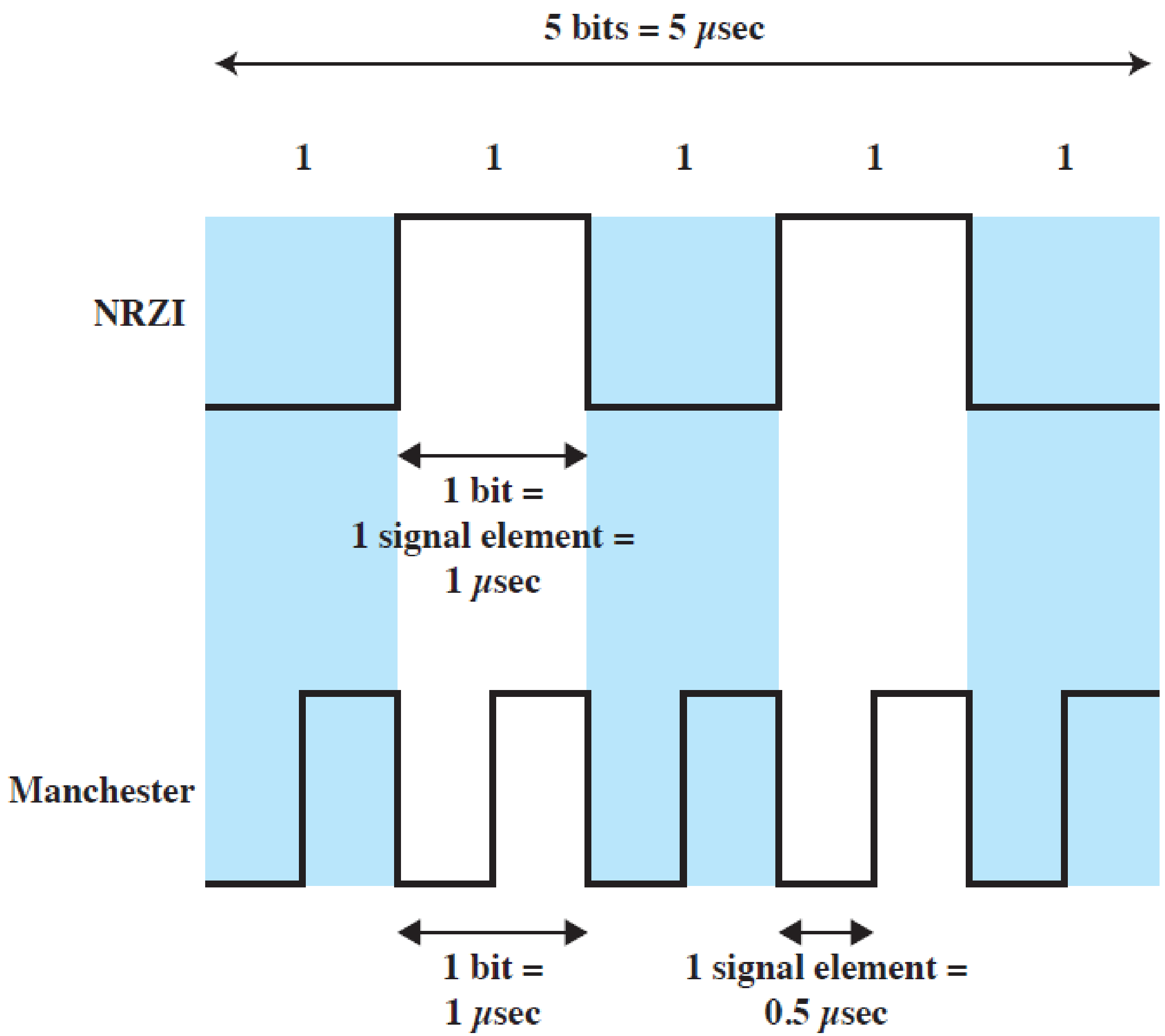
Pros

- synchronization on midbit transition (self clocking)
- has 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

Example: A Stream of Binary Ones at 1Mbps



Comparison of Polar and Bipolar Schemes

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

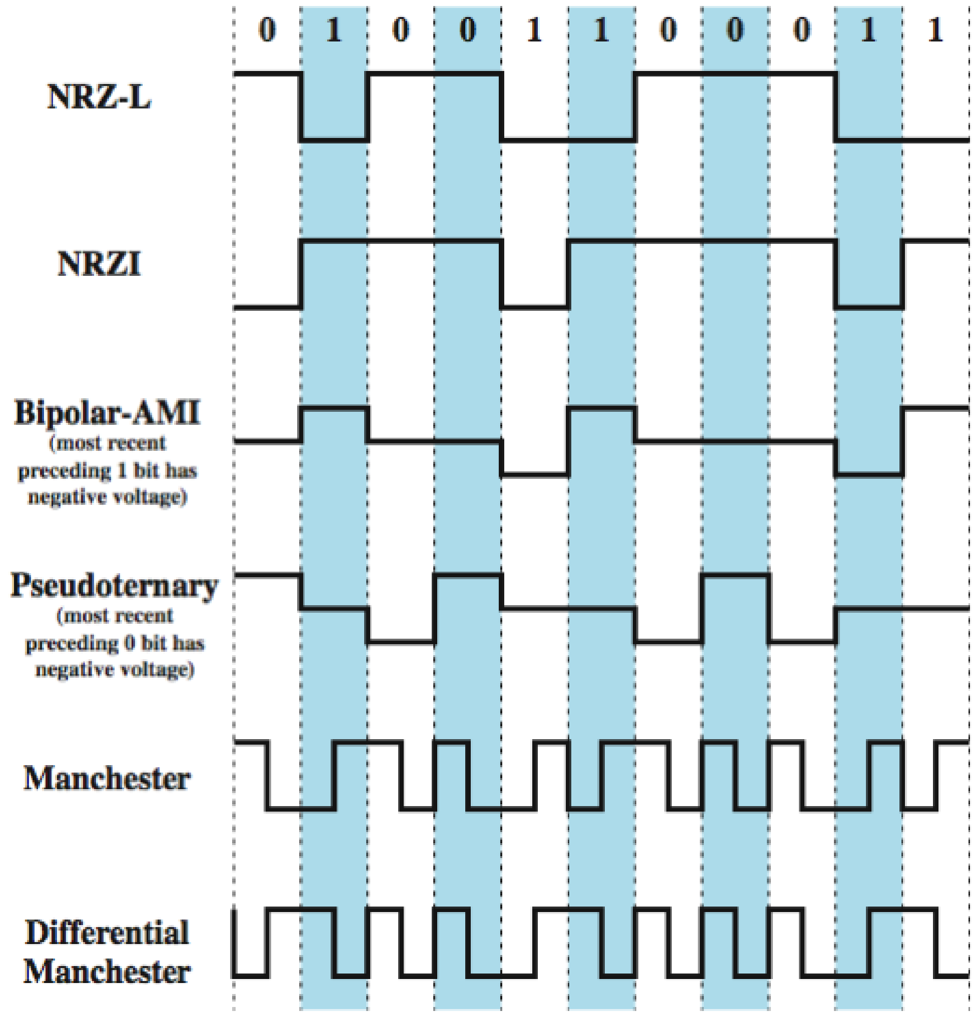
Nonreturn to Zero Inverted (NRZI)
0 = no transition at beginning of interval
1 = transition at beginning of interval

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

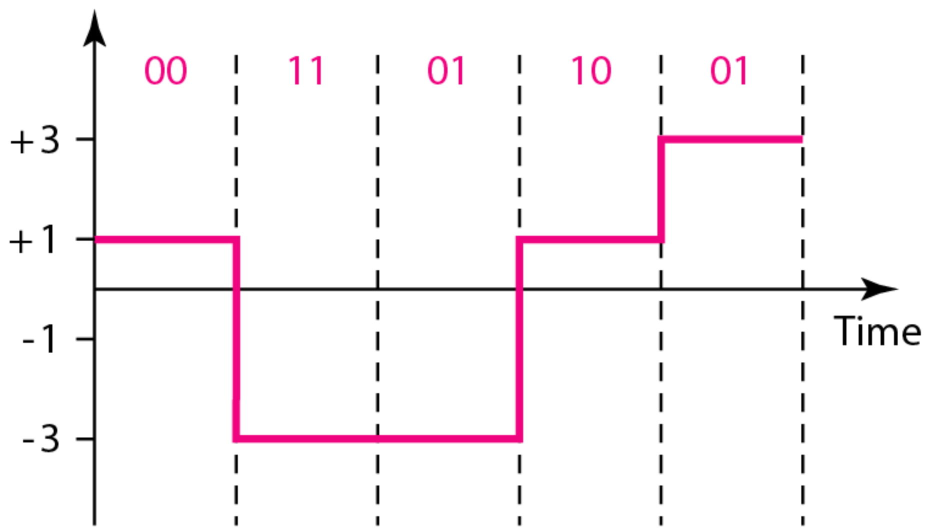
Differential Manchester
Always a transition in middle of interval
0 = transition at beginning of interval
1 = no transition at beginning of interval



Multilevel Scheme – Two Binary One Quaternary (2B1Q)

- Multiple data bits are sent per signal element to increase date rate
- 2B1Q encodes 2-bit patterns as one signal element belonging to a four-level signal
- Can send data 2 times faster than NRZ-L
- Used in DSL technology

Multilevel Scheme – Two Binary One Quaternary (2B1Q)

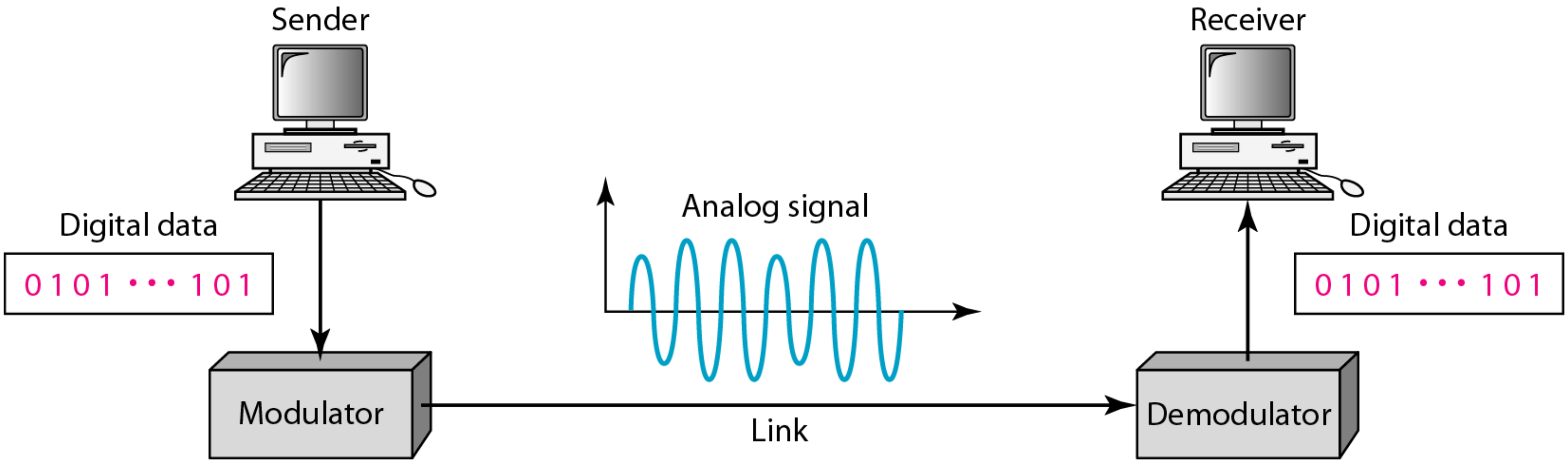


Assuming positive original level

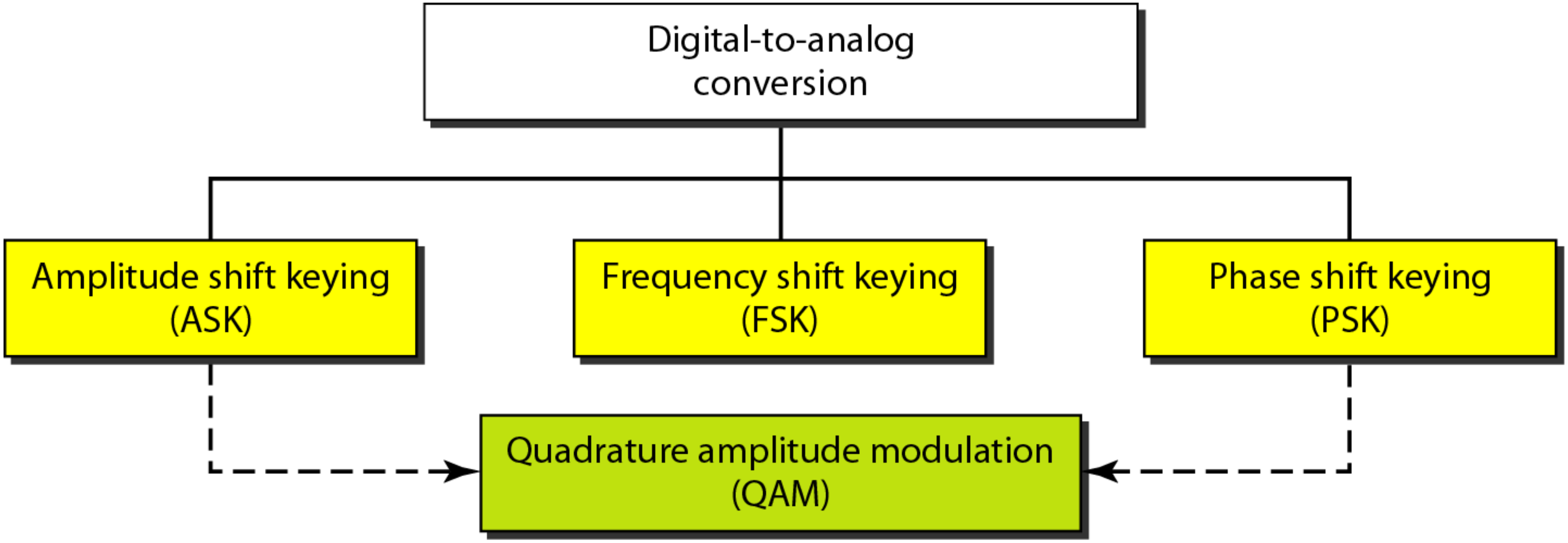
	Previous level: positive	Previous level: negative
Next bits	Next level	Next level
00	+1	-1
01	+3	-3
10	-1	+1
11	-3	+3

Transition table

Digital-to-Analog Conversion



Types of Digital-to-Analog Conversion



Digital Data, Analog Signal

Encoding Techniques

Amplitude shift keying (ASK)

- **used to transmit digital data over optical fiber**

Frequency shift keying (FSK)

- **most common form is binary FSK (BFSK)**

Phase shift keying (PSK)

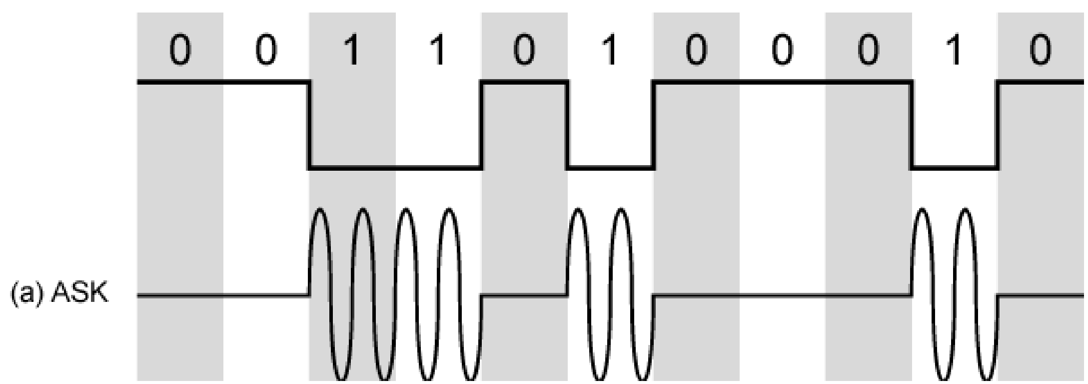
- **phase of carrier signal is shifted to represent data**

- main use is public telephone system
  - has frequency range of 300Hz to 3400Hz
  - uses modem (modulator-demodulator)

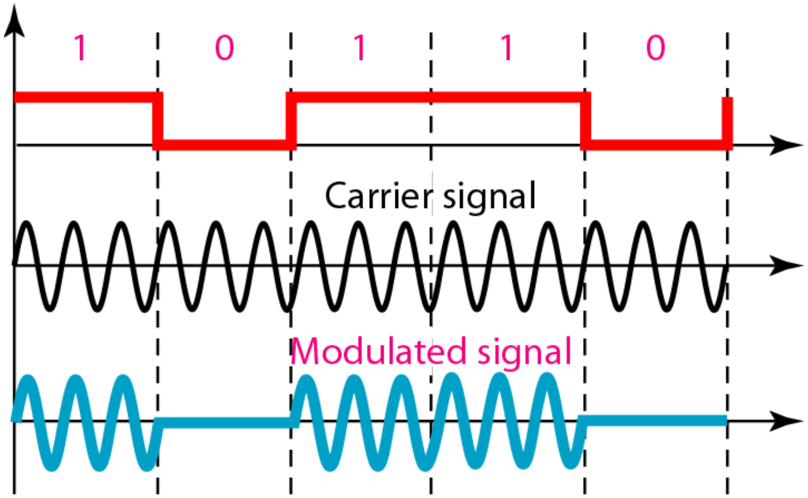
Amplitude Shift Keying

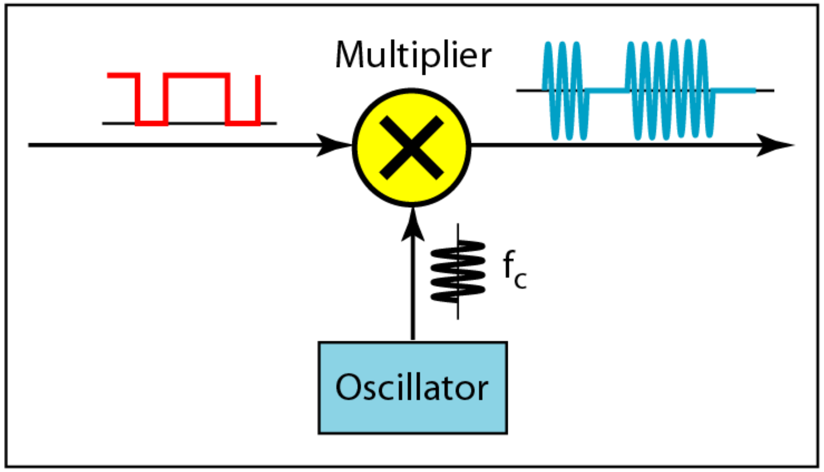
- encode 0/1 by different carrier amplitudes
  - usually have one amplitude zero
- susceptible to sudden gain changes
- inefficient
- used for:
  - up to 1200bps on voice grade lines
  - very high speeds over optical fiber

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



Implementation of Binary ASK

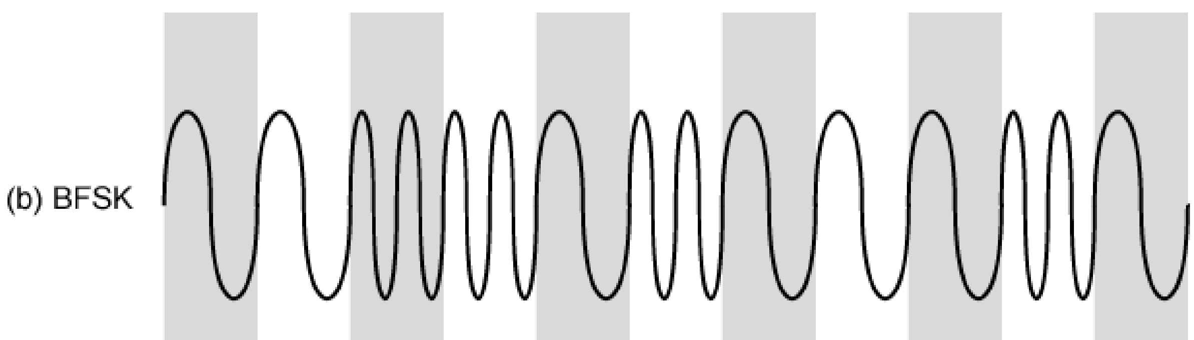




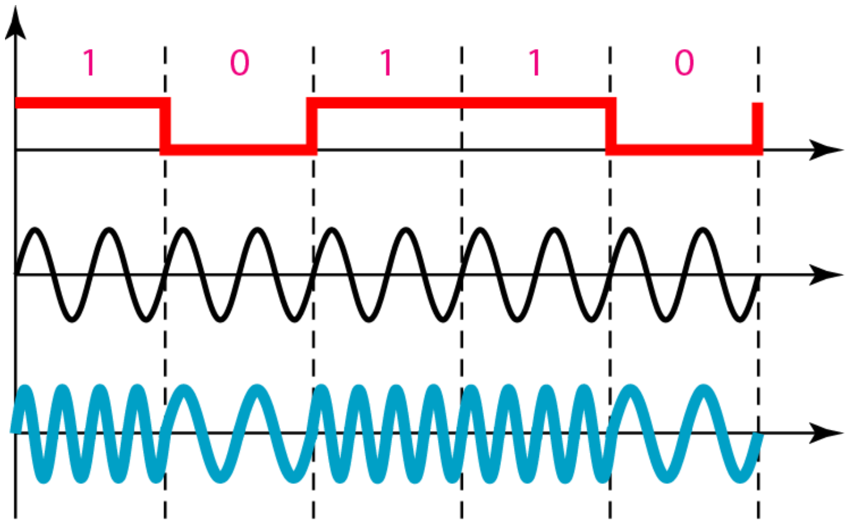
Binary Frequency Shift Keying

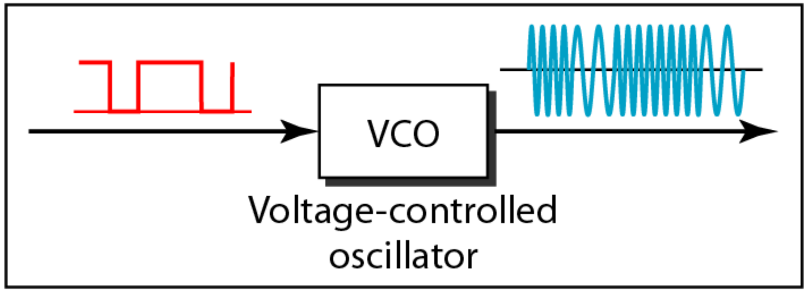
- two binary values represented by two different frequencies (near carrier)
- less susceptible to error than ASK
- used for:
  - up to 1200bps on voice grade lines
  - high frequency radio
  - even higher frequency on LANs using coaxial cable

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



Implementation of BFSK





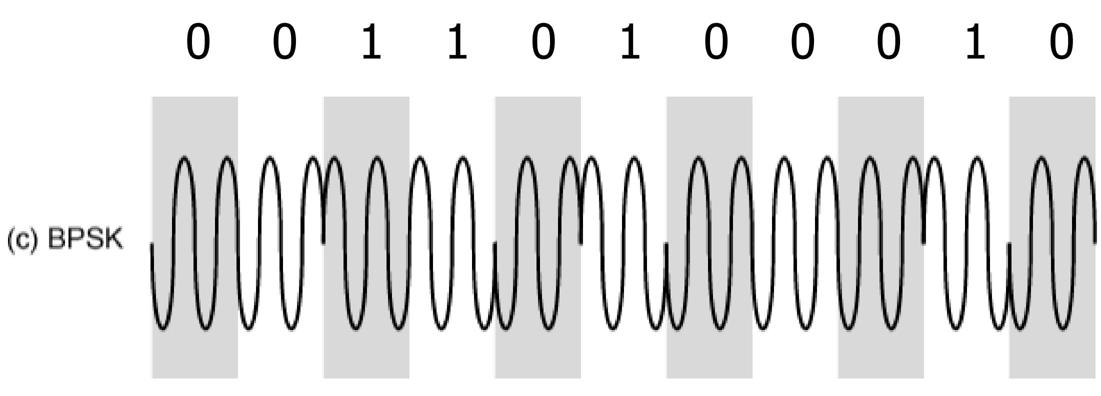
- VCO – Higher voltage gives higher frequency carrier, while lower voltage produces lower frequency carrier.

Multiple FSK (MFSK)

- each signalling element represents more than one bit
- more than two frequencies used
- more bandwidth efficient
- more prone to error

Phase Shift Keying (PSK)

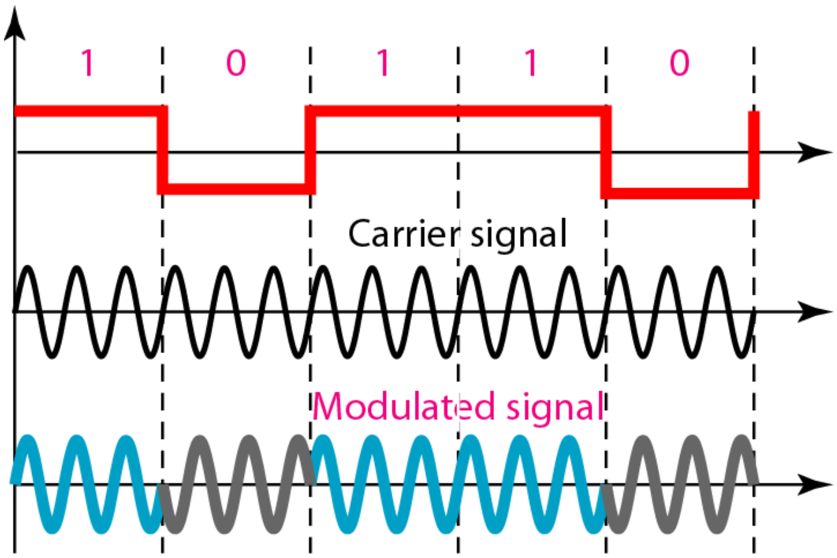
- phase of carrier signal is shifted to represent data
- binary PSK
  - two phases represent two binary digits
- differential PSK
  - phase shifted relative to previous transmission rather than some reference signal

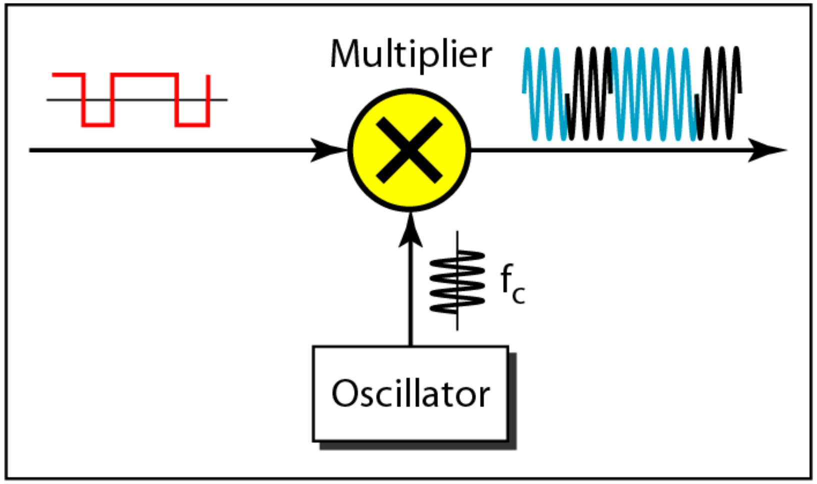


$$s(t) = \begin{cases} A\cos(2\pi f_c t) \\ A\cos(2\pi f_c t + \pi) \end{cases}$$

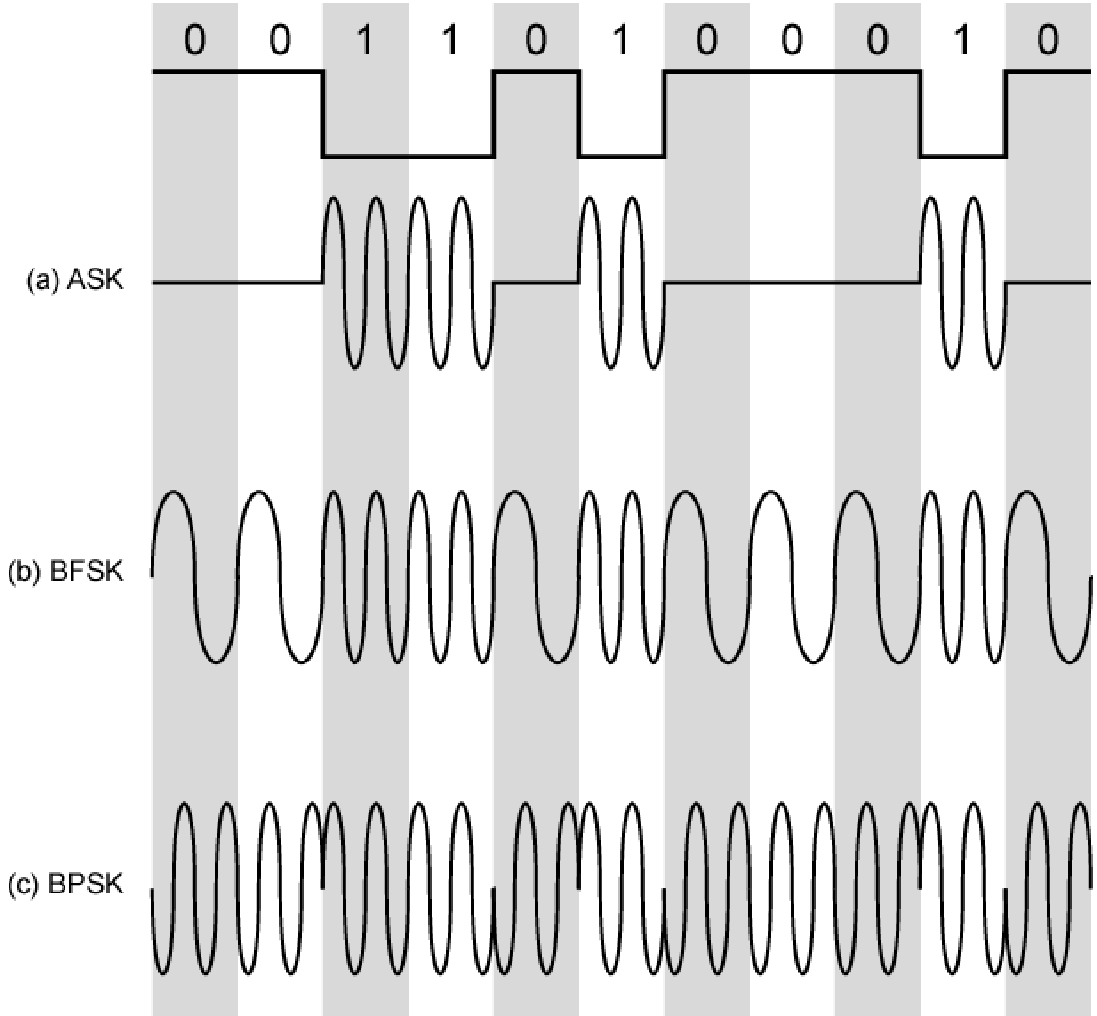
$$= \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ -A\cos(2\pi f_c t) & \text{binary } 0 \end{cases}$$

Implementation of BPSK/BASK





Modulation Techniques



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

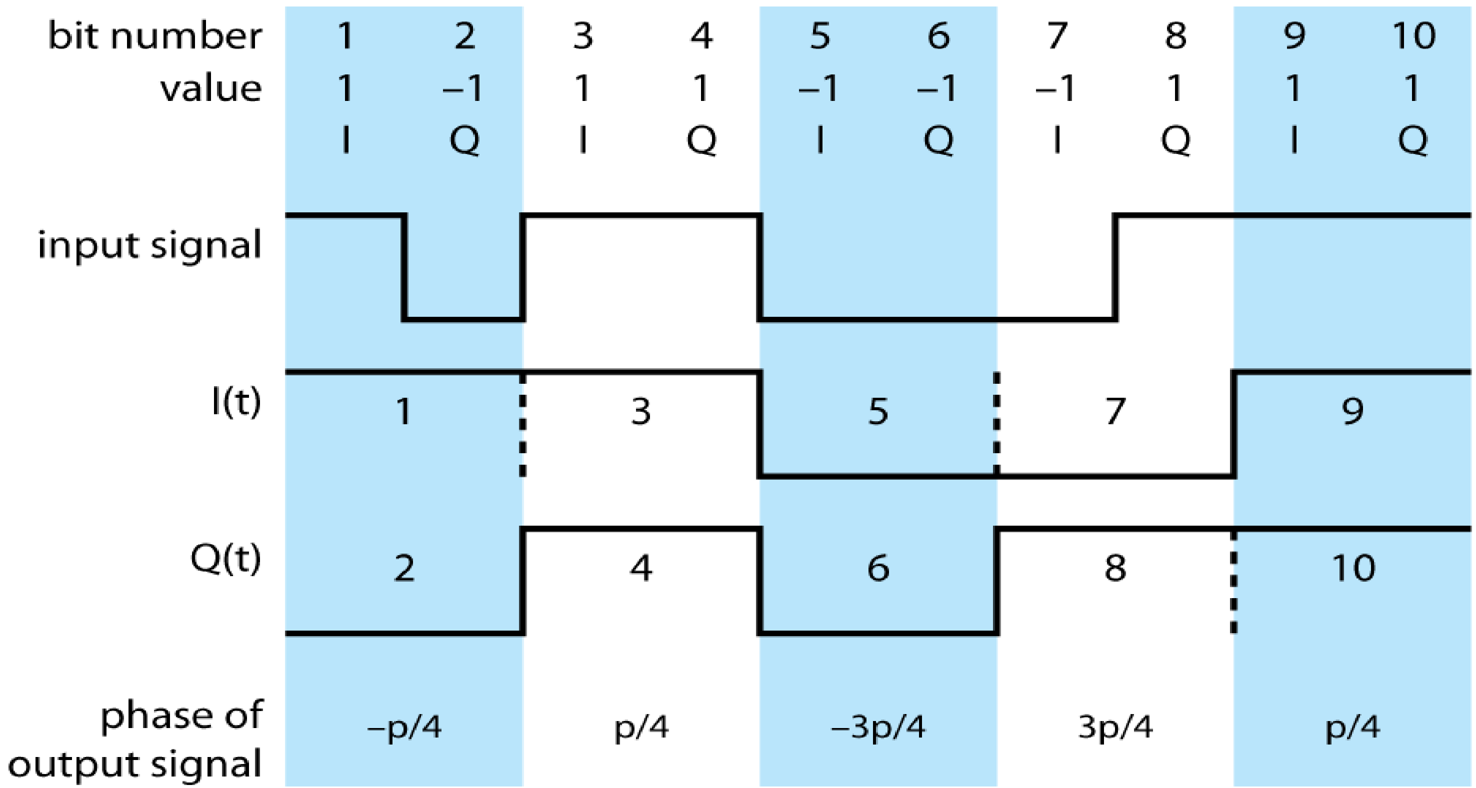
$$s(t)=\begin{cases} A\cos(2\pi f_1 t) & \text{binary } 1 \\ A\cos(2\pi f_2 t) & \text{binary } 0 \end{cases}$$

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

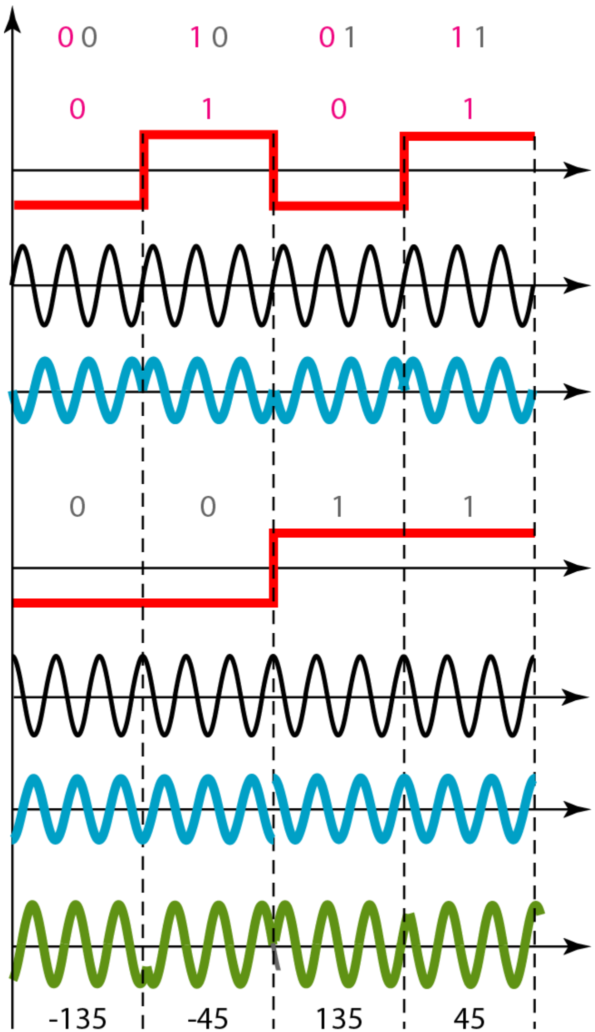
Quadrature PSK (QPSK)

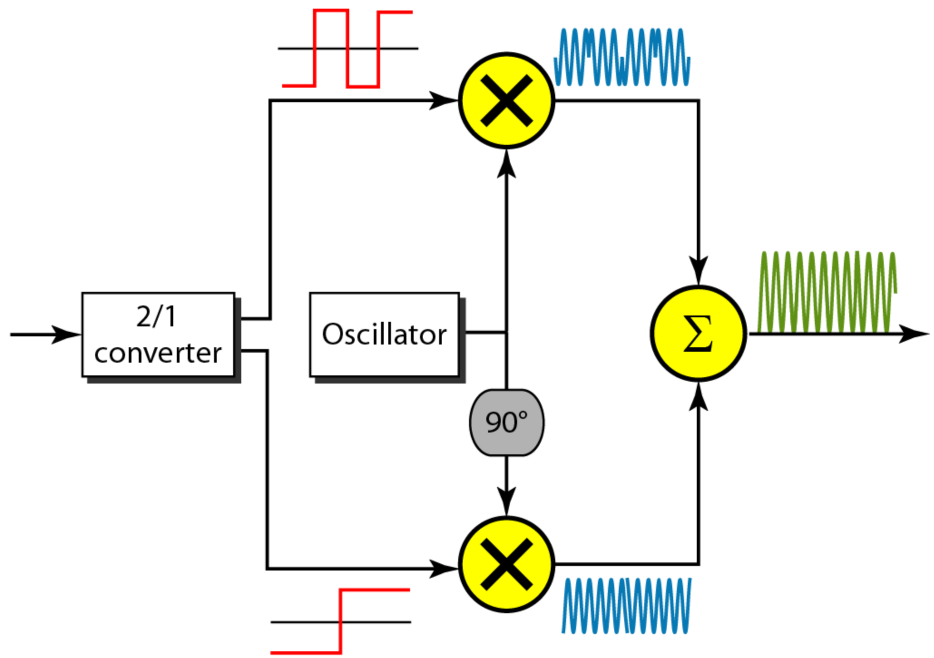
- more efficient use if each signal element represents more than one bit
  - uses phase shifts separated by multiples of $\pi/2$ (90^o)
  - each element represents two bits
  - split input data stream in two and modulate onto carrier and phase shifted carrier
- can use 8 phase angles (8PSK) and more than one amplitude (QAM)
  - 9600bps modem uses 12 angles, four of which have two amplitudes

QPSK


bit number
value
input signal
I(t)
Q(t)
phase of
output signal
1 2 3 4 5 6 7 8 9 10
1 –1 1 1 –1 –1 –1 1 1 1
I Q I Q I Q I Q I Q
1 3 5 7 9
2 4 6 8 10
–p/4
p/4
–3p/4
3p/4
p/4

Implementation of QPSK



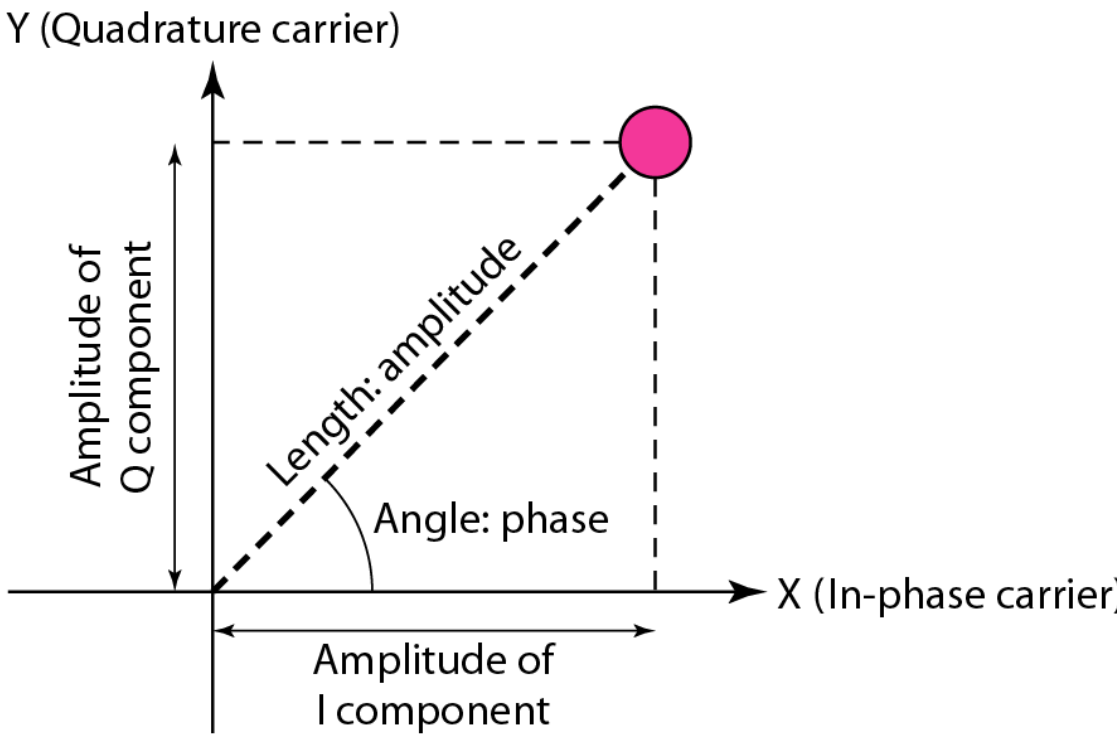


Quadrature Amplitude Modulation (QAM)

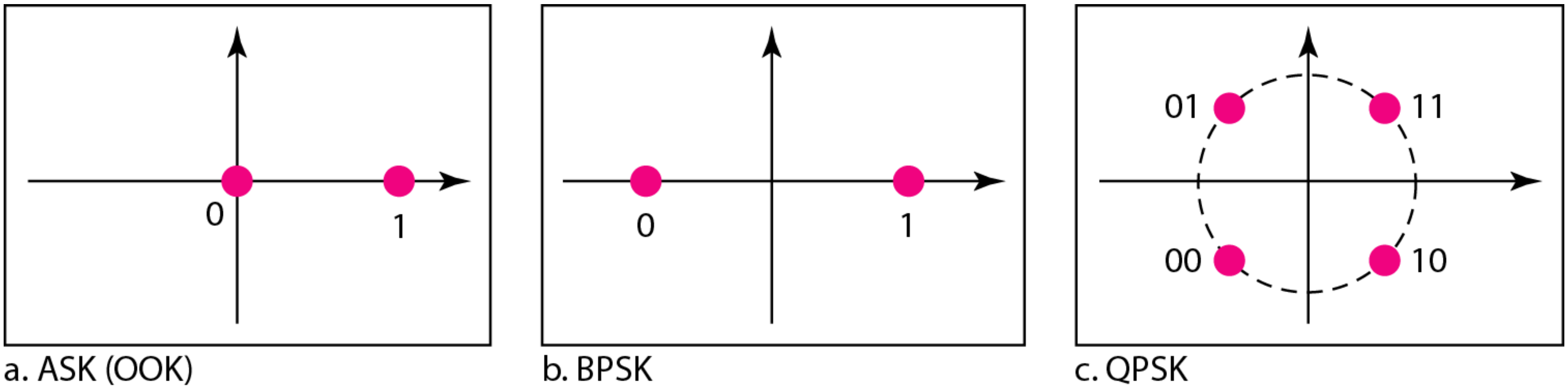
- QAM used on asymmetric digital subscriber line (ADSL) and some wireless
- combination of ASK and PSK
- logical extension of QPSK $\boxed{s(t) = d_1(t)\cos 2\pi f_c t + d_2(t)\sin 2\pi f_c t}$
- send two different signals simultaneously on same carrier frequency
  - use two copies of carrier, one shifted 90°
  - each carrier is ASK modulated
  - two independent signals over same medium
  - demodulate and combine for original binary output

Concept of Constellation Diagram

- A constellation diagram can help us define the amplitude and phase of a signal element



Examples of Constellation Diagrams



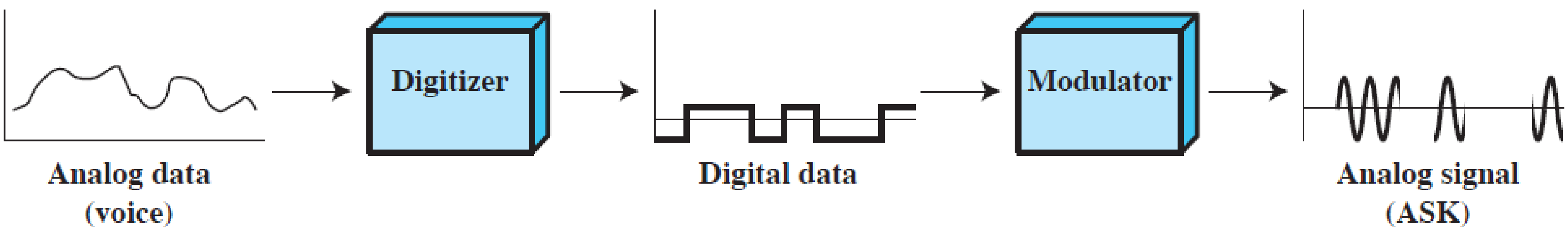
- Can you draw a constellation diagram for 16 QAM?
- What about 8PSK?

Analog Data, Digital Signal

- digitization is 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 done using a codec
  - Pulse Code Modulation (PCM)
  - Delta Modulation (DM)

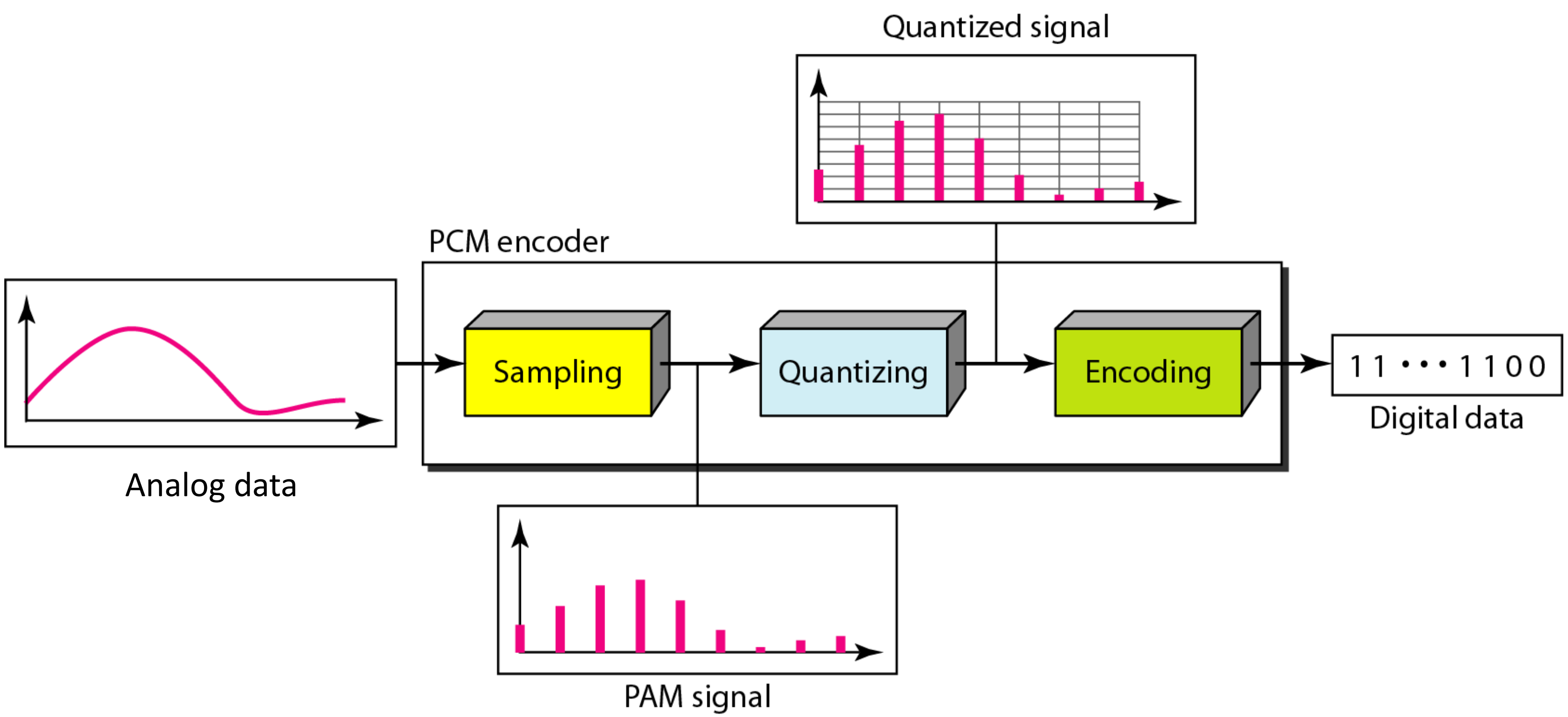
Digitizing Analog Data

- Analog data are first digitalized using PCM, DM, etc.
- Digital data are then modulated using ASK, FSK, PSK, QAM, etc.



Three Components of PCM

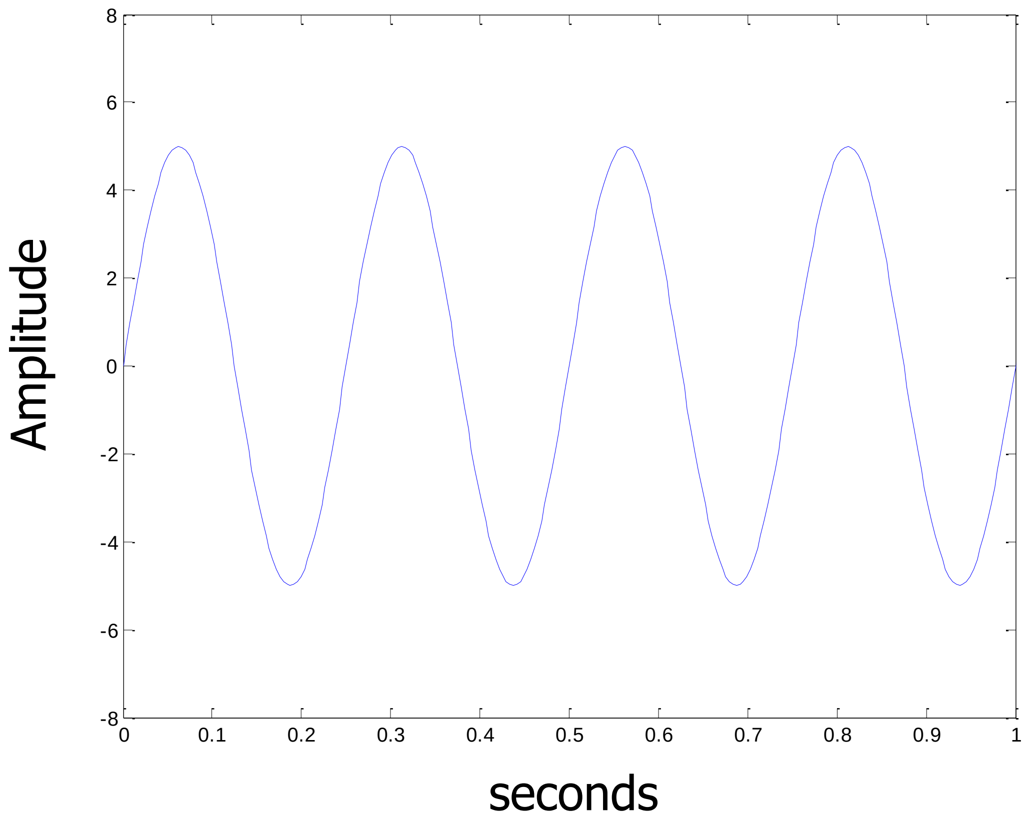
- Step 1: Sampling → PAM signal
- Step 2: Quantizing → Quantized signal
- Step 3: Encoding → Digital data



Sampling Theorem

- The analog signal is sampled at a regular interval, called sampling
- The inverse of the sampling interval is called <u>sampling rate</u> or <u>sampling frequency</u>
- *If a signal is sampled at regular intervals at a rate higher than **<u>twice</u>** the highest signal frequency, the samples contain all information in original signal*
- eg. 4000Hz voice data, requires 8000 samples per second

To digitalize a sine wave

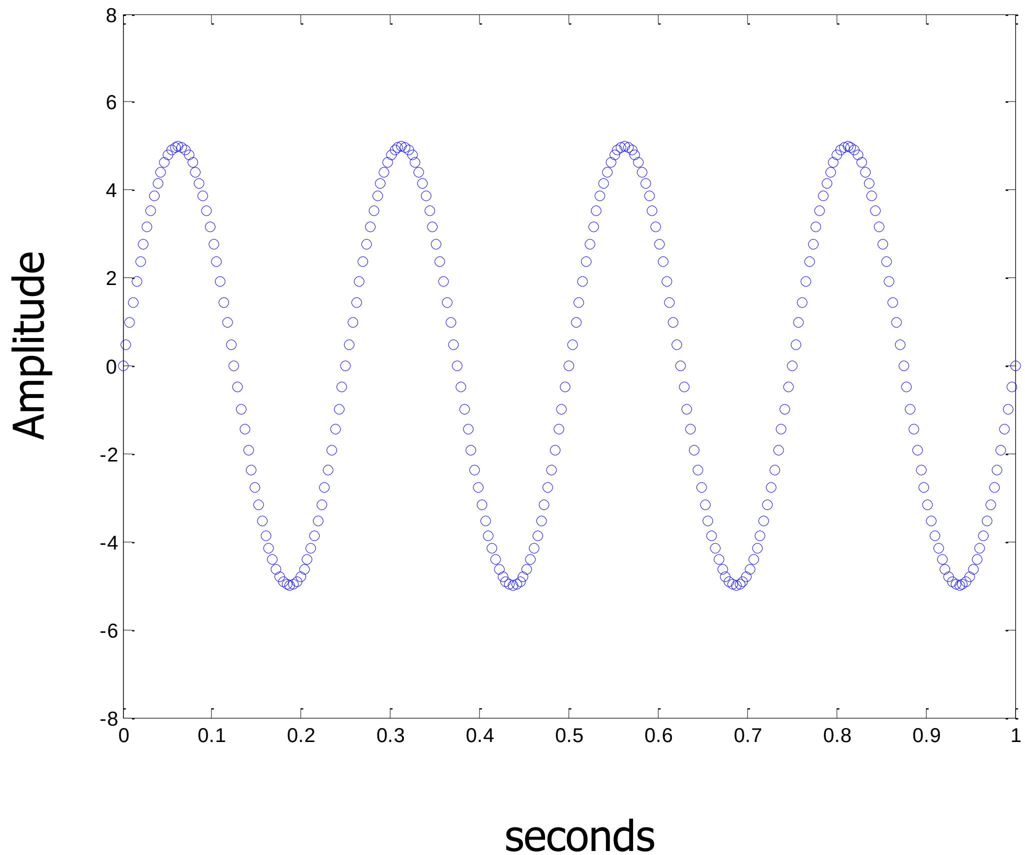


5*sin (2π4t)

Amplitude = 5

Frequency = 4 Hz

A sine wave signal



$5*\sin(2\pi 4t)$

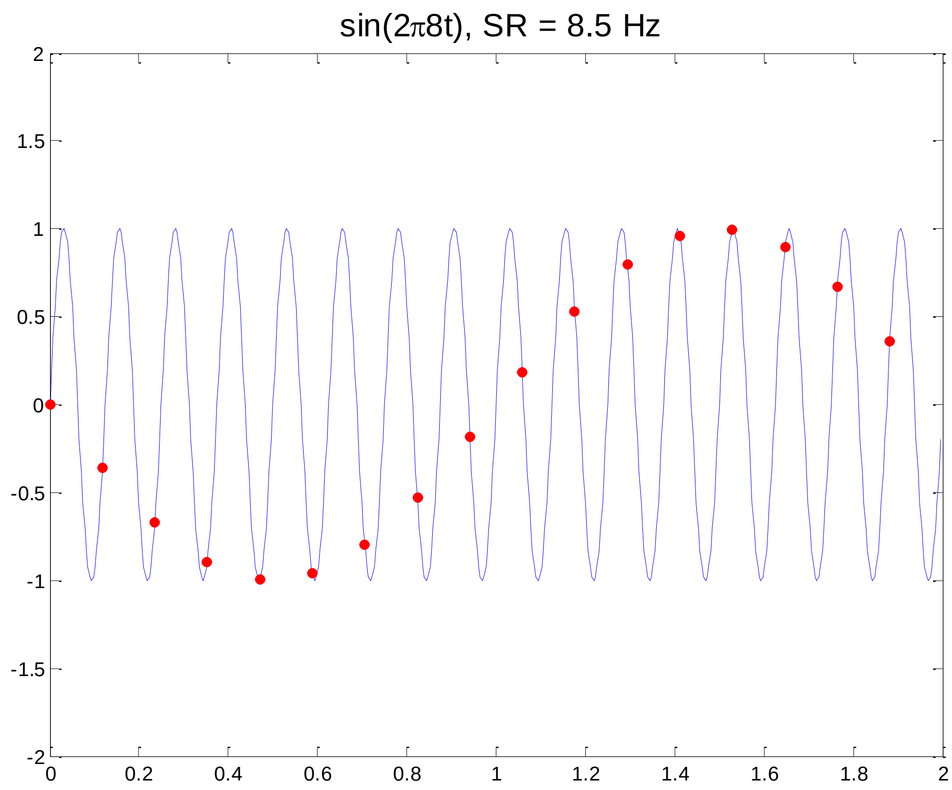
Amplitude = 5

Frequency = 4 Hz

Sampling rate = 256 samples/second

Sampling duration = 1 second

An undersampled signal



sin(2π8t)

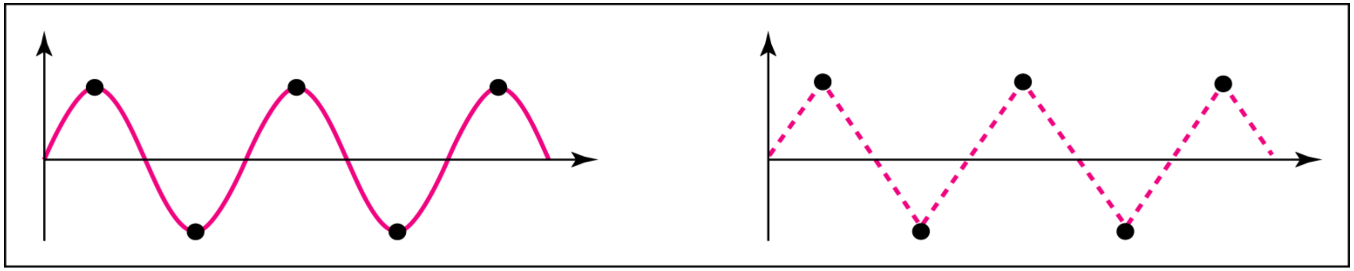
Amplitude = 1

Frequency = 8 Hz

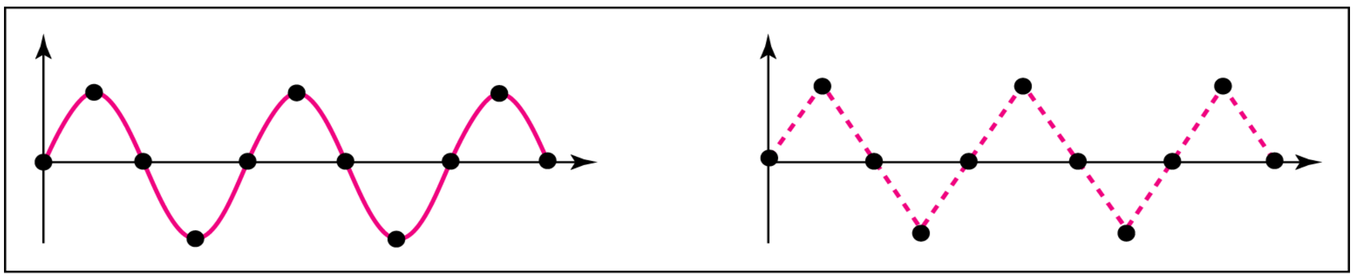
Sampling rate = 8.5 samples/second

Sampling duration = 2 second

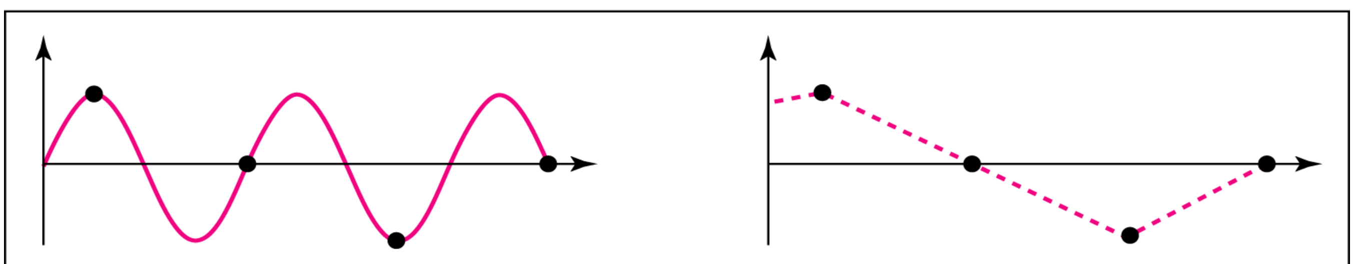
Recovery of a Sampled Sine Wave for Different Sampling Rate



a. Nyquist rate sampling: $f_s = 2\,f$



b. Oversampling: $f_s = 4\,f$



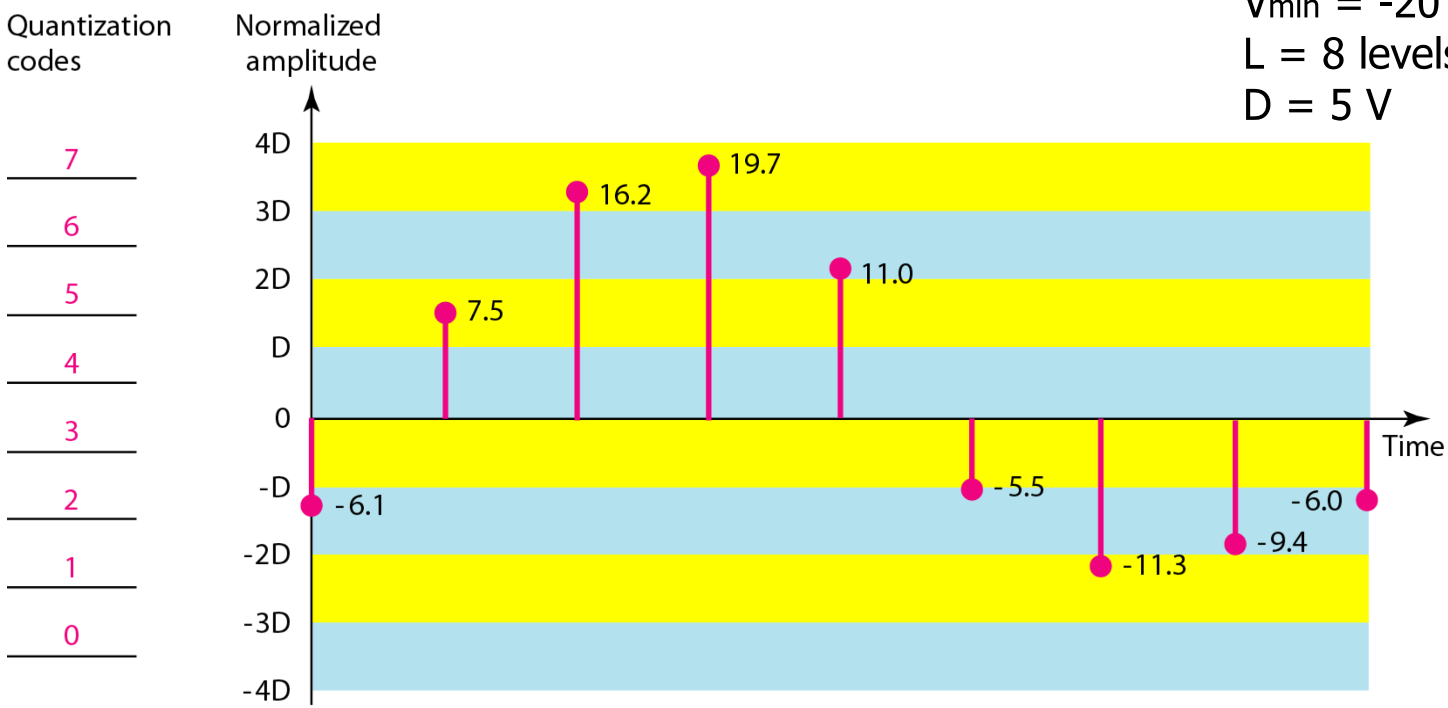
c. Undersampling: $f_s = f$

Quantization

- Assume the maximum and minimum amplitudes of the PAM signal be V_{max} and V_{min}
- We divide the range into L zones, each of height $\triangle = (V_{max} - V_{min})/L$
- We assign quantized values to 0 to L-1 to the midpoint of each zone
- We approximate the value of the sample amplitude to the quantized values.

Quantization

V_{max} = 20 V
V_{min} = -20 V
L = 8 levels
D = 5 V

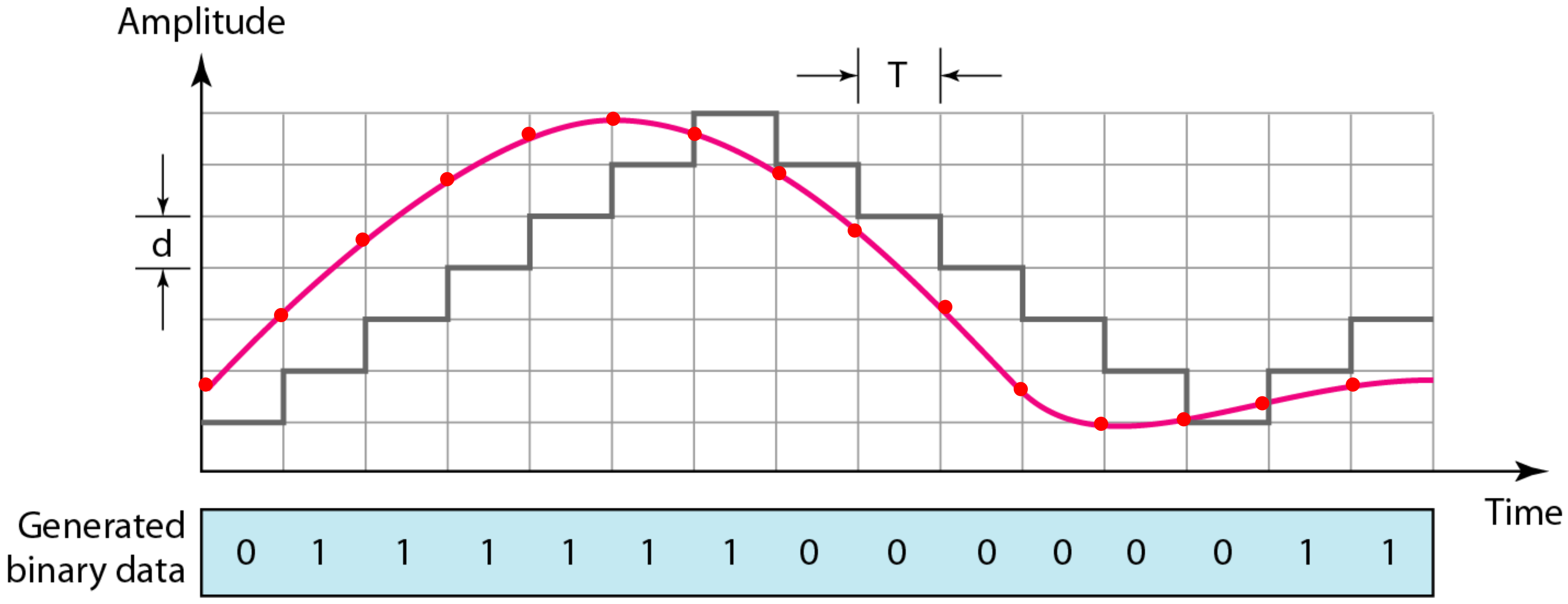


Normalized PAM values	-1.22	1.50	3.24	3.94	2.20	-1.10	-2.26	-1.88	-1.20
Normalized quantized values	-1.50	1.50	3.50	3.50	2.50	-1.50	-2.50	-1.50	-1.50
Normalized error	-0.38	0	+0.26	-0.44	+0.30	-0.40	-0.24	+0.38	-0.30
Quantization code	2	5	7	7	6	2	1	2	2
Encoded words	010	101	111	111	110	010	001	010	010

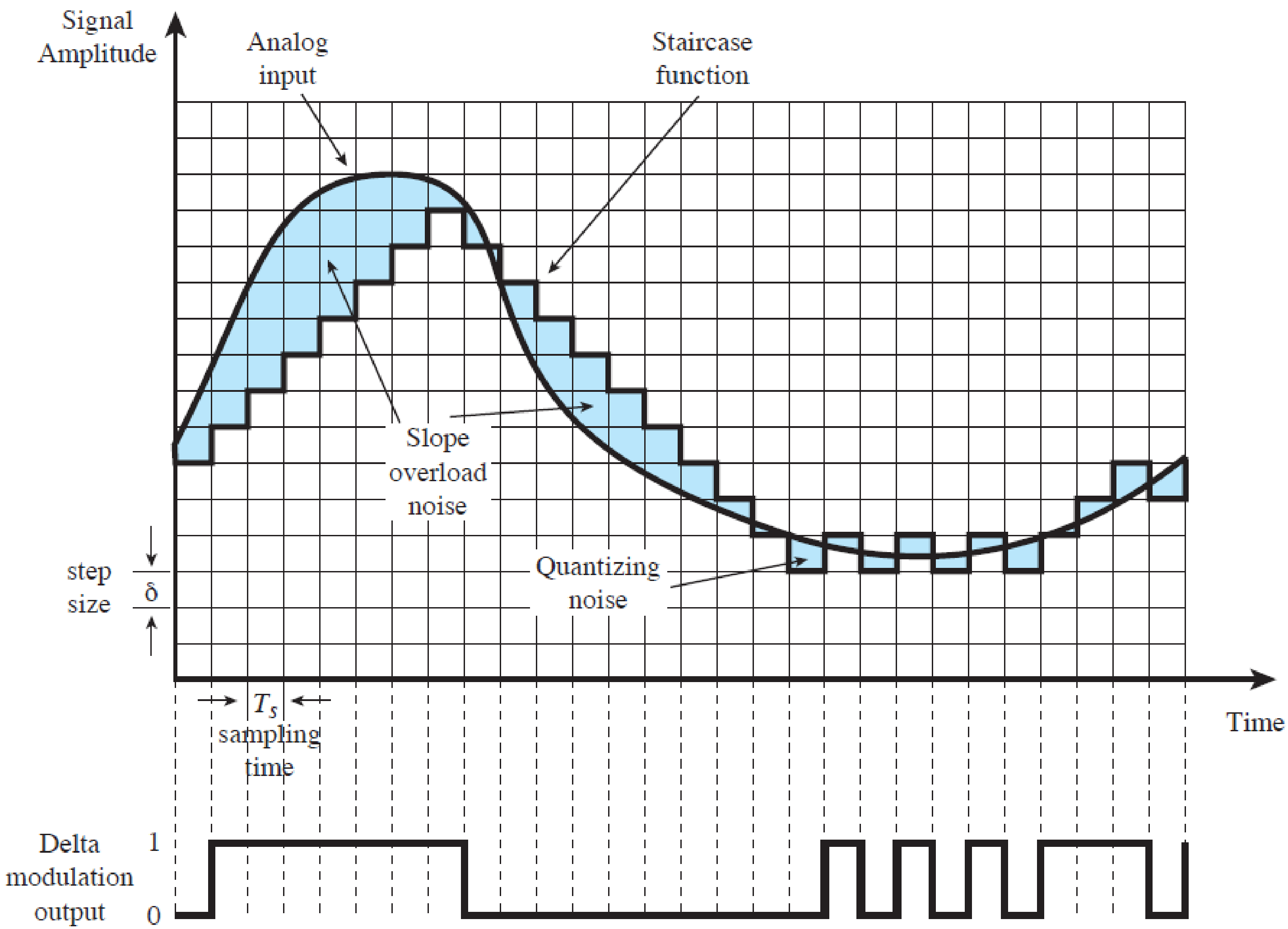
Delta Modulation (DM)

- Developed to reduce the complexity of PCM
- analog input is approximated by a staircase function
  - can move up or down one level (δ) at each sample interval
- has binary behavior
  - function only moves up or down at each sample interval
  - hence can encode each sample as single bit
  - 1 for up or 0 for down

The Process of Delta Modulation



Delta Modulation Example



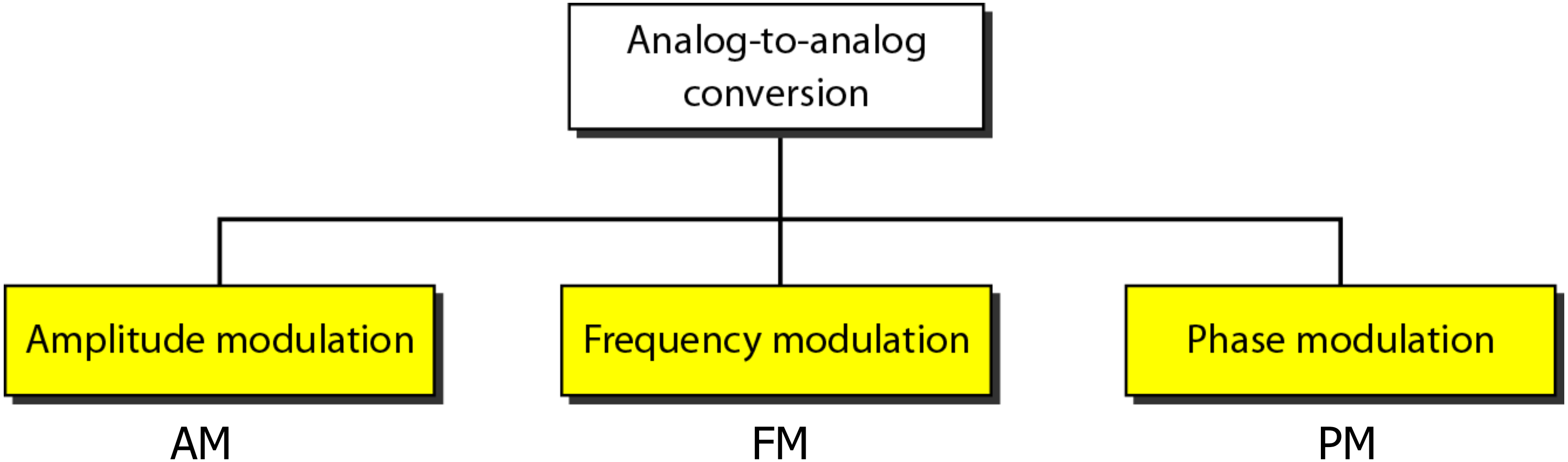
PCM verses Delta Modulation

- DM has simplicity compared to PCM but has worse SNR
- issue of bandwidth used
  - for good voice reproduction with PCM:
    - want 128 levels (7 bit) & voice bandwidth 4khz
    - need 8000 x 7 = 56kbps
- data compression can improve on this
- still growing demand for digital signals
- PCM preferred to DM for analog signals

Analog Data, Analog Signals

- modulate carrier frequency with analog data
- why modulate analog signals?
  - higher frequency can give more efficient transmission (carrier frequency relates to antenna size)
  - permits frequency division multiplexing (discuss later)
- types of modulation:
  - Amplitude
  - Frequency
  - Phase

Analog Data, Analog Signals

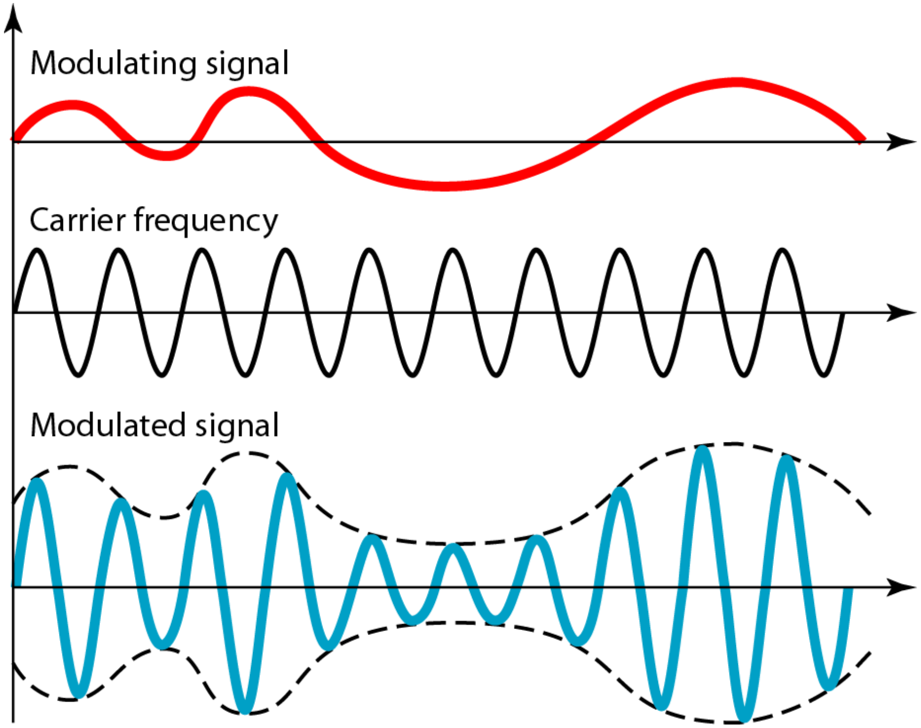


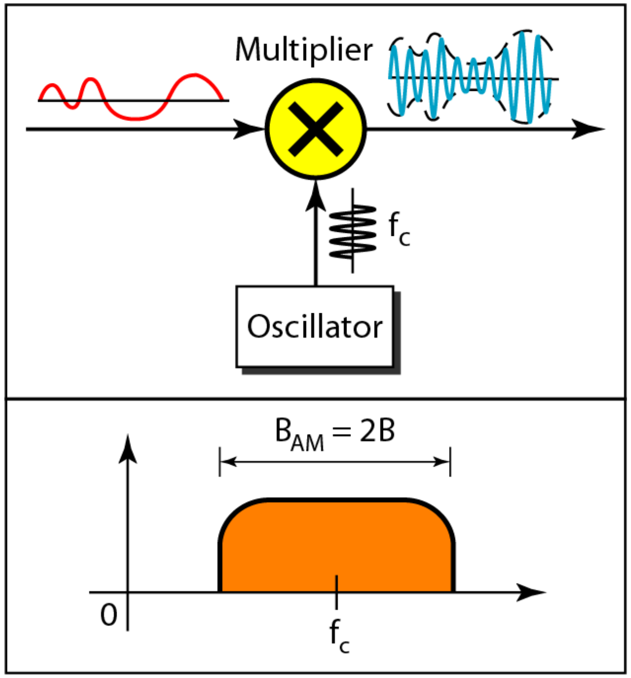
Modulation and Demodulation

- The conversion of digital signals to analog signals suitable for transmission is called modulation.
- The conversion of modulated analog signals to digital signals is called demodulation.
- A device that performs modulation and demodulation is called a modem.
- Both modems at the transmitter and receiver must use the same modulation methods.

Amplitude Modulation (AM)

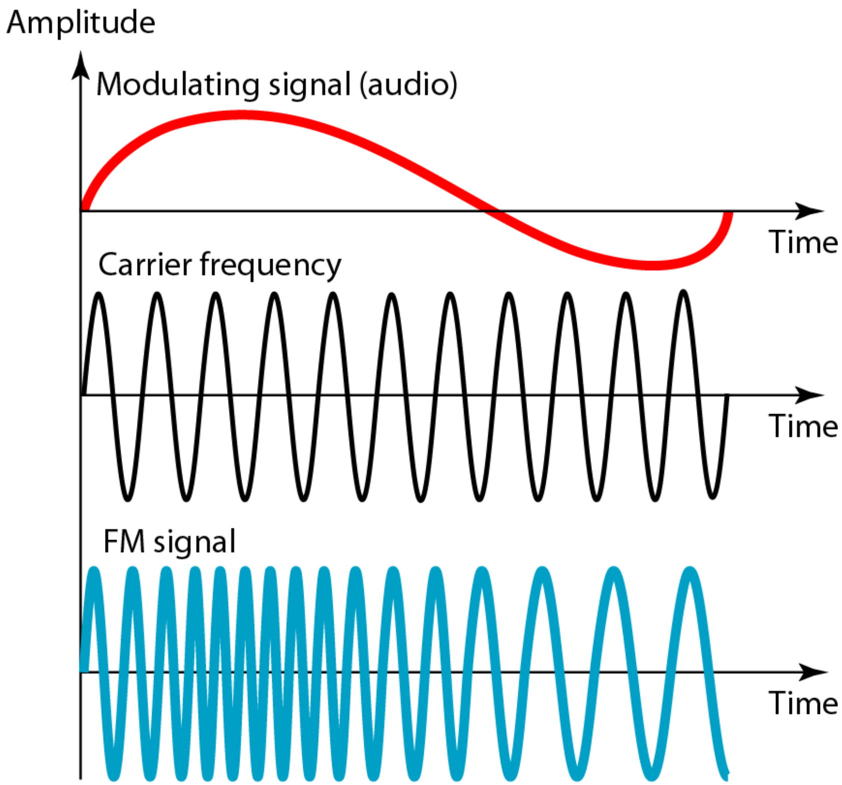
- Analog data is embedded in the <u>envelop (amplitude)</u> of the modulated signal

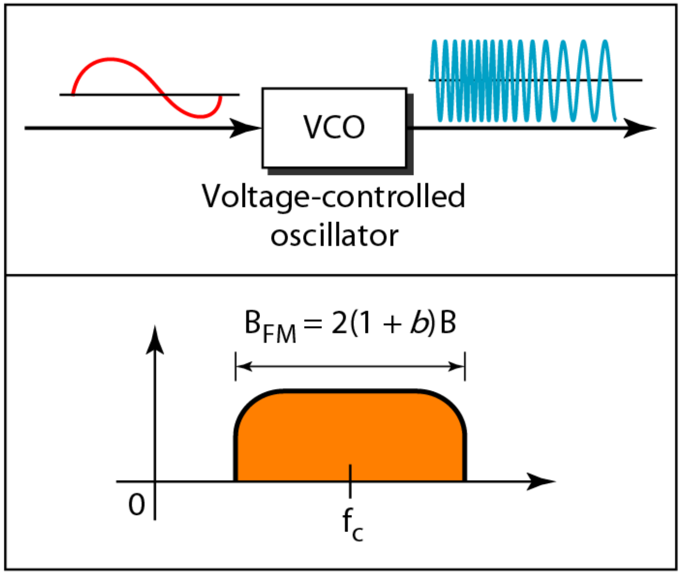




Frequency Modulation (FM)

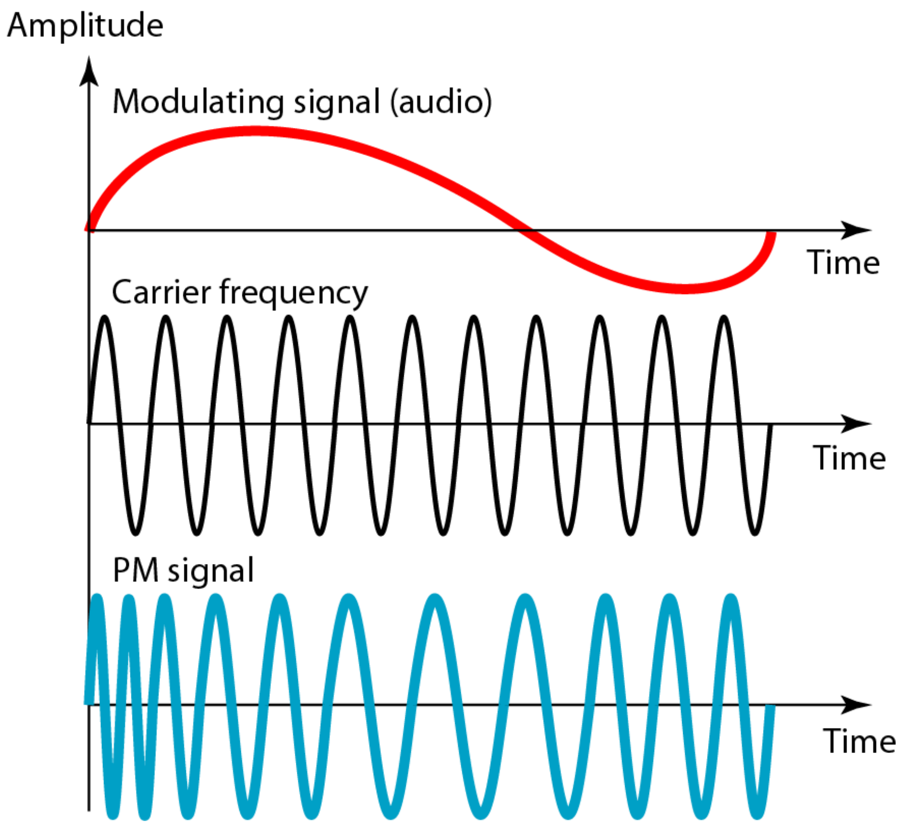
- Analog data is embedded in the <u>frequency</u> of the modulated signal

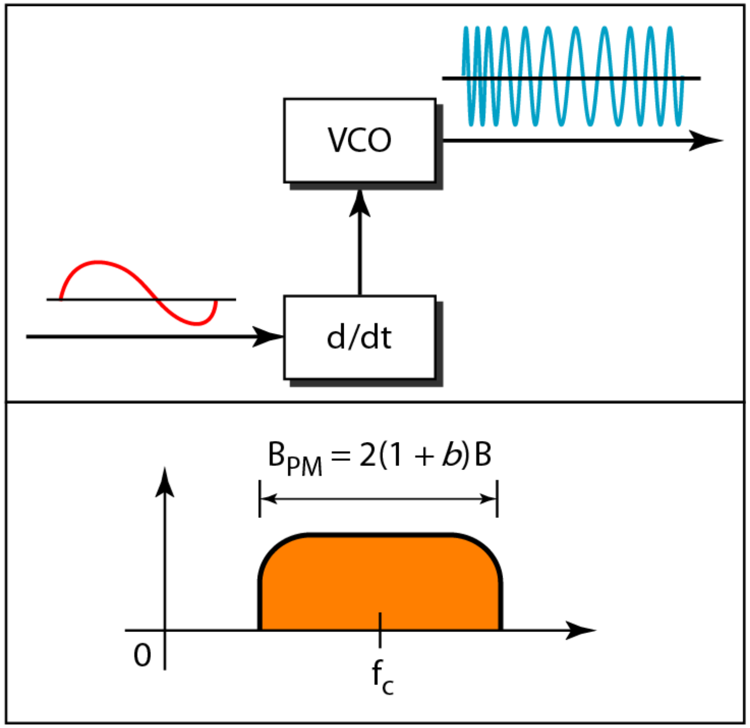




Phase Modulation (PM)

- Analog data is embedded in the <u>phase</u> of the modulated signal





Summary

- Signal encoding techniques
  - digital data, digital signal
    - NRZ, multilevel binary, biphase, modulation rate
  - analog data, digital signal
    - PCM, DM
  - digital data, analog signal
    - ASK, FSK, BFSK, PSK
  - analog data, analog signal
    - AM, FM, PM