Lecture 2

Physical Layer

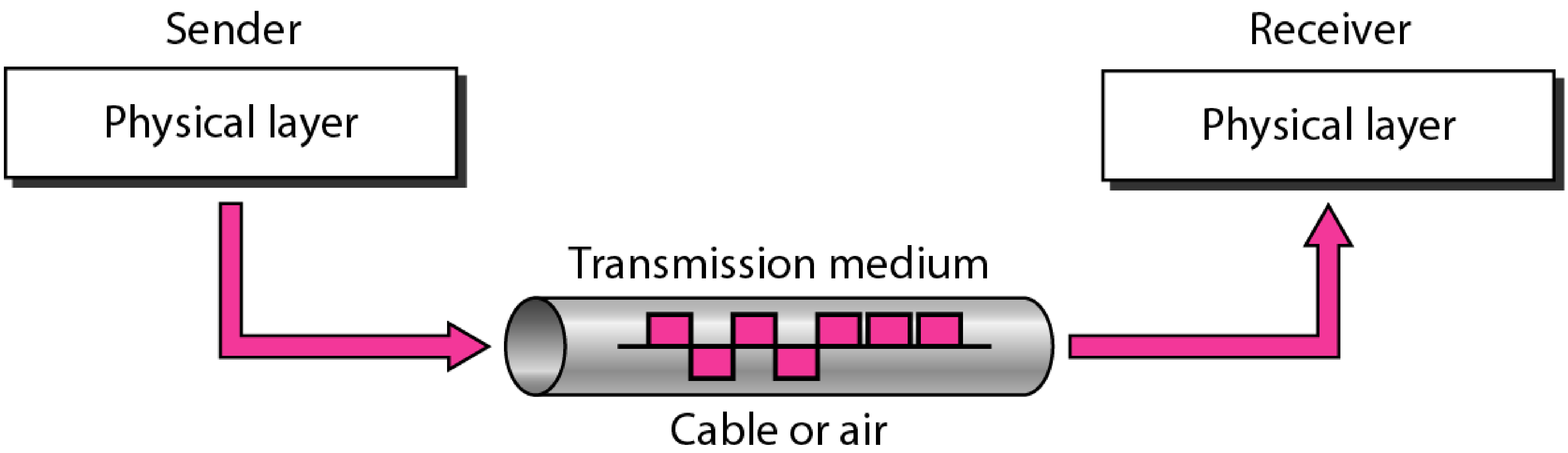
ELEC 3506/9506
Communication Networks

Dr Wibowo Hardjawana
School of Electrical and Information Engineering

Topics of the Day

- Fundamental Concepts
- Digital and Analog Signals
- Signal Encoding and Modulation
- Multiplexing
- Switching
- Transmission Media
- Propagation Modes
- Network Topologies

Transmission Medium



Digital/Analog Communication

We want to send letter A and represent each letter with a combination of 0 and 1. There are 26 letters.

1. How many bits are required to represent all letters?

2. Efficient transmission?

3. Reliable transmissions? Sending multiple letters to someone?

Fundamental Question

Is it possible to transmit reliably over a communication channel at any arbitrary rate?

If yes how?

In 1948, Claude E. Shannon proved that it is possible if and only if the rate is below a certain threshold, called *Channel Capacity*.

Fundamental Question

Let us assume that the channel capacity if C, we can transmit with any rate $R<C$ with the error probability approaching zero, asymptotically.

For a communication channel with limited bandwidth B, the objective is to

1. Maximise the transmission rate R
2. Or to minimise the error probability for a given rate R below the capacity

In other words, we want to put as many bit as possible in a signal such that the bits can be distinguished with vanishing error probability at the receiver side.

Fundamental Question

If the received signal power is P and the noise power is N and the channel bandwidth is B, the channel capacity can be derived as

$$C = B \log_2(1+P/N)$$

B $\uparrow$ C $\uparrow$

P $\uparrow$ C $\uparrow$

N $\downarrow$ C $\uparrow$

What if the channel is noiseless? N=0 and C=inf

Fundamental Question

The maximum rate is characterised by Nyquist Theorem.

*Bit rate = 2 B * (number of bits per signal)*

$$\textit{Bit rate} = 2\,B * \log_2 (L \textit{ signal level})$$

What if the channel is noiseless? *No limits on the number of bit levels encoded, but still limited by B*

Example

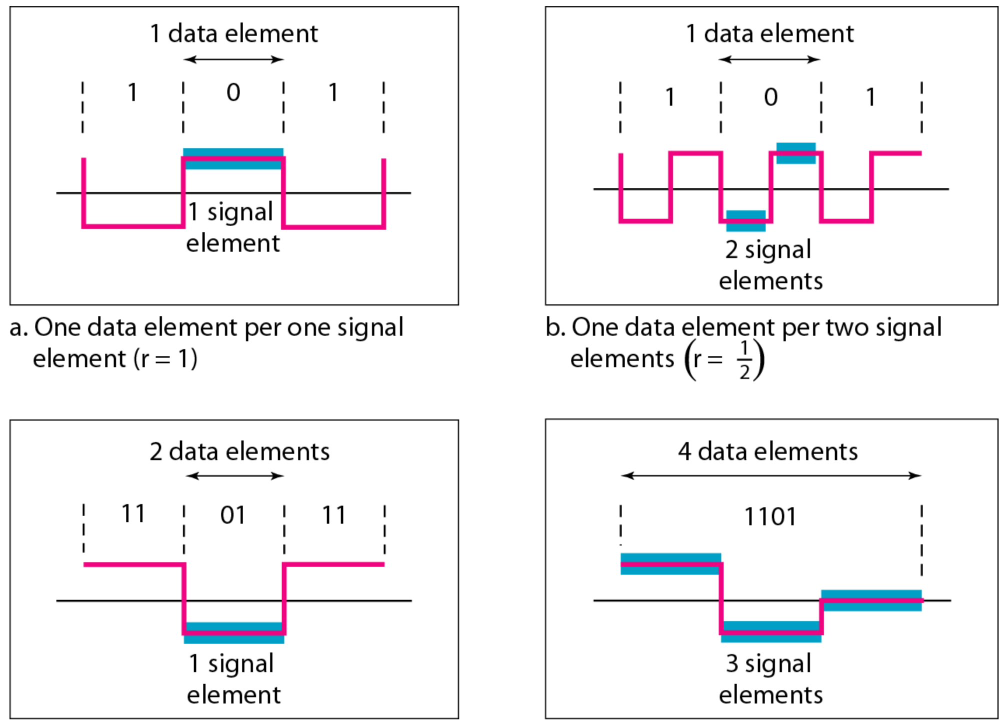
We have a channel with a 1-MHz bandwidth. The SNR for this channel is 63. What are the appropriate bit rate and signal level?

Fundamental Concepts

Signal Element vs. Data Element

r can be thought as a bit rate per signal element

- Data Element:
  - Smallest entity that can represent a piece of information – the bit
- Signal Element:
  - The shortest (time wise) unit of a digital signal (frequency for an analog signal)
  - Carrier of 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 $\left(r = \frac{4}{3}\right)$

- Analogy:
  - Signal Element = The vehicle
  - Data Element = No of people travelling in the vehicle
  - Signal Elements can have different levels (different types of vehicles)

Fundamental Concepts

Data Rate vs. Signaling Rate

- Data rate/Bit rate:
  – The number of bits transmitted in one second
  – Measured as “Bits per second” – bps

- Signaling rate/Baud rate/Pulse rate/Modulation rate
  - The number of signal elements per second
  - The unit is “baud”
  - Define bandwidth

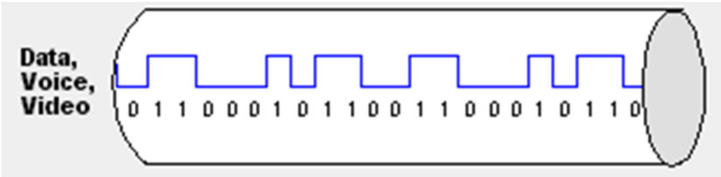
- Goal: Increase the data rate (speed of transmission) and decrease the signaling rate (save bandwidth) – increasing spectral efficiency

Fundamental Concepts

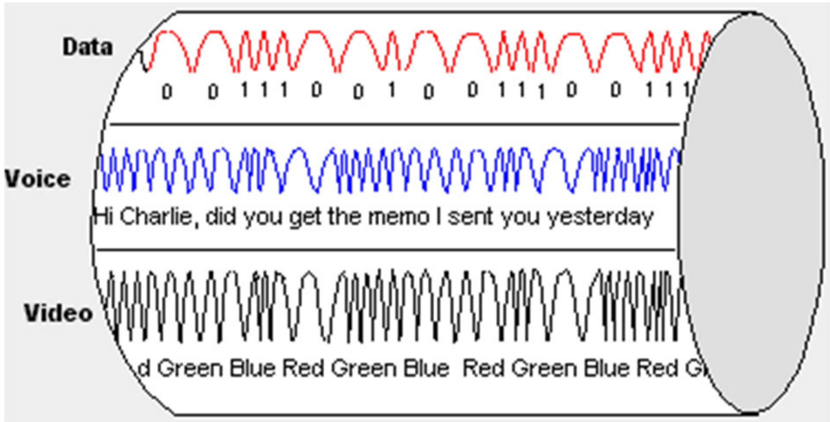
- Channel:
  - In communications, it refers to communications path between two computers or devices.
  - It can refer to the physical medium (the wires) and TV channels refer to particular frequencies at which radio waves are transmitted.
- Propagation Delay:
  - The amount of time it takes for a signal to travel from its source to its destination.
- Bandwidth (Digital):
  - The measurement of the amount of information that can be transmitted per unit of time.
  - Digital systems: measured as “Bits per second”

Fundamental Concepts

- Baseband signaling
  - – Sends data along a single channel by means of voltage fluctuations.
  - – Entire bandwidth of the cable is used to carry data.

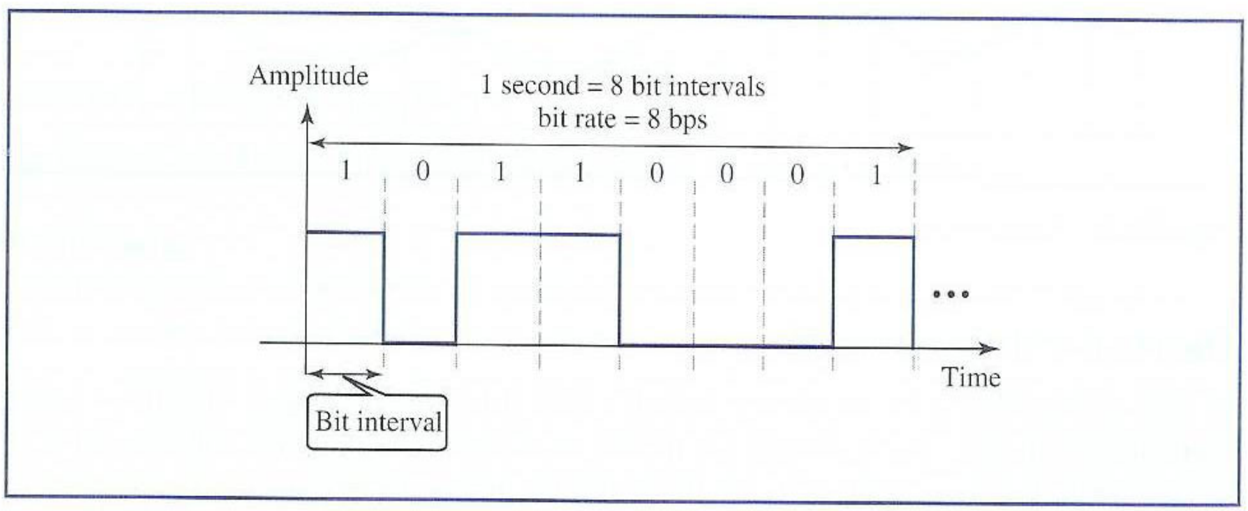


- Broadband signaling
  - – Data is carried on high frequency carrier waves
  - – Carrying capacity of medium divided into number of sub-channels, such as video, low speed data, high speed data, voice, etc.
  - – allows medium to satisfy several communication needs.



Digital vs. Analog Signals

- Digital Signal:
  - Data (digital or analogue) can be represented by a digital signal
  - Bit interval: time required to send one single bit
  - Bit rate: Number of bit intervals per second

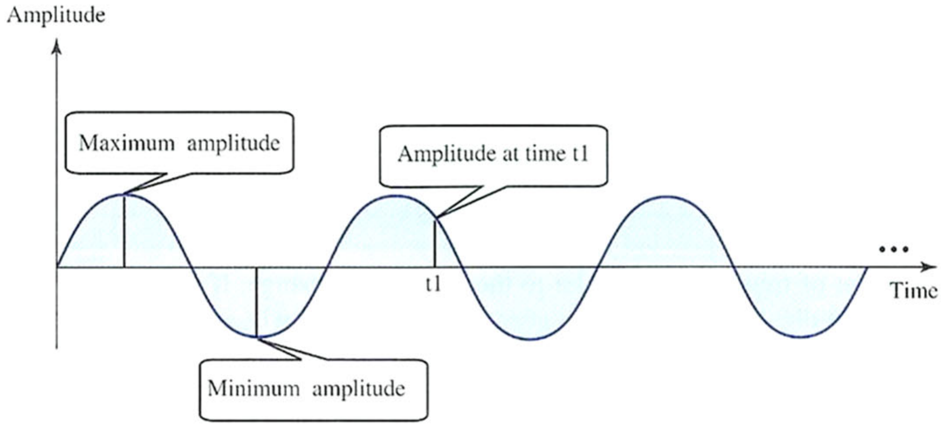


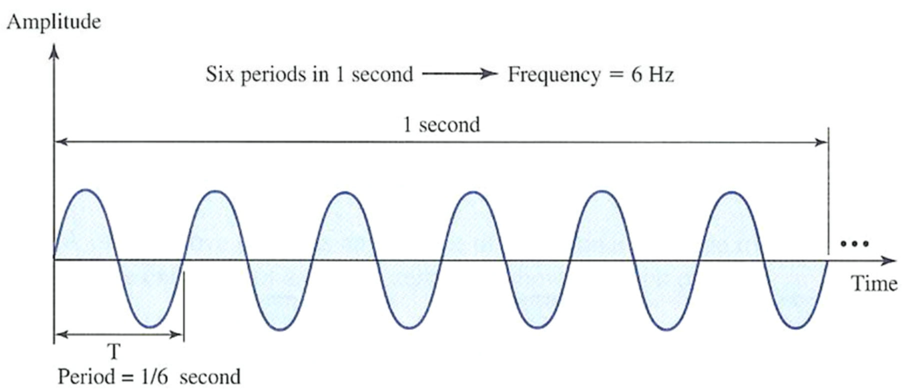
Digital vs. Analogue Signals

Analog Signals

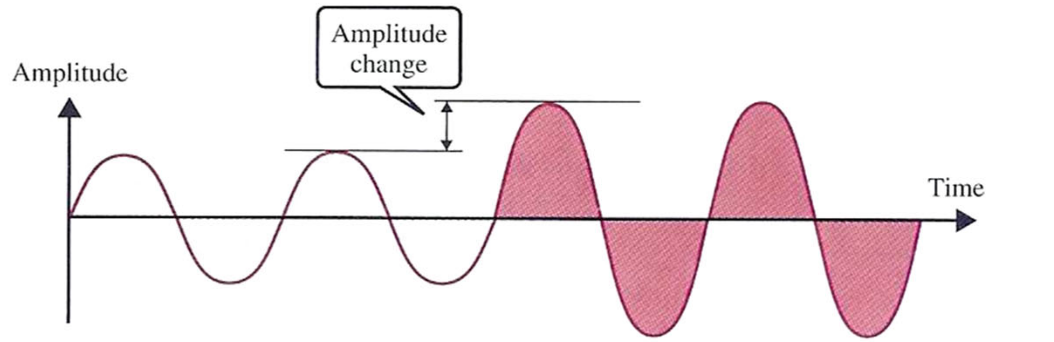
- Analog waves could be simple or composite (a combination of more than one simple signal)
- Example for a simple signal is a sine wave.
- Sine wave can be fully described by the following characteristics:
  - Peak Amplitude – The absolute value of its highest intensity, proportional to the energy it carries.
  - Frequency – The rate of change with respect to time
  - Phase – The position of the waveform relative to time 0
- Peak and Phase determine the levels in the signal element
- Frequency determines the number of signal elements

Amplitude and Frequency

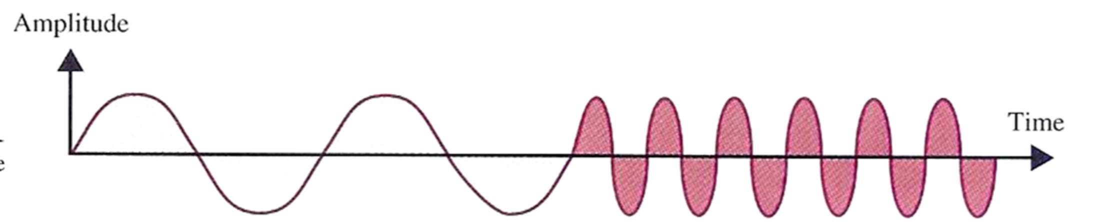




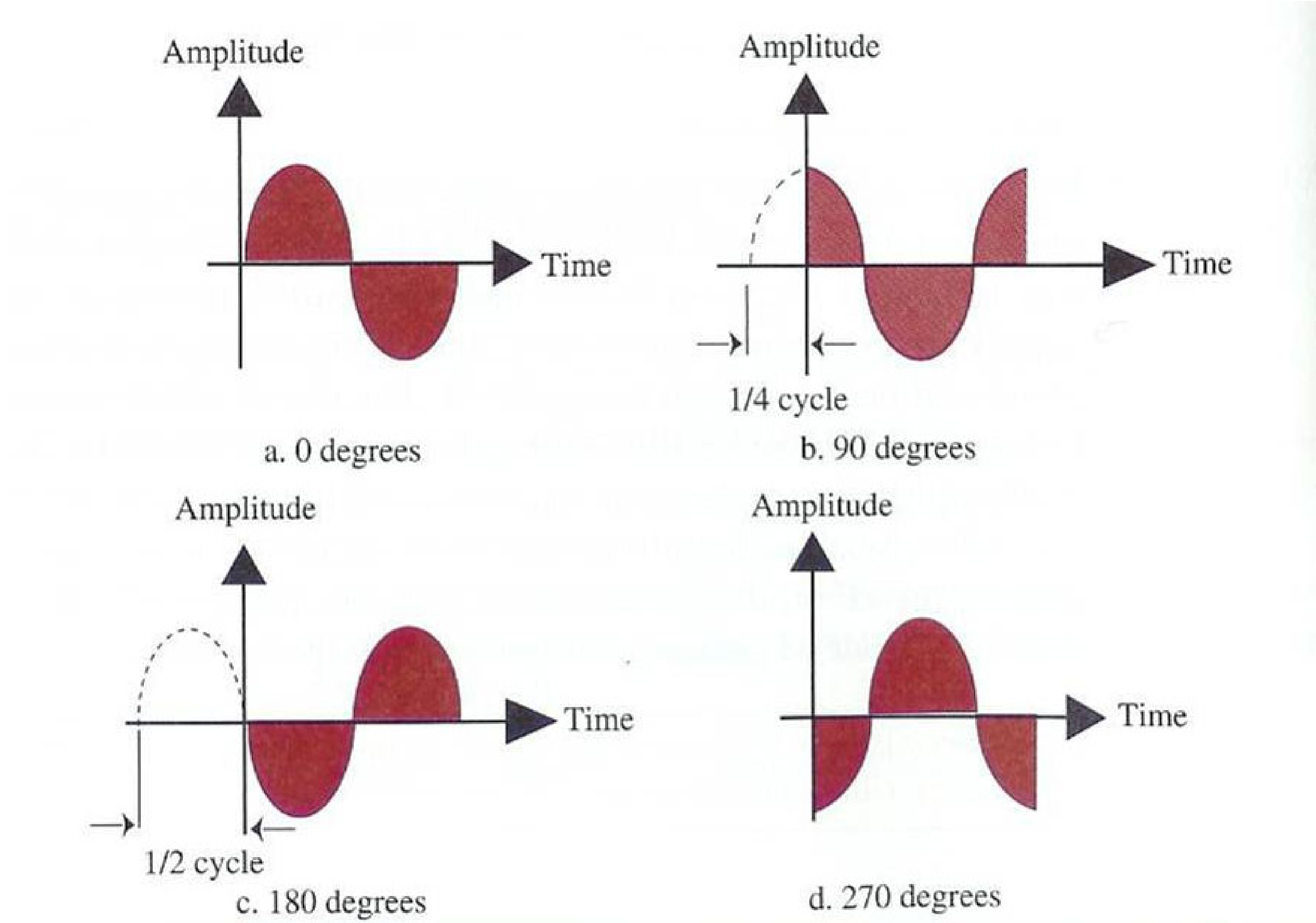
re 4.8 *Amplitude change*



re 4.9 *Frequency change*



Phase



Amplitude
Time
a. 0 degrees
Amplitude
Time
1/4 cycle
b. 90 degrees
Amplitude
Time
1/2 cycle
c. 180 degrees
Amplitude
Time
d. 270 degrees

Signal Encoding and Modulation

- Digital/analogue Modulation
  - ASK, FSK, PSK,
- Digital/digital encoding
  - Unipolar encoding
  - Polar encoding
    - NRZ encoding
    - RZ encoding
    - Biphase
      - Manchester encoding
      - Differential Manchester encoding
- Analogue/digital Modulation
  - PCM, PAM
- Analogue/analogue Modulation – Out of Scope
  - AM, FM

Digital to Digital Conversion

Digital to digital Encoding

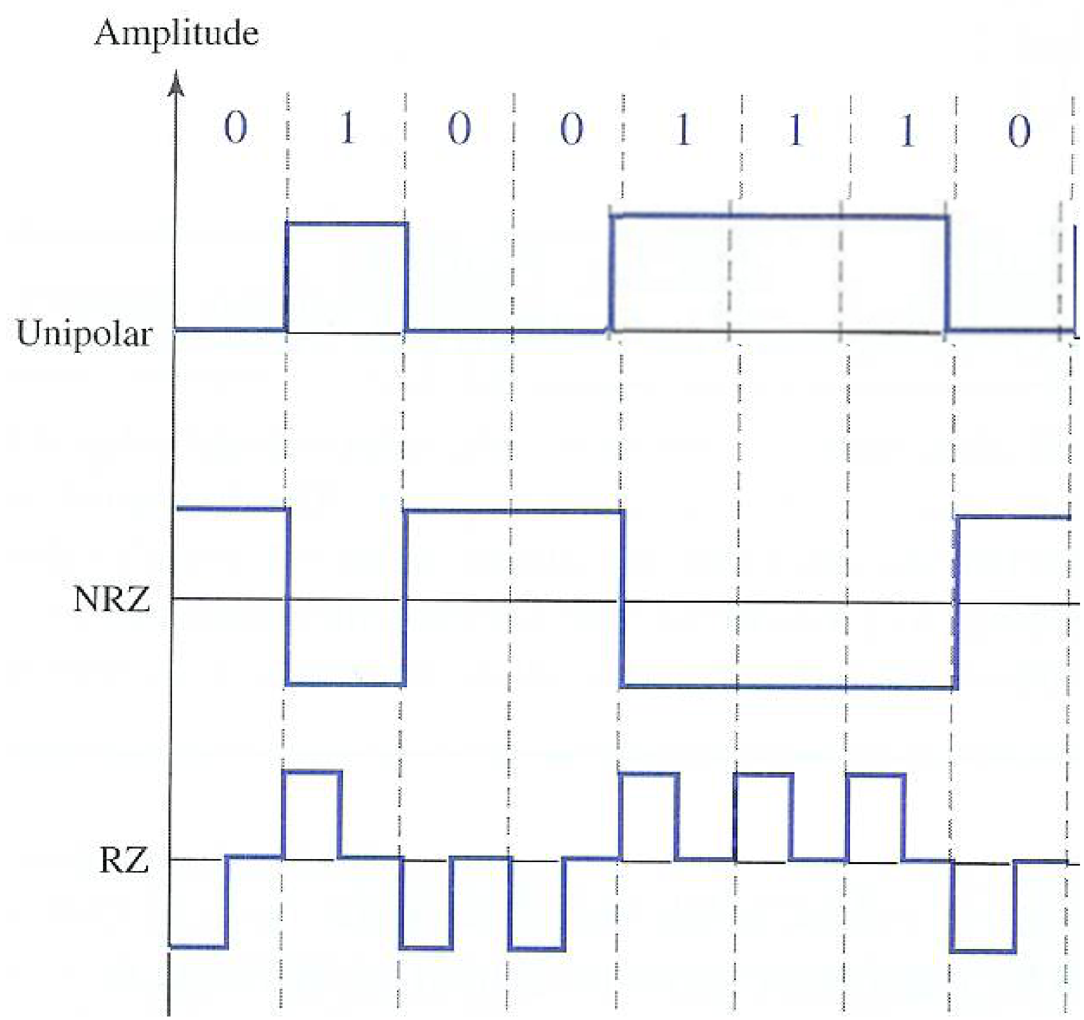
Line Coding

Unipolar

- NRZ (Non Return to Zero):
  - One level of value (same side of time axis)
  - Problems: Cost and (Clock) Synchronization

Polar

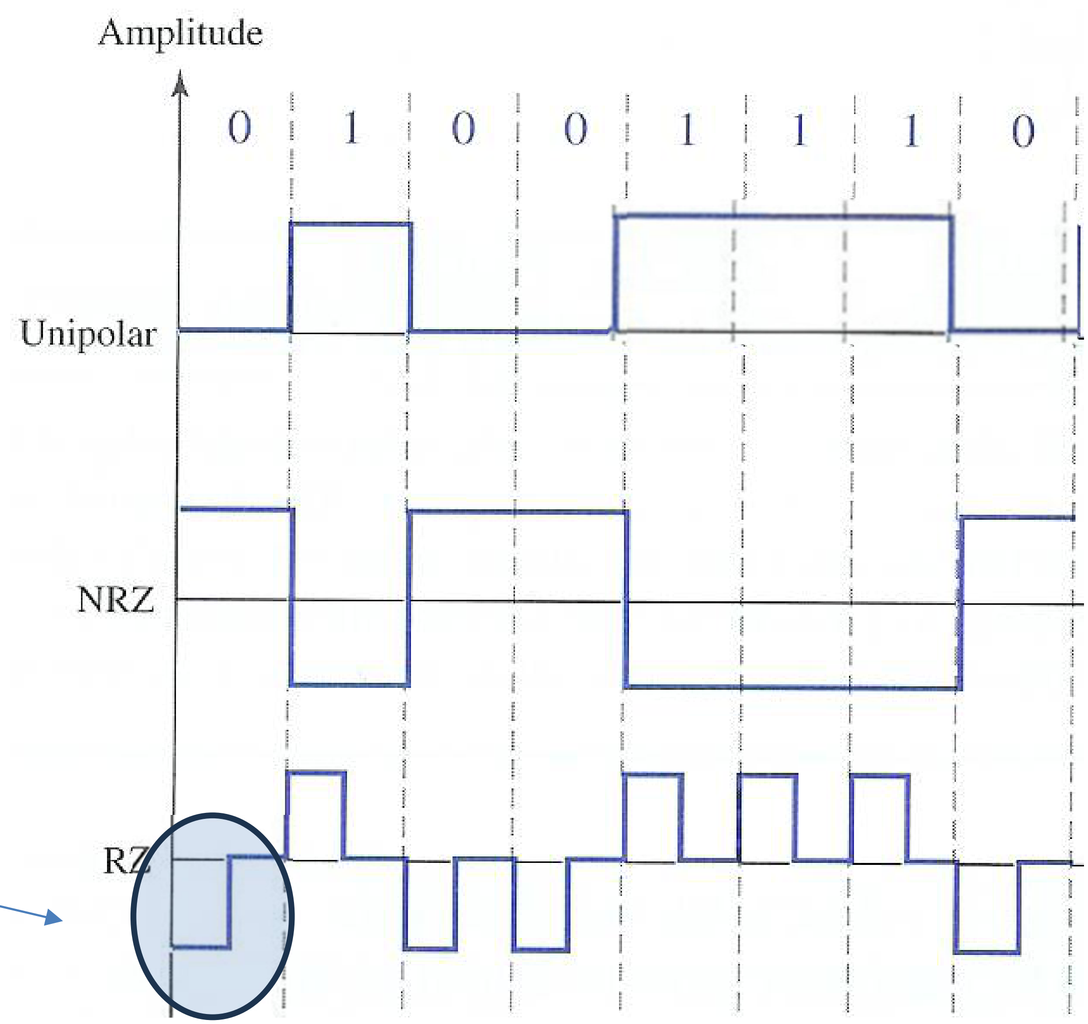
- NRZ (Non Return to Zero):
  - Level of the signal is either positive or negative
  - Problem arises when transmitting a continuous stream of 0 or 1.



Digital to digital Encoding

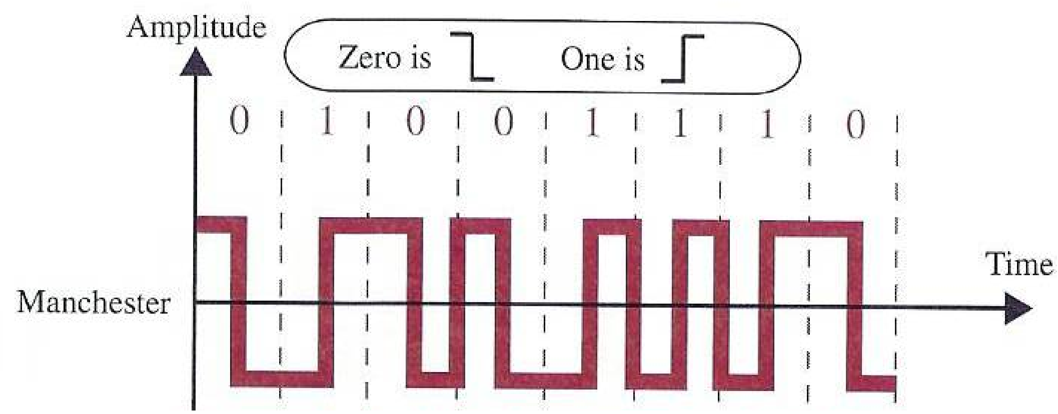
Polar

- Return to Zero:
  - Three levels of the signal used, +ve, -ve or 0
  - Binary 1 represented by +ve to 0 and binary 0 represented by –ve to 0 (or vice versa)
  - The transition of the signal at each bit is used for synchronization.
  - Two signal elements to represent one bit occupy more bandwidth.



Digital/digital Encoding

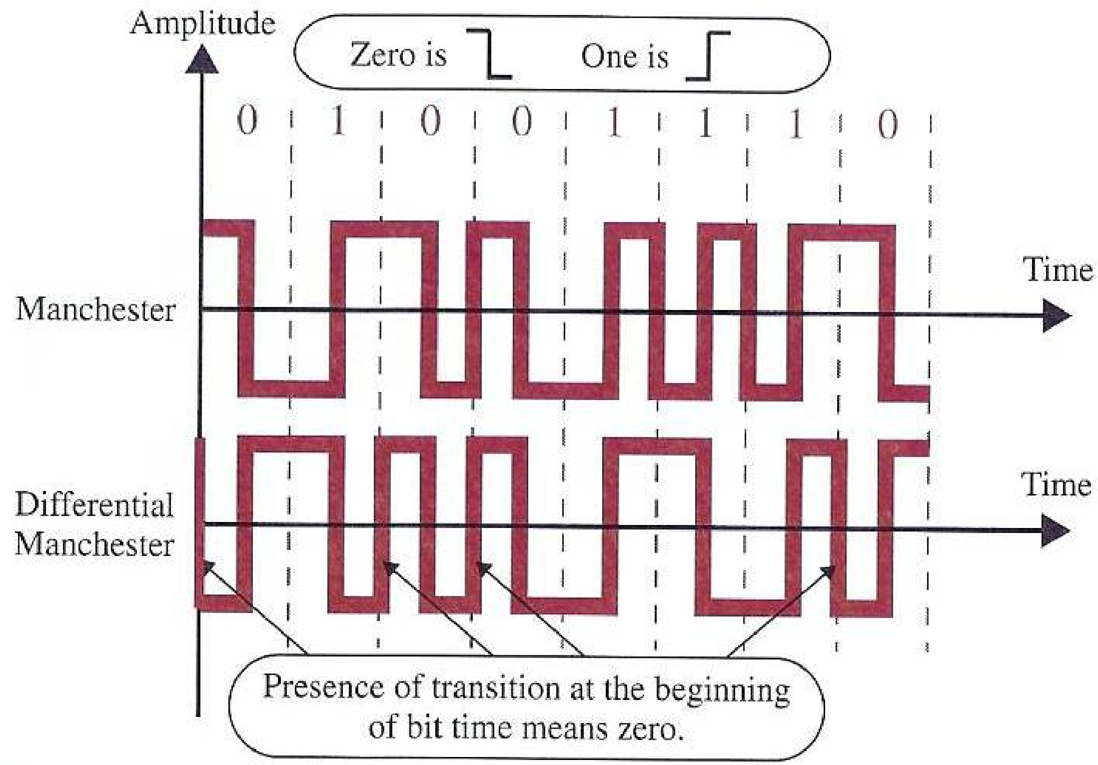
- Manchester Encoding:
  - Transition at the middle used for both synchronization and bit representation.
  - binary 1 = -ve to +ve
  - binary 0 = +ve to -ve (or vice versa)



This is used for 10Mbps Ethernet.

Digital/digital Encoding

- Differential Manchester Encoding:
  - Presence or absence of a transition at the beginning of the interval is used to identify a bit.
  - Binary 1 – No transition, Binary 0 – Represents a transition
  - Transition at the middle used only for synchronization



There are many others, such as MLT-3 encoding (Multi-Level Transmit)

More details on line encoding for Ethernet https://en.wikipedia.org/wiki/Gigabit_Ethernet

Digital signals make signals less susceptible to noise
Note that two signal elements are used for each bit at cost of bandwidth

Digital to Analog Conversion

Digital/analogue Modulation

- Digital to Analogue Conversion:

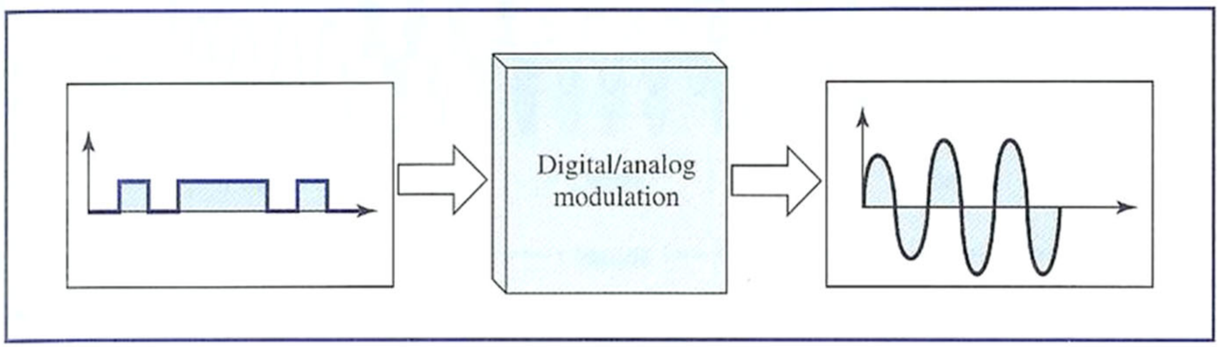


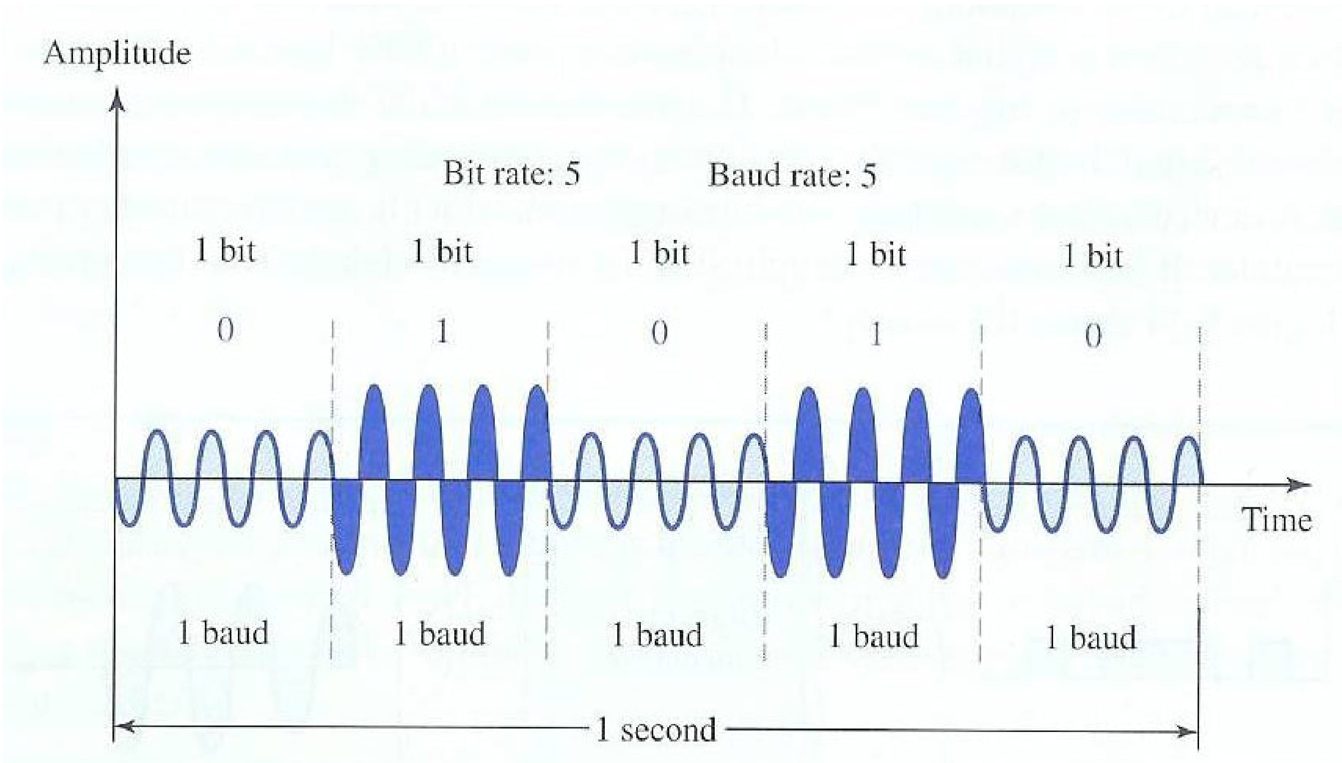
Figure 6.14 Digital-to-analog modulation

- Main mechanisms:
  - Amplitude Shift Keying (ASK)
  - Frequency Shift Keying (FSK)
  - Phase Shift Keying (PSK)
  - Quadrature Phase Shift Keying (QPSK)
  - Quadrature Amplitude Modulation (QAM) – Combines ASK and PSK

Sending digital signals as analogue waveforms (wireless data) limit usage of spectrum bandwidth

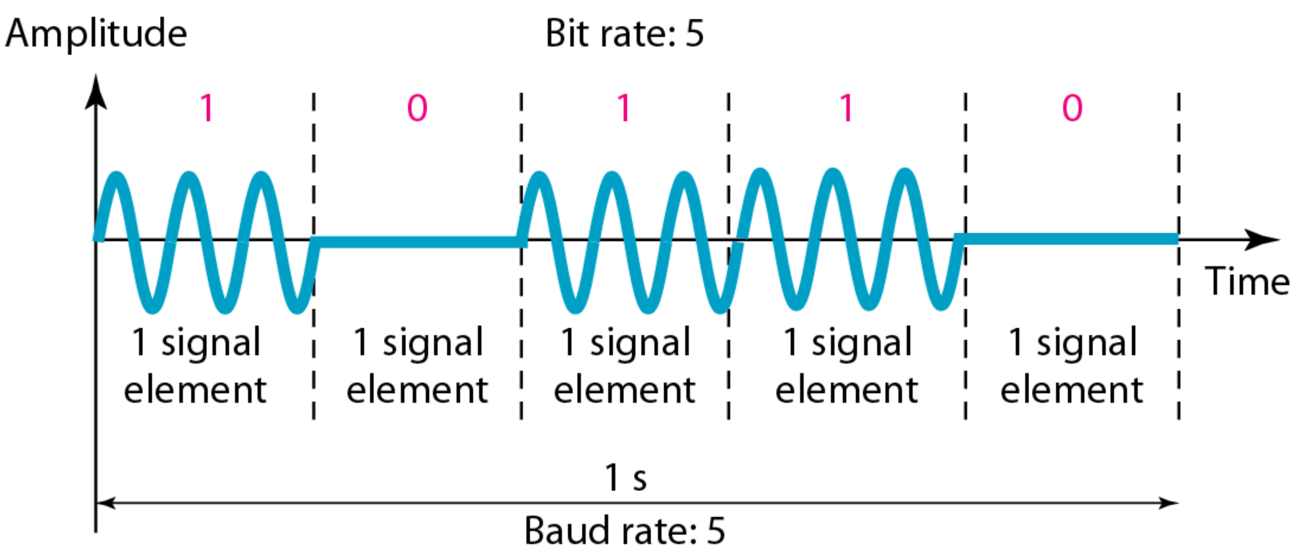
Amplitude Shift Keying (ASK)

- Amplitude of the carrier signal is varied to represent binary 1 or 0. Frequency and Phase remains constant.
- Highly susceptible to noise.



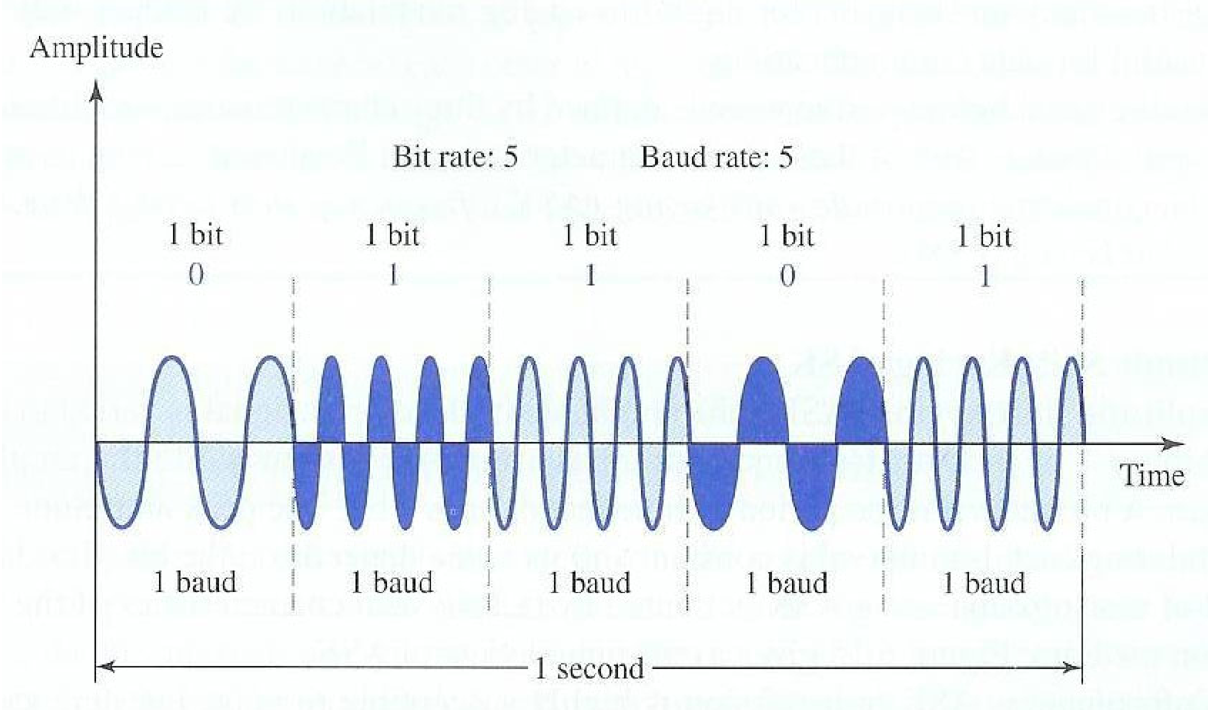
Binary Amplitude Shift Keying (BASK)

- ASK is normally implemented using only two levels referred to as Binary Amplitude Shift Keying (BASK)



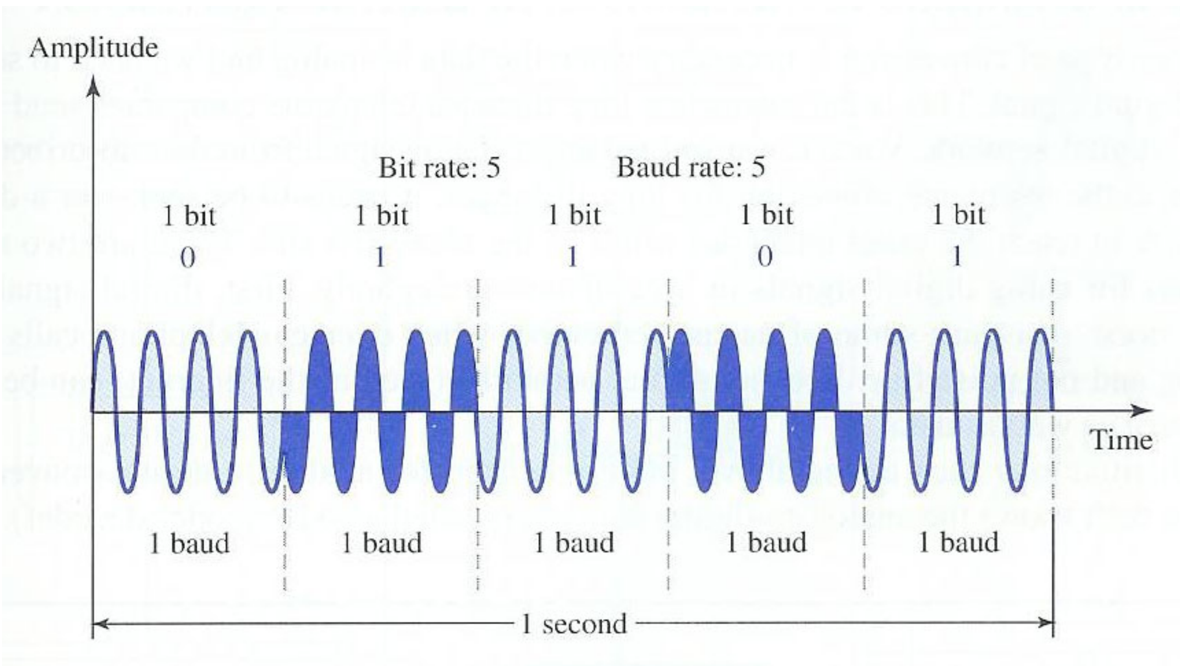
Frequency Shift Keying (FSK)

- Frequency of the carrier signal is varied to represent binary 1 or 0. Amplitude and Phase remains constant.
- The simplest is Binary Frequency Shift Keying (BFSK)



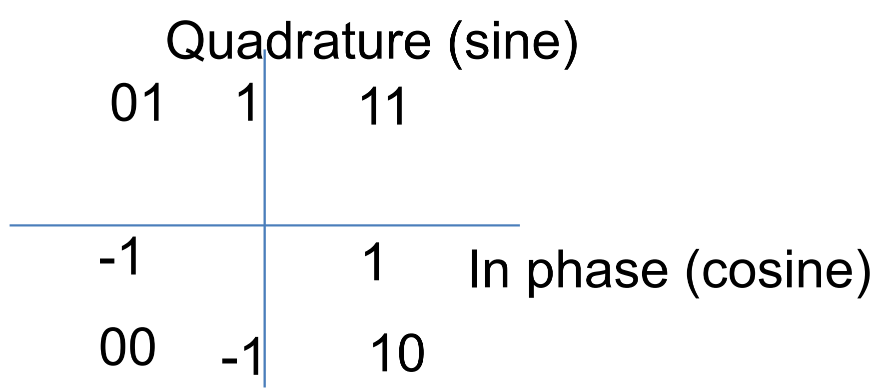
Phase Shift Keying (PSK)

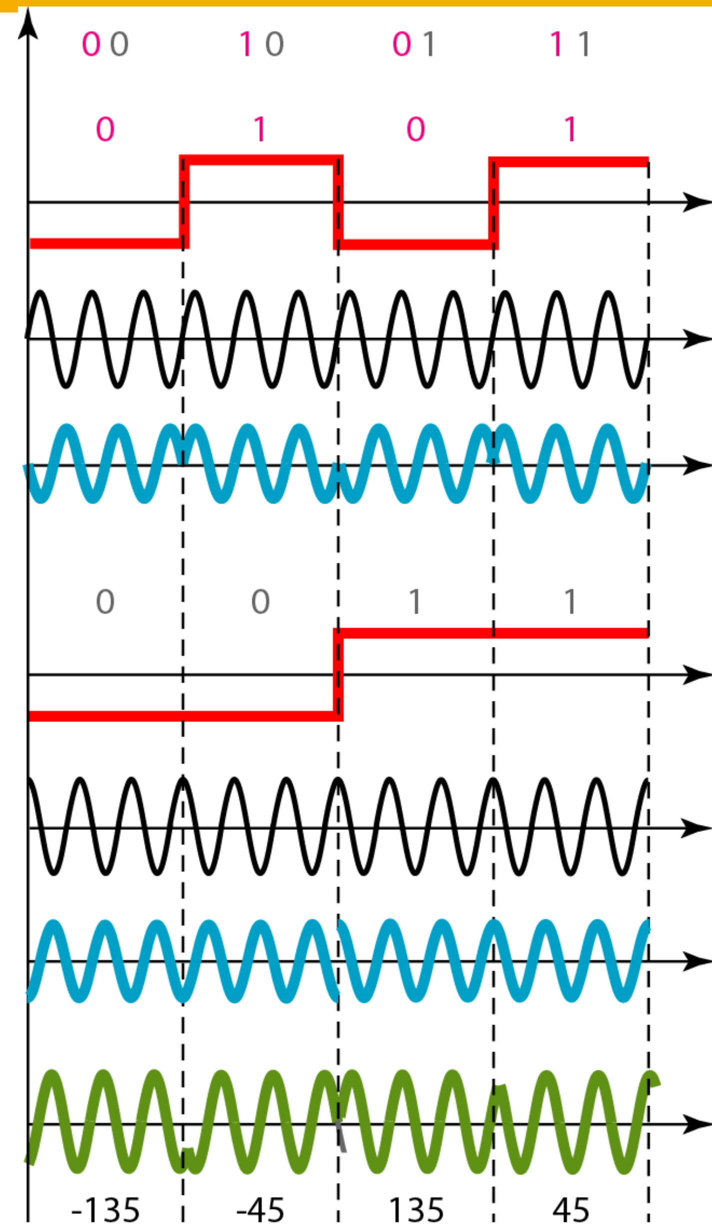
- Phase of the carrier signal is varied to represent binary 1 or 0. Amplitude and Frequency remains constant.
- The simplest is Binary PSK



Quadrature Amplitude Modulation(QAM)

- 2 bits at a time in a signal element per baud
- 2 Separate PSK modulators
- In phase and Quadrature (out-of-phase)
- Two composite signals created have the same frequency but different phases.
- When added, the resultant wave becomes **a signal element** with M=4 possible phases: 45^o, -45^o, 135^o, -135^o, thus named M-QAM

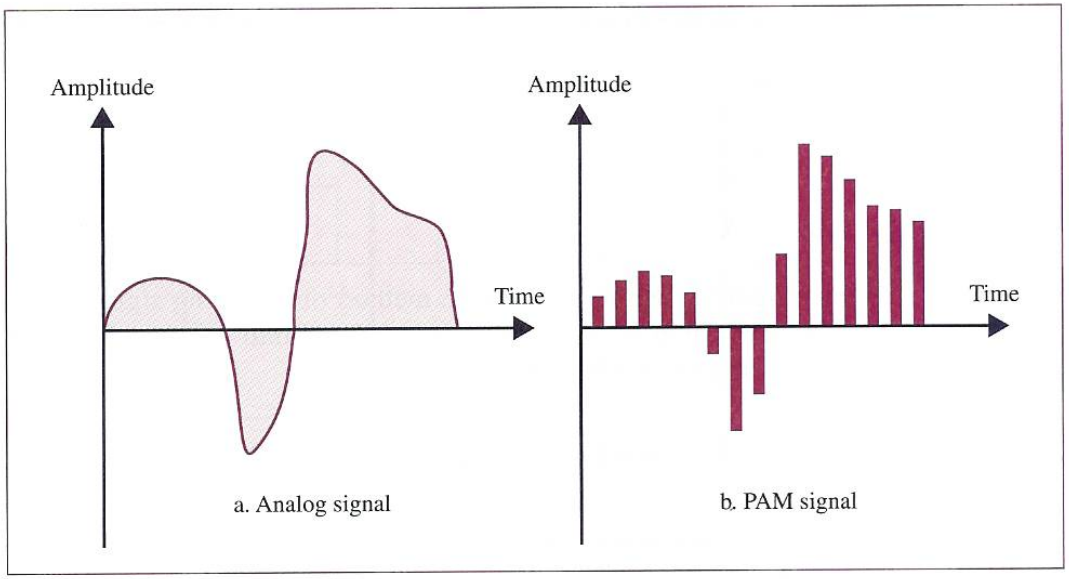




Analog to Digital Conversion

Analogue to Digital Modulation

- The most common technique is Pulse Code Modulation (PCM)
- PCM is made up of the following steps:
  - Sampling
  - Quantization
  - Encoding
- First step is Sampling
  - This takes an analogue signal and measures the signal at equal intervals, called sampling.
  - Only transforms the signal to a series of pulses not a full digital signal (PAM Signal).



Digitalised analog signals (from microphone, camera etc) make signal less susceptible to noise

Analogue to Digital Conversion

Second step is Quantization

- Quantization assigns values in a specific range to sampled instances.
- A sign (+/-) and a magnitude assigned to quantized samples.
- Telephone companies usually assign a value from 0 to 127.

The third step is to encode the quantized values to a stream of bits

- Each value is translated to its seven-bit binary equivalent and the eighth bit indicates the sign.
- The signal is transformed to a digital signal

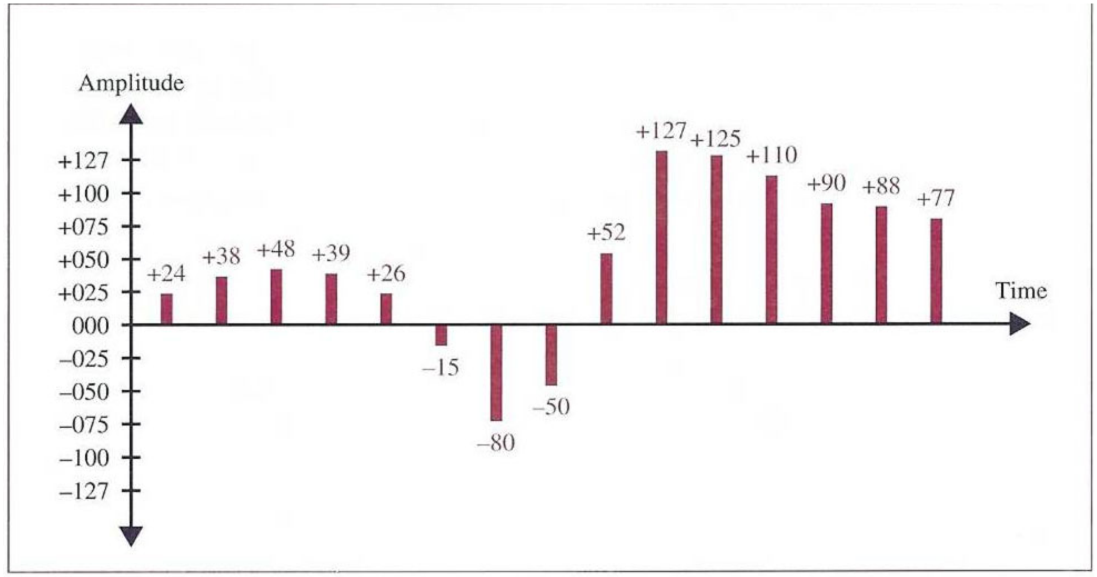


Figure 5.18 shows a simple method of assigning sign and magnitude values to quantized samples. Each value is translated into its seven-bit binary equivalent. The eighth bit indicates the sign.

Figure 5.18 *Quantizing using sign and magnitude*

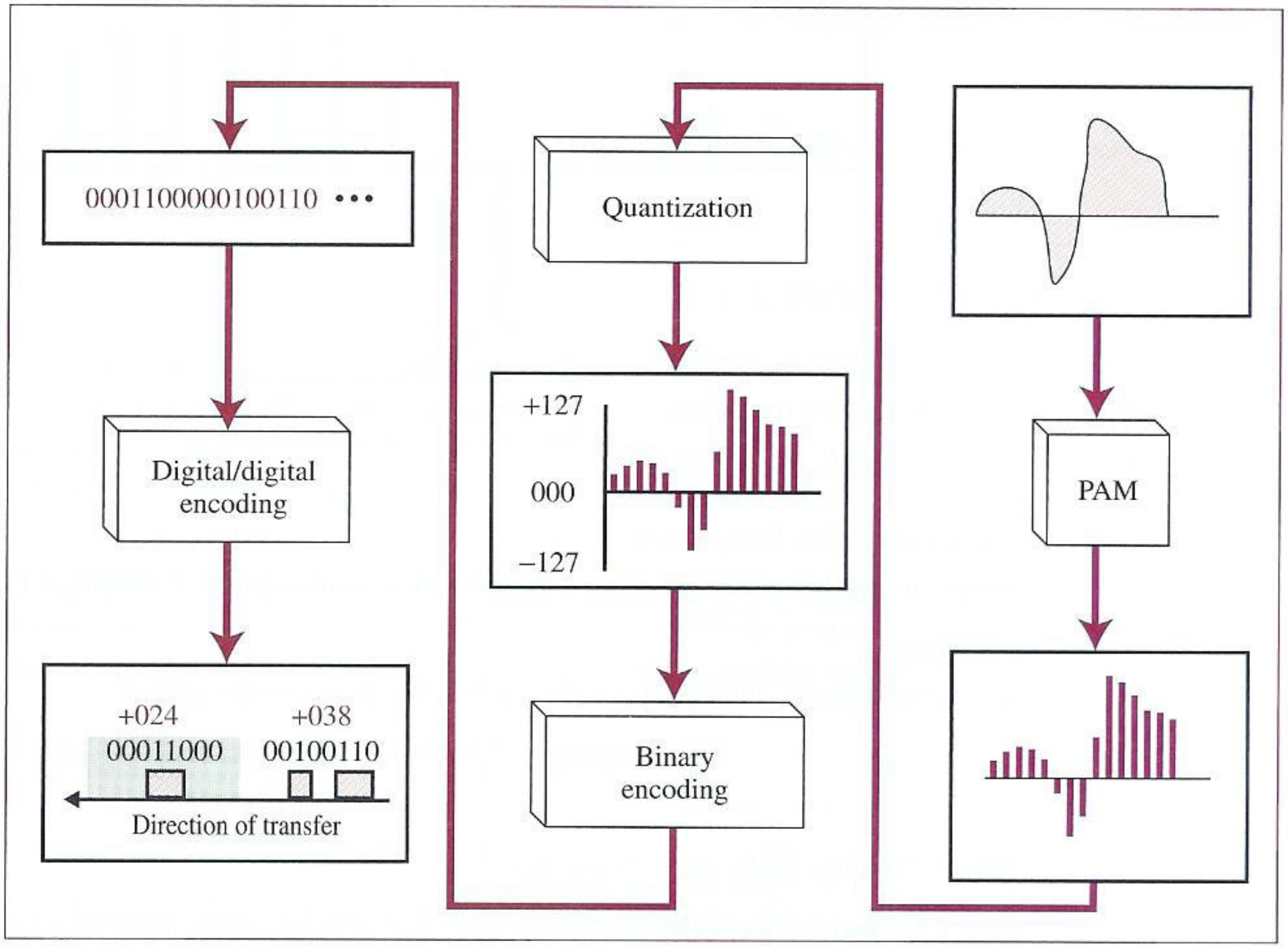
+024	00011000	–015	10001111	+125	01111101
+038	00100110	–080	11010000	+110	01101110
+048	00110000	–050	10110010	+090	01011010
+039	00100111	+052	00110110	+088	01011000
+026	00011010	+127	01111111	+077	01001101

Sign bit
+ is 0 – is 1

The binary digits are then transformed into a digital signal using one of the digital

PCM

Figure 5.20 *From analog signal to PCM digital code*



The Accuracy

- The accuracy of digital production depends on the number of samples taken.

Question: How many samples are sufficient?

- Nyquist theorem says to ensure accurate reproduction of an analogue signal using PAM, the sampling rate must be at least twice the highest frequency of the original signal.
- Hence, to sample telephone voice with max frequency 4000Hz, we need a sampling rate of 8000 samples per second.

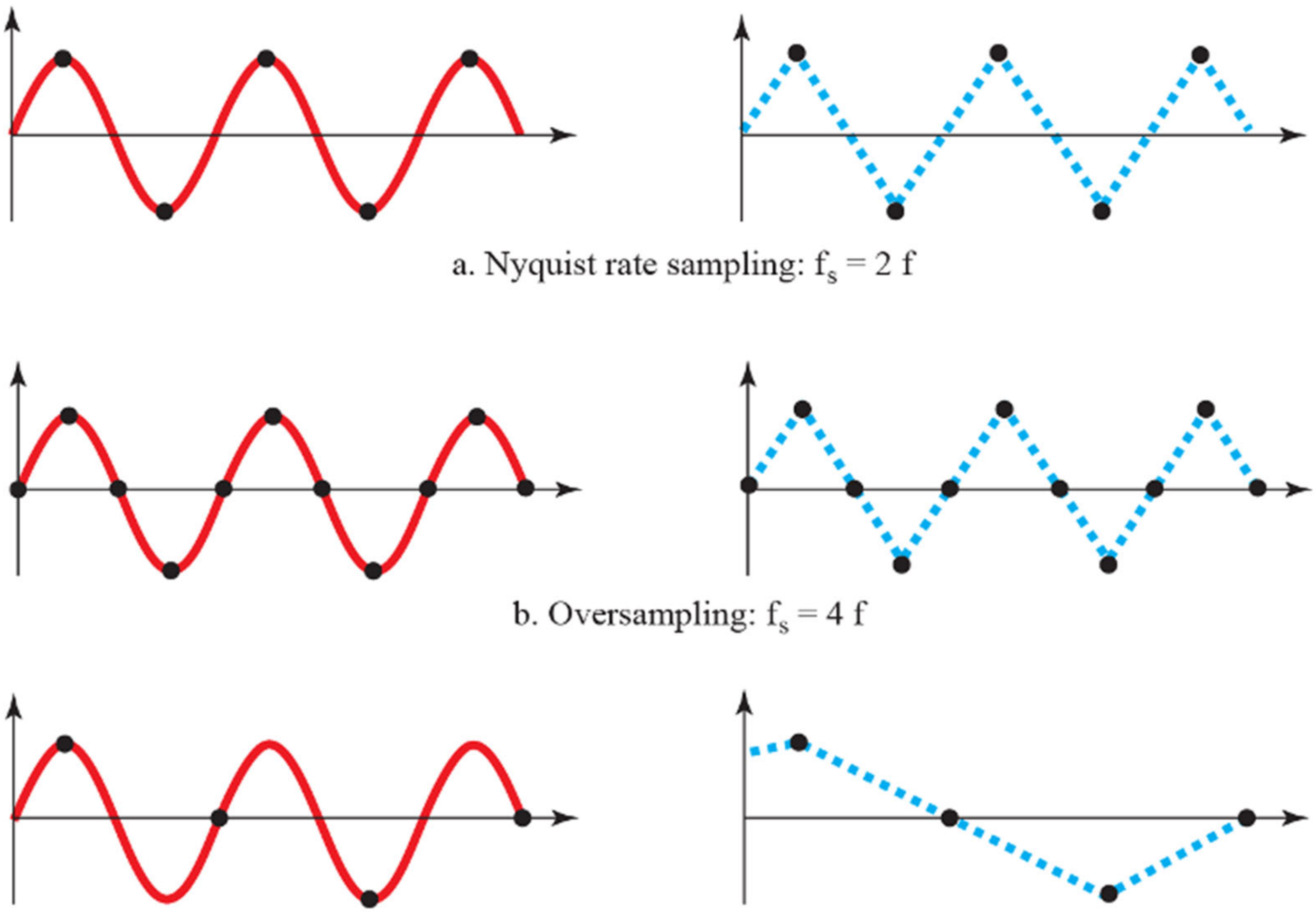
Question: How many Bits per PCM Sample?

- Depends on the level of precision needed, phone companies use 7 bits per sample (Plus one bit for sign), Hence 8 bits/1 byte
- Bit Rate = Sampling Rate * No of bits per sample

  = 8000 * 8

  = 64,000 bps = 64 Kbps

Recovery of a sampled sine wave for different sampling rates



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

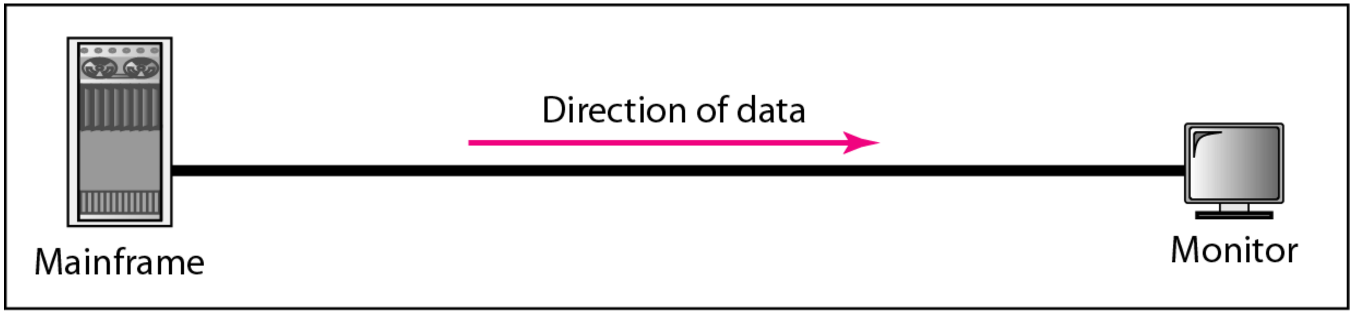
b. Oversampling: $f_s = 4\ f$

c. Undersampling: $f_s = f$

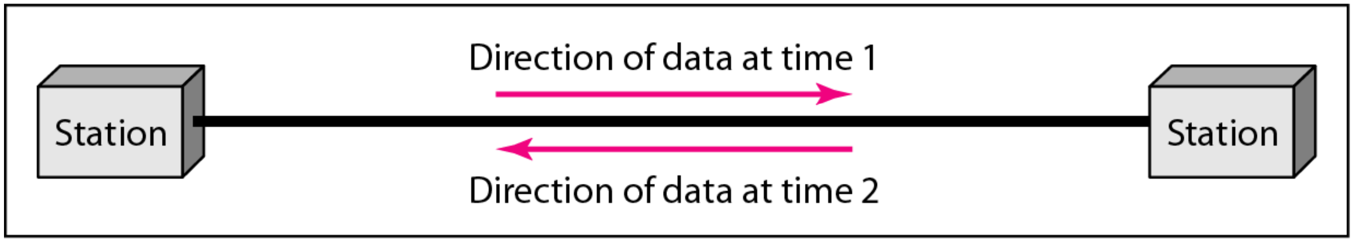
Intuition: For a sinusoid (sin or cos waveform) you need minimum 2 points for waveform reconstructions

Bandwidth Utilization

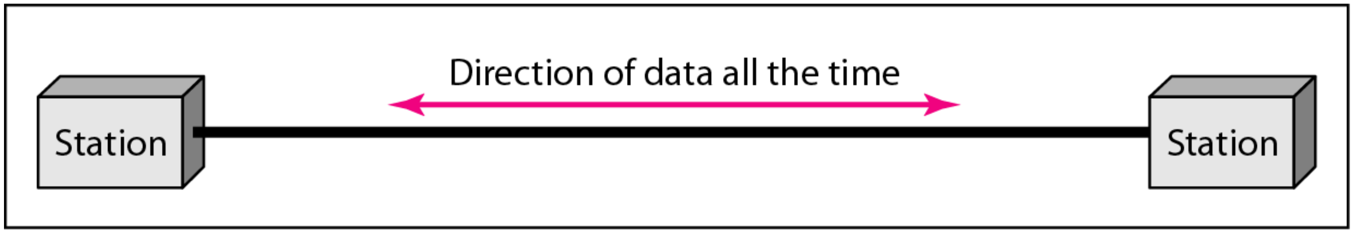
Transmission Modes



a. Simplex



b. Half-duplex



c. Full-duplex

Multiplexing

Lucy, 2014 , by Luc Besson

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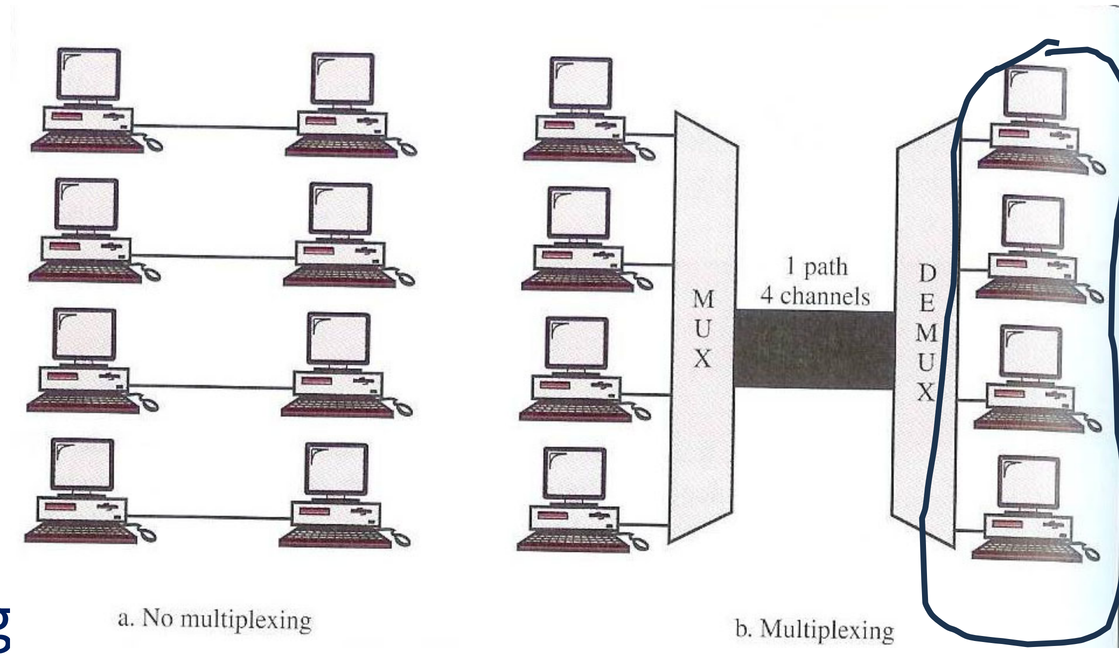
Multiplexing

- This is the technique that allows the simultaneous transmission of multiple signals across a single data link.
- Three main types:
  - Frequency –Division Multiplexing
  - Time-Division Multiplexing
  - Statistical Time-Division Multiplexing

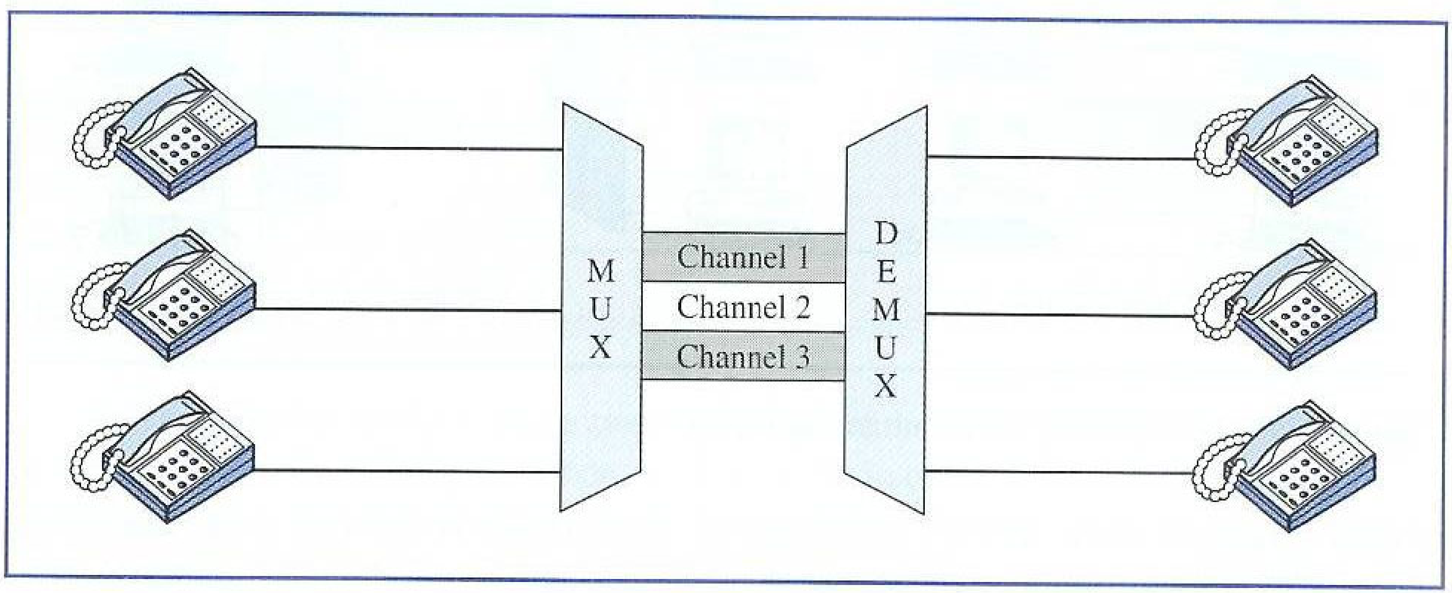
Info



Lucy

Frequency Division Multiplexing

- Analogue technique that can be applied when the bandwidth of a link is greater than the combined bandwidths of the signals to be transmitted.
- Channels/frequencies must be separated by strips of unused bandwidth (guard bands) to prevent signals from overlapping.



Time Division Multiplexing

- The usage of a high capacity link is divided into time slots. Each device has a time slot.
- Can only be used with a digital signal.
- Also known as synchronous time division multiplexing.

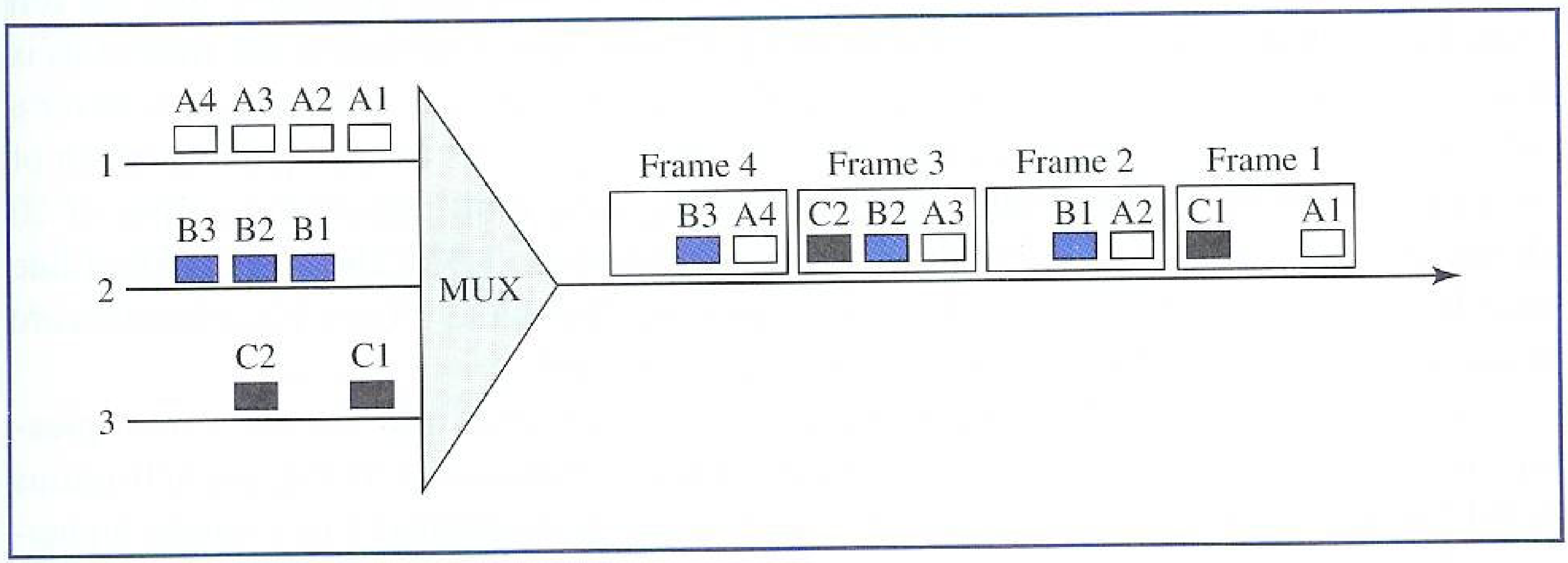
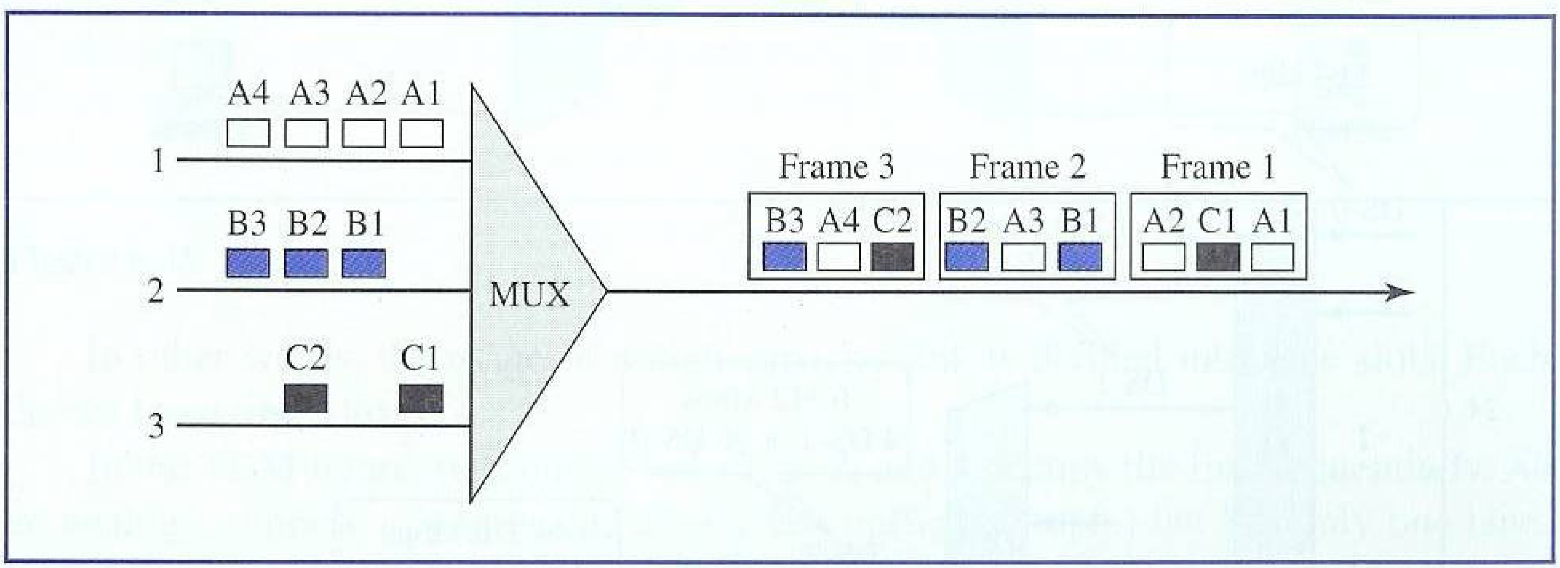


Figure 6.34 Synchronous TDM

Statistical (Asynchronous) Time Division Multiplexing

- STDM guaranties the full capacity of a link.
- The STDM frame is based on a statistical analysis of the number of input lines that are likely to be transmitting at any given time.
- The multiplexer scans the input lines until the frame is filled and then sends the frame across the link.



Digital/Analog Communication

We want to send letter A and represent each letter with a combination of 0 and 1. There are 26 letters.

1. How many bits are required to represent all letters?

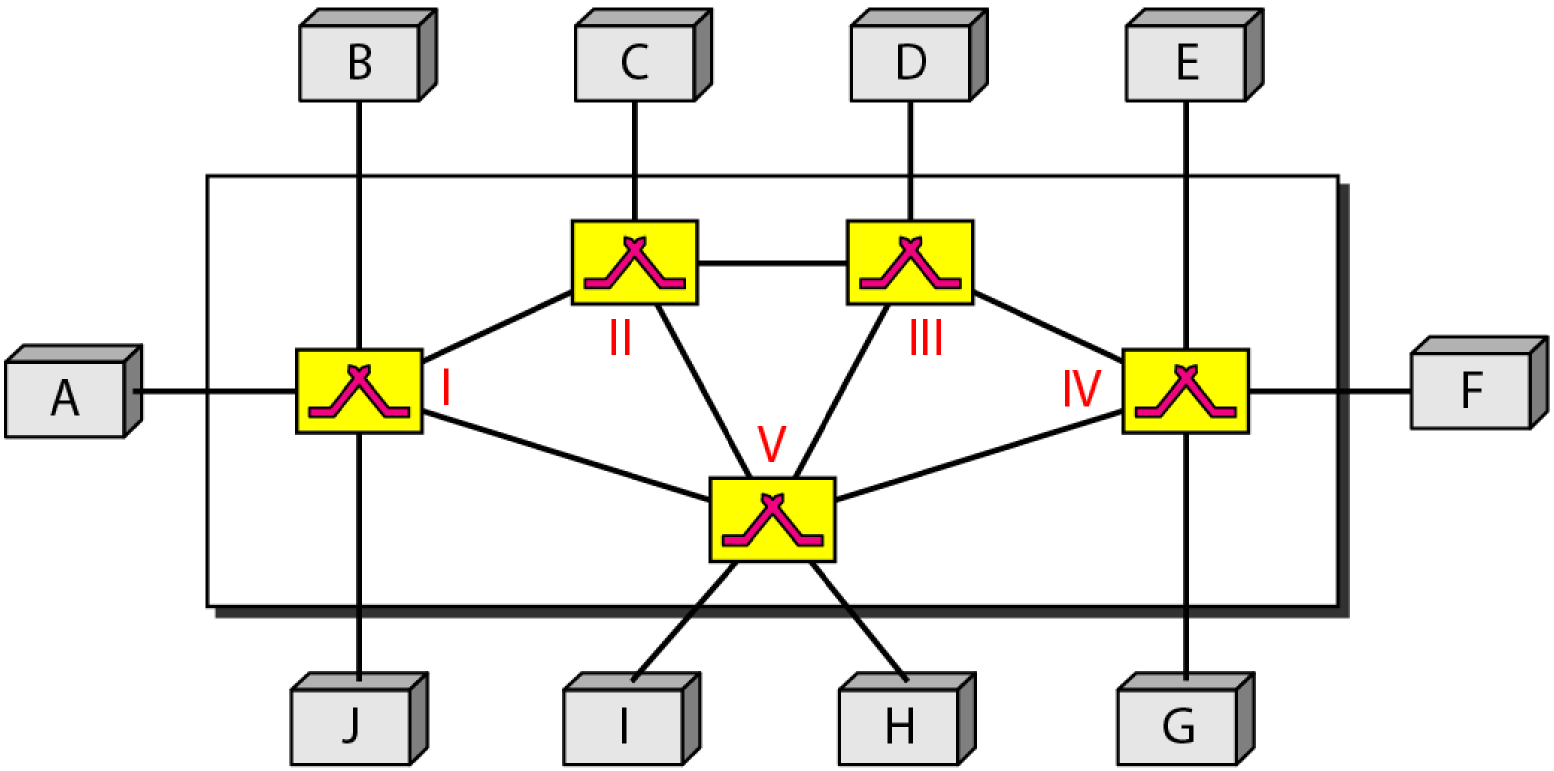
2. Efficient transmission?

3. Reliable transmissions? Sending multiple letters to someone?

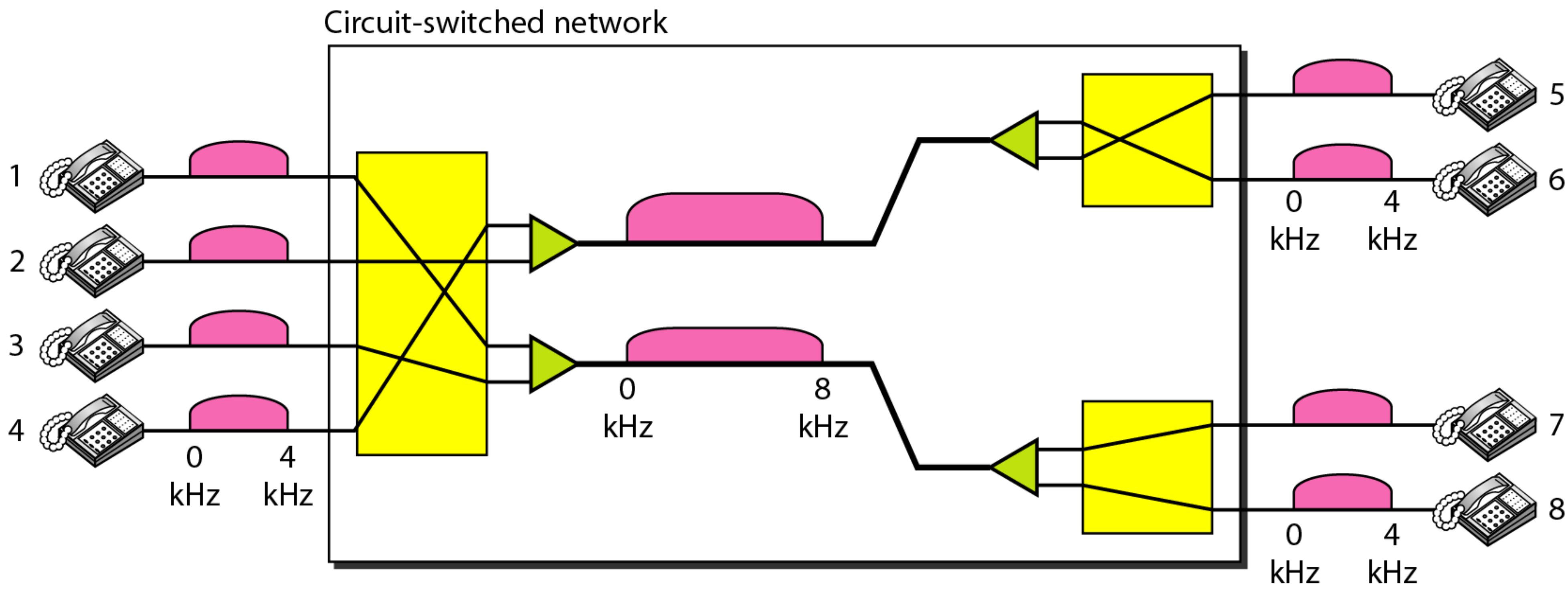
Switching

Switching Techniques

- A switched network



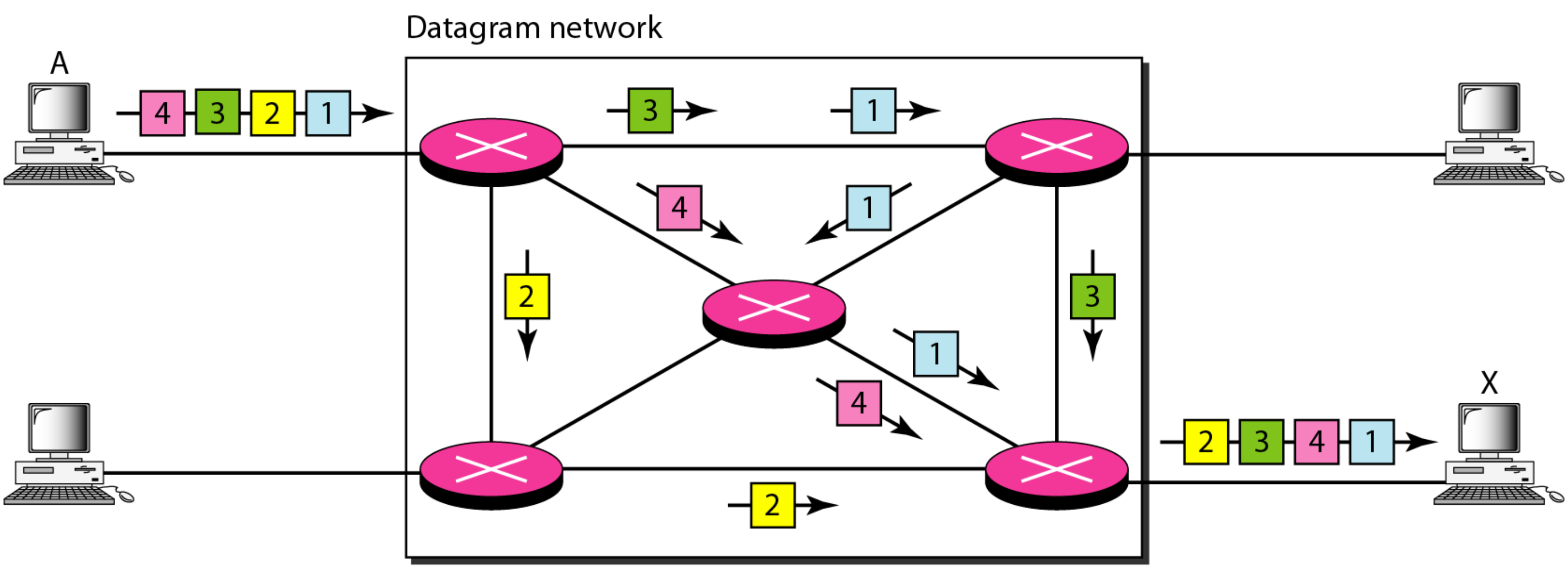
Circuit Switched Network



Packet Switched Networks

Datagram networks

- In a packet switched network, there is no resource reservation.
- Resources are allocated on demand on a first come first served basis.
- Each datagram treated independently .
- Also referred as connectionless networks.
- Packet switching is done at the Network Layer and will be discussed later.

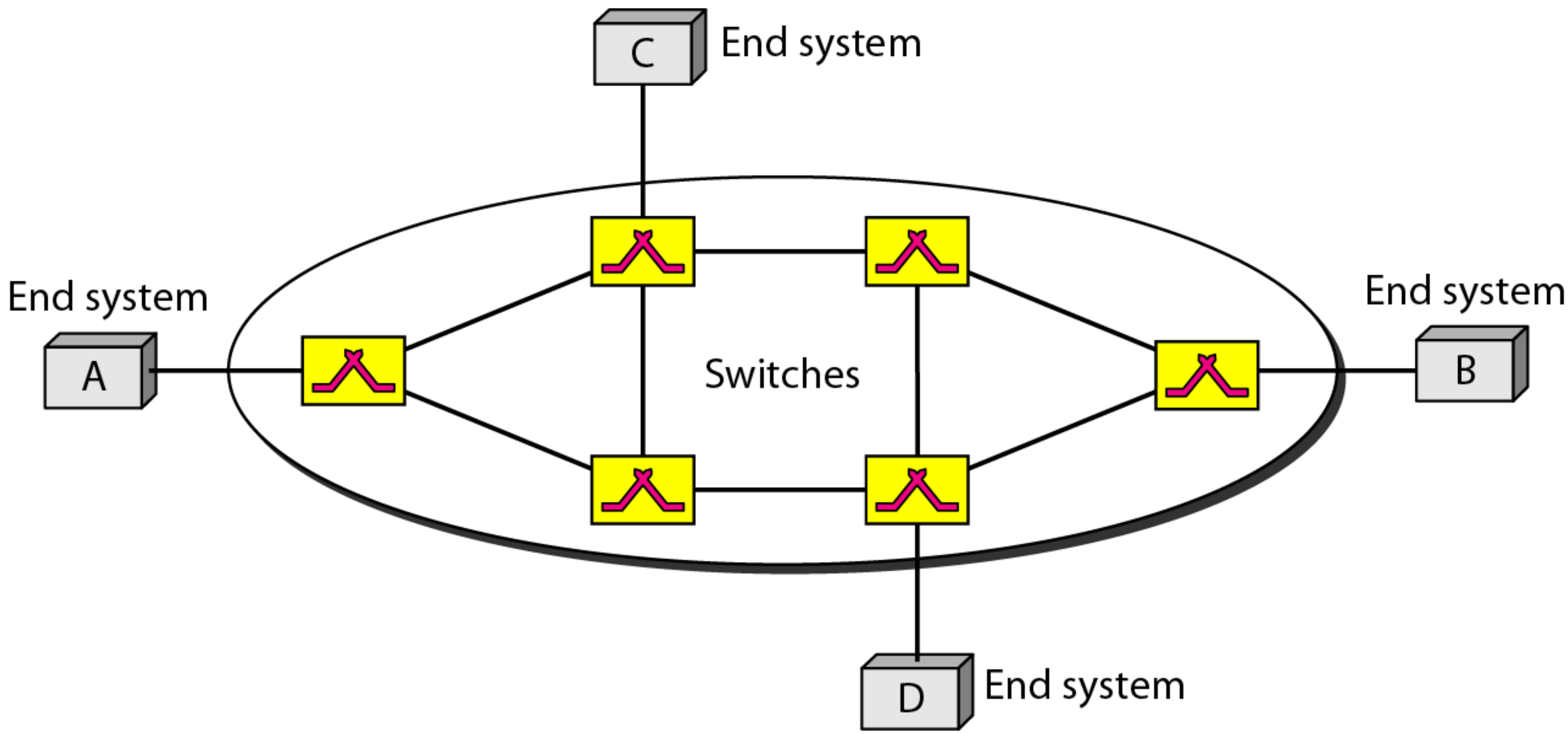


Packet Switched Networks

Virtual-Circuit Networks

- A combination of a circuit switched network and a packet switched network usually implemented at the data link layer
- Similar to circuit switched networks:
  - Three phases for setup, transfer, and teardown
  - Resources allocated at setup phase
  - All datagrams follow the same path established during the connection
  - Keep the sequence/order of flow
- Similar to datagram networks
  - Data are packetized in to datagrams
- Two types of VCs:
  - Switched virtual circuit – VC is established on demand (modem connection)
  - Permanent virtual circuit - VC is established via prior arrangement (for control signalling)

Virtual-Circuit Network



Comparison

Virtual circuit approach:

- More complex – circuit establishment is required
- Several control messages have to be exchanged prior to data transmission, however subsequent packets are treated the same way (no further routing decision is required)

Datagram approach

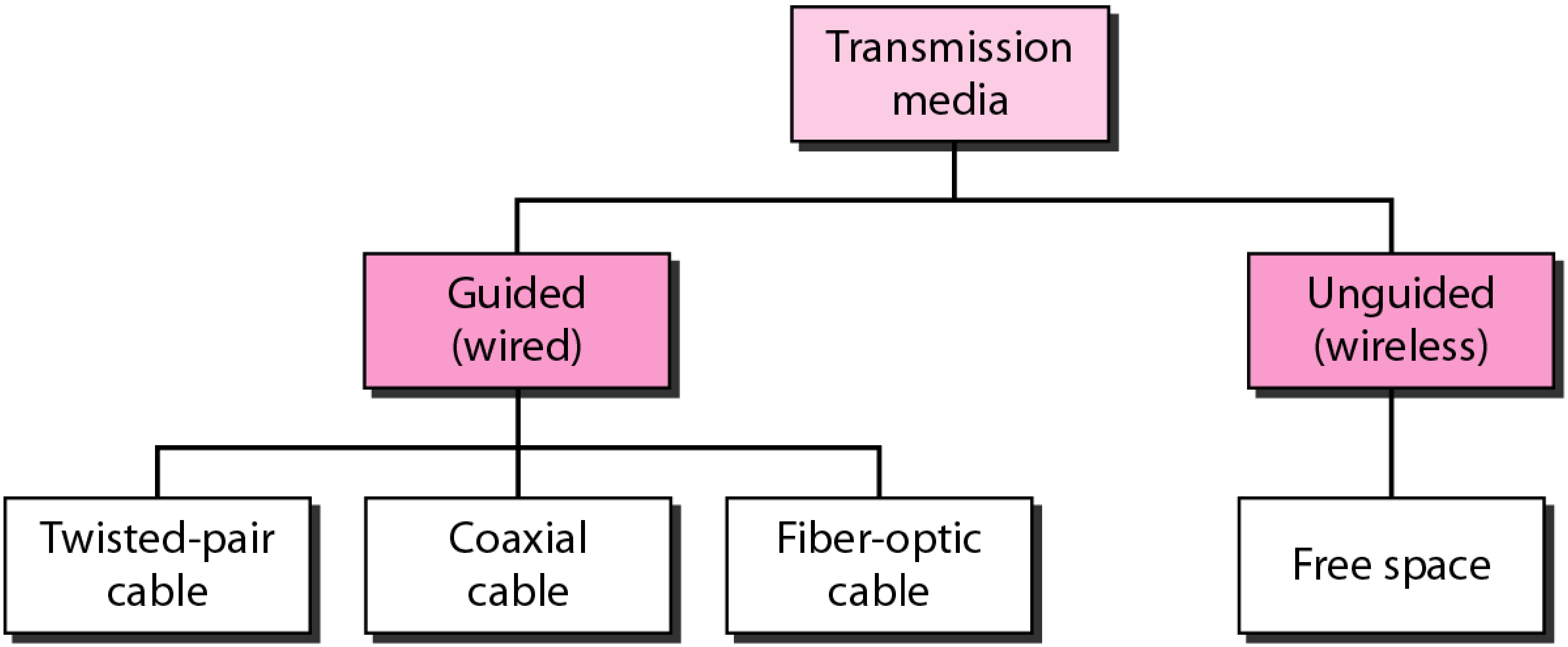
- Simpler – no circuit establishment
- No control message needs to be exchanged prior to data transmission
- A routing decision is required on each packet
- Inherently more reliable

Conclusion:

- Virtual circuit approach is more suitable for transferring longer messages
- Datagram approach is better for transmitting short messages

Transmission Media

Classes of transmission media



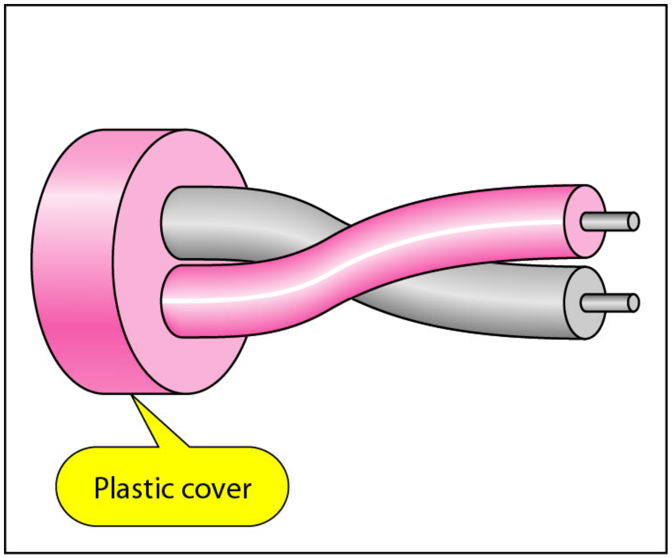
Communication Media

- Guided Media
  - Twisted Pair cabling
    - Unshielded Twisted Pair (UTP)
    - Shielded Twisted Pair (STP)
  - Coaxial Cabling
  - Fiber Optic Cabling
- Unguided Media
  - Radio Frequency Allocation and Usage
  - Terrestrial Microwave
  - Satellite Communications
  - Geosynchronous Satellites
  - Cellular Telephony

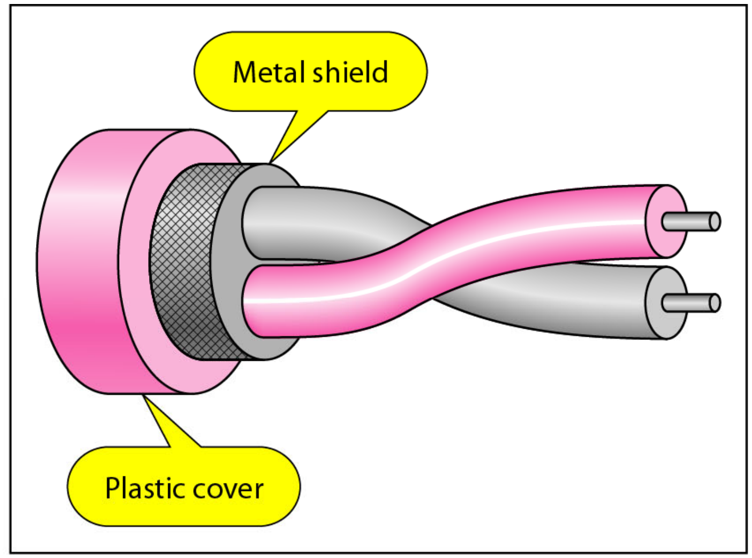
Twisted Pair Cabling

- Carries a frequency range from 100 Hz to 5 MHz
- A twisted pair consists of two insulated copper wires wrapped around each other.
- If the wire is covered with a metal braid to reduce outside electrical interferences, it is called Shielded Twisted Pair (STP) cable.
- If the braid is absent it is called Unshielded Twisted Pair (UTP) cable.
  - Ethernet, Token Ring run on grades (1 to 5) of UTP.
  - Top grade known as Cat 5 used for data transmission up to 100 Mbps.

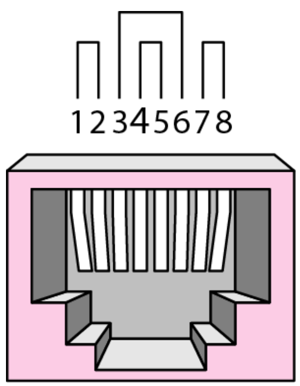
UTP and STP Cables and Connectors



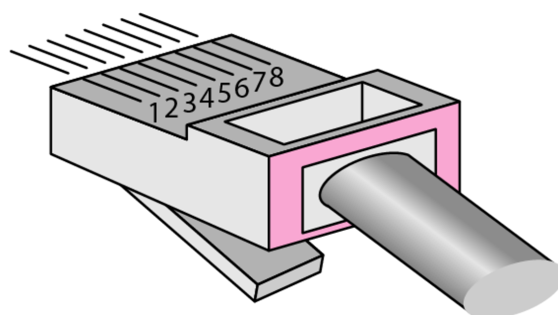
a. UTP



b. STP



RJ-45 Female



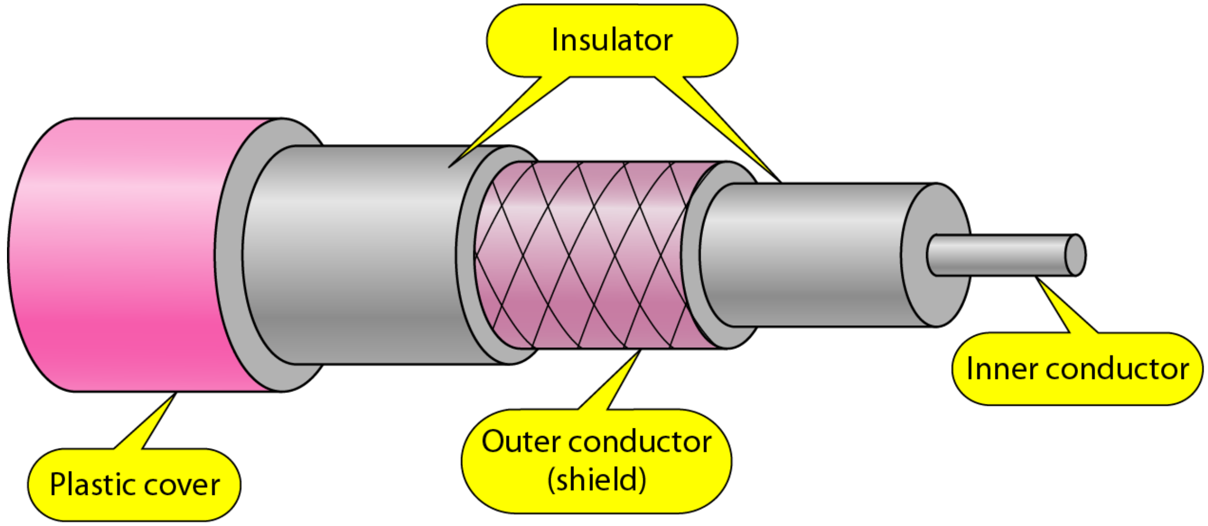
RJ-45 Male

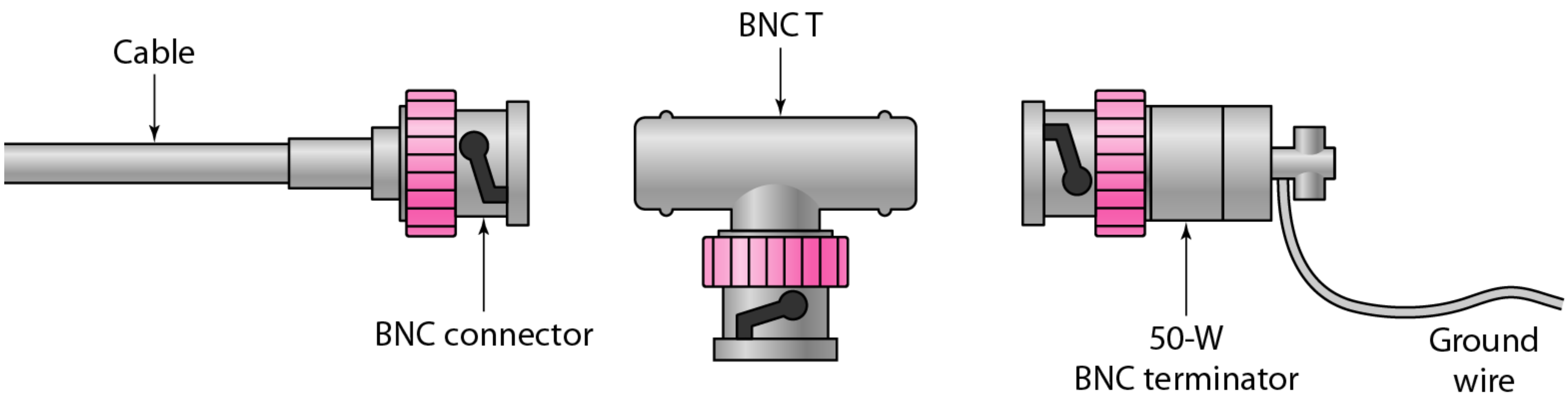
Coaxial cabling

- Carries a frequency range from 100 KHz to 500 MHz
- Composed of an inner conducting wire that is wrapped in insulation which is surrounded by a hollow outer conducting wire. Plastic insulation covers the outer conductor.
- Two varieties:
  - Standard or thick coax (10Base5)
  - Thin coax (10Base2)

Category	*Impedance*	*Use*
RG-59	75 Ω	Cable TV
RG-58	50 Ω	Thin Ethernet
RG-11	50 Ω	Thick Ethernet

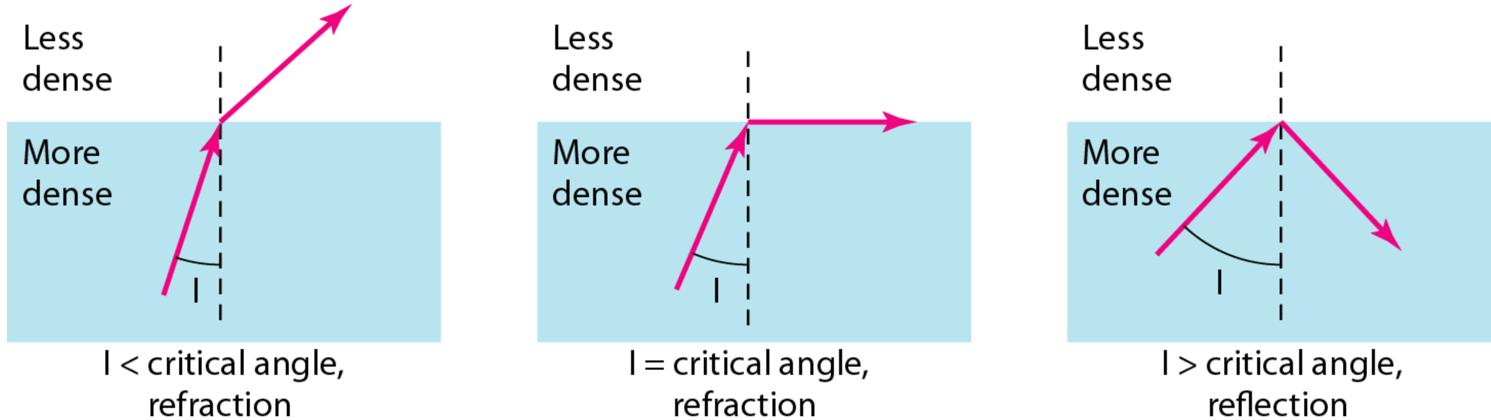
Coaxial Cables and Connectors



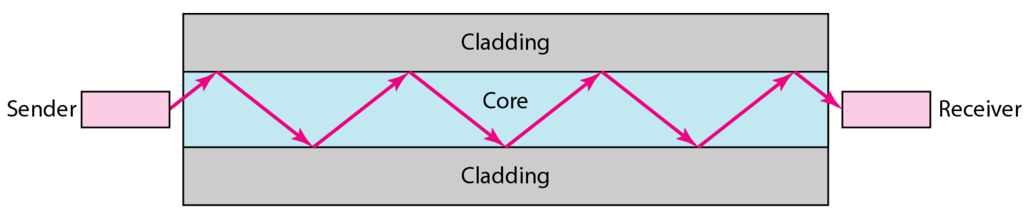


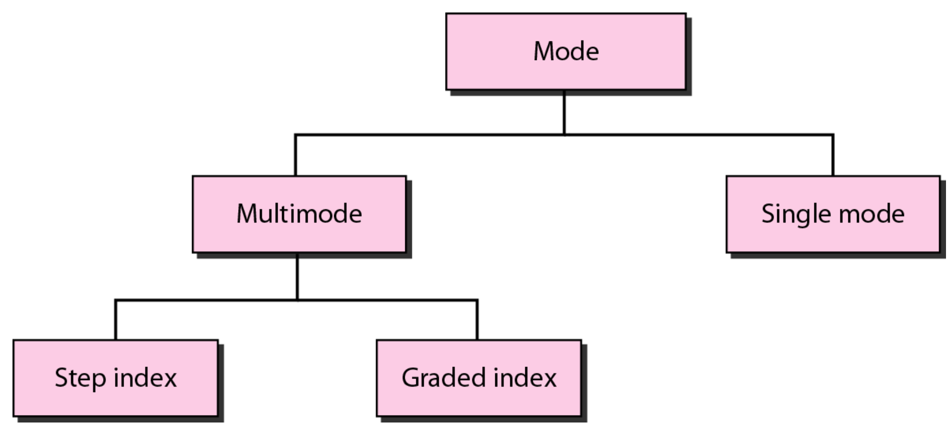
Fiber Optic Cabling and Propagation

- Bending of light ray



- Optical Fiber





Advantages and Disadvantages

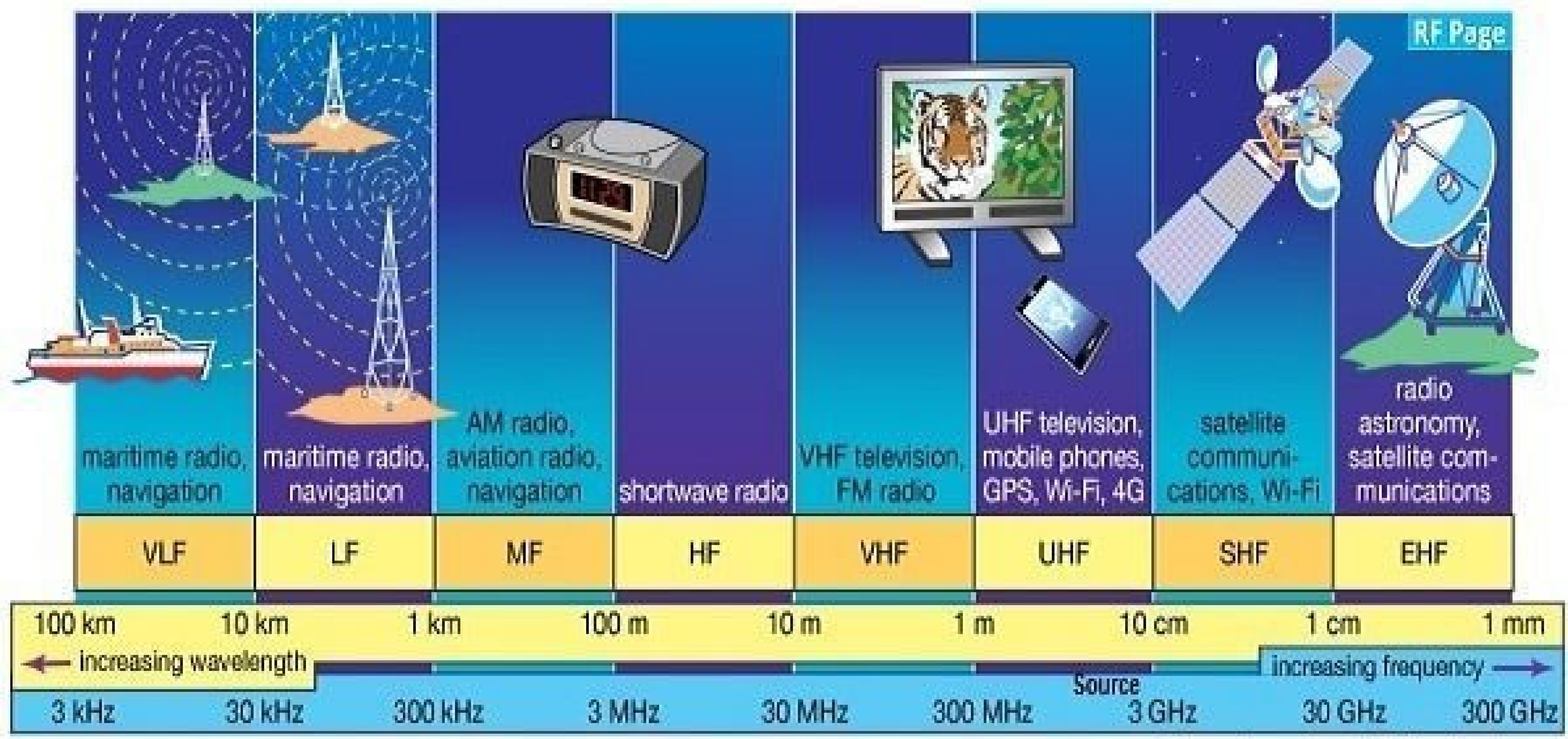
Advantages

- Higher bandwidth
- Less signal attenuation
- Immunity to electro magnetic interference
- Resistance to corrosive material
- Light weight
- Greater immunity to tapping

Disadvantages

- Installation and maintenance
- Unidirectional light propagation
- Cost

Unguided Media: Wireless Bands



Source: Encyclopaedia Britannica, Inc.

Advantages and Disadvantages

Advantages

- High Mobility: Users connect on the move
- No Cable Layout: Saves material and labour costs
- Fast Deployment: Speeds up network setup times.
- Overcomes Terrain: Bypasses physical obstacles easily.
- Easy Scalability: Adds users without new hardware

Disadvantages

- Weak Security: Signals are easily intercepted
- High Interference: Vulnerable to weather and walls.
- Lower Bandwidth: Delivers slower maximum speeds.
- Fast Attenuation: Signal strength drops rapidly.

Physical Topology

Topology refers to the way a network is laid out, either physically or logically.

Figure 2.8 *Bus topology*

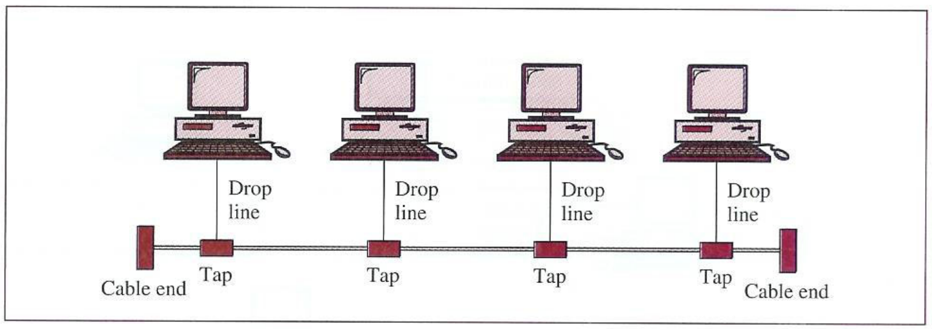


Figure 2.5 *Fully connected mesh topology (for five devices)*

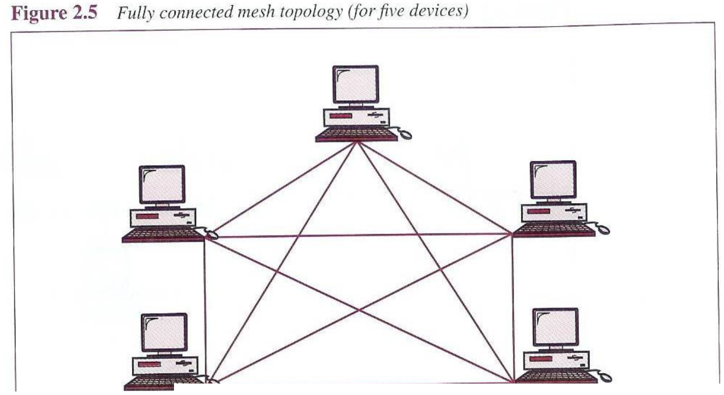


Figure 2.7 *Tree topology*

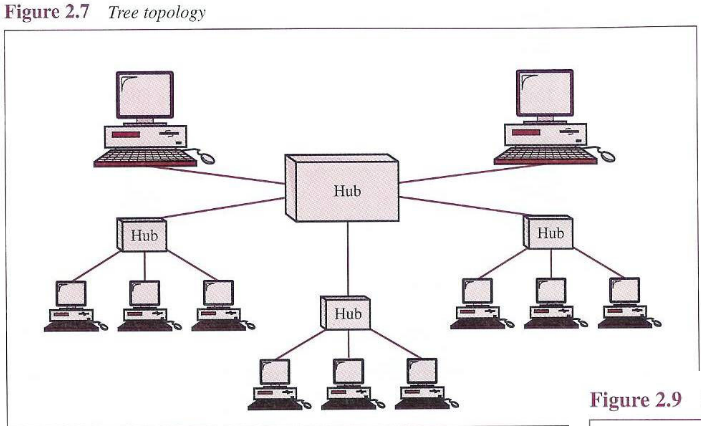


Figure 2.6 *Star topology*

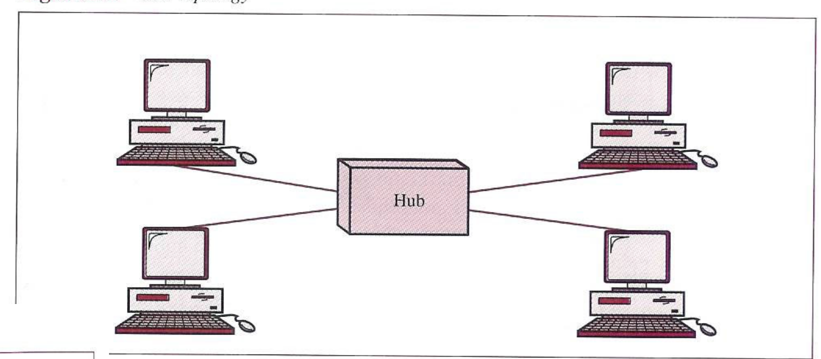
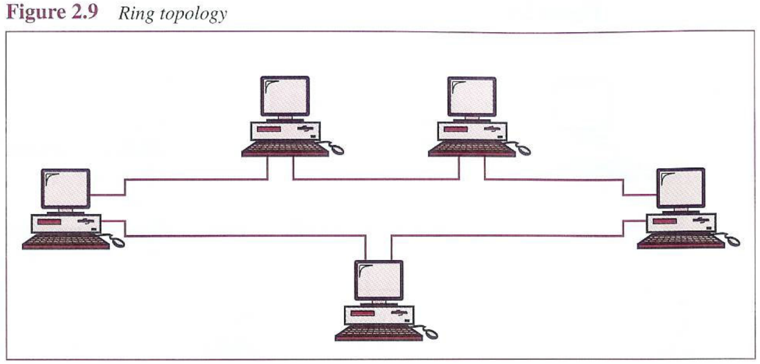
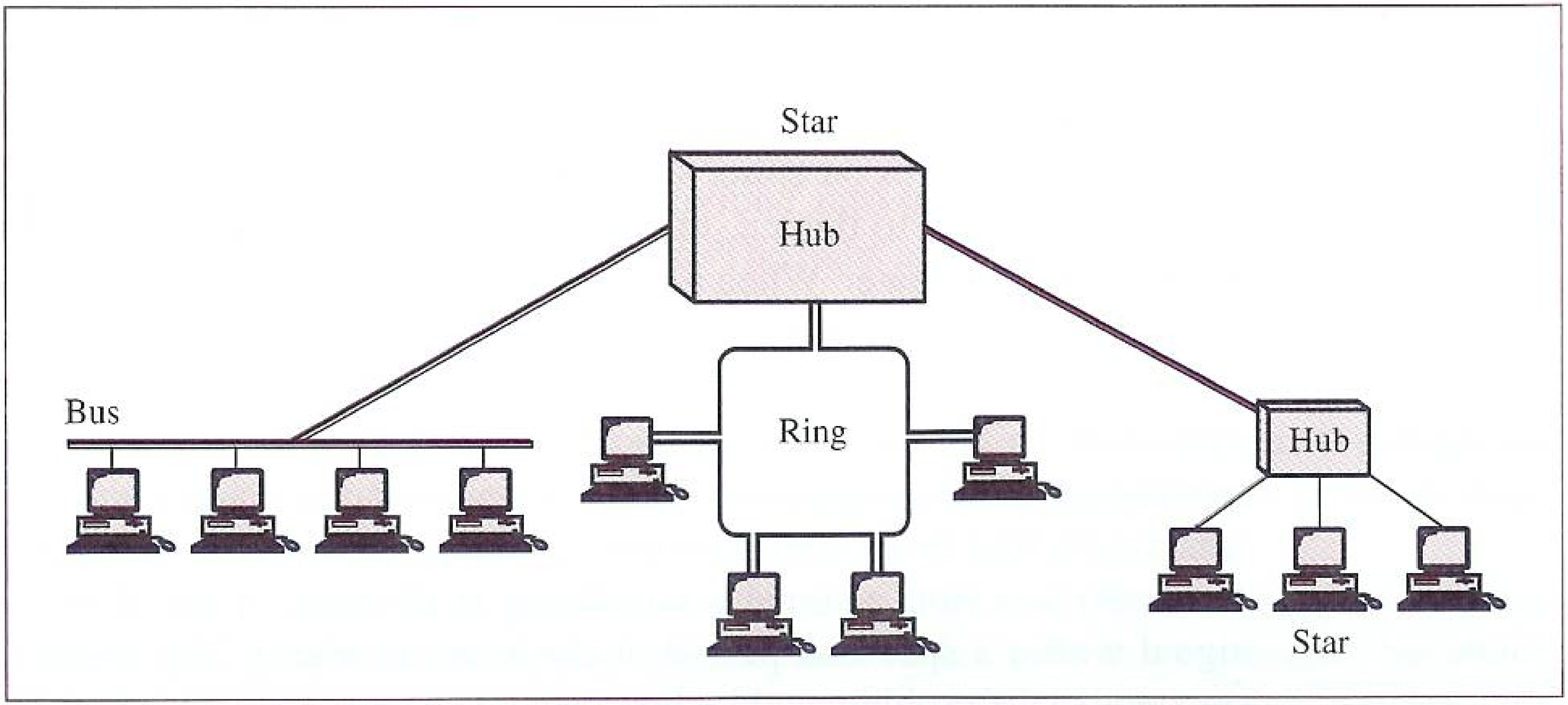


Figure 2.9 *Ring topology*



Hybrid Topologies

Figure 2.10 *Hybrid topology*



Recommended Reading

- Behrouz A. Forouzan, Data Communications and Networking with TCP/IP Protocol Suite, 6th ed., 2022, Chapter 2