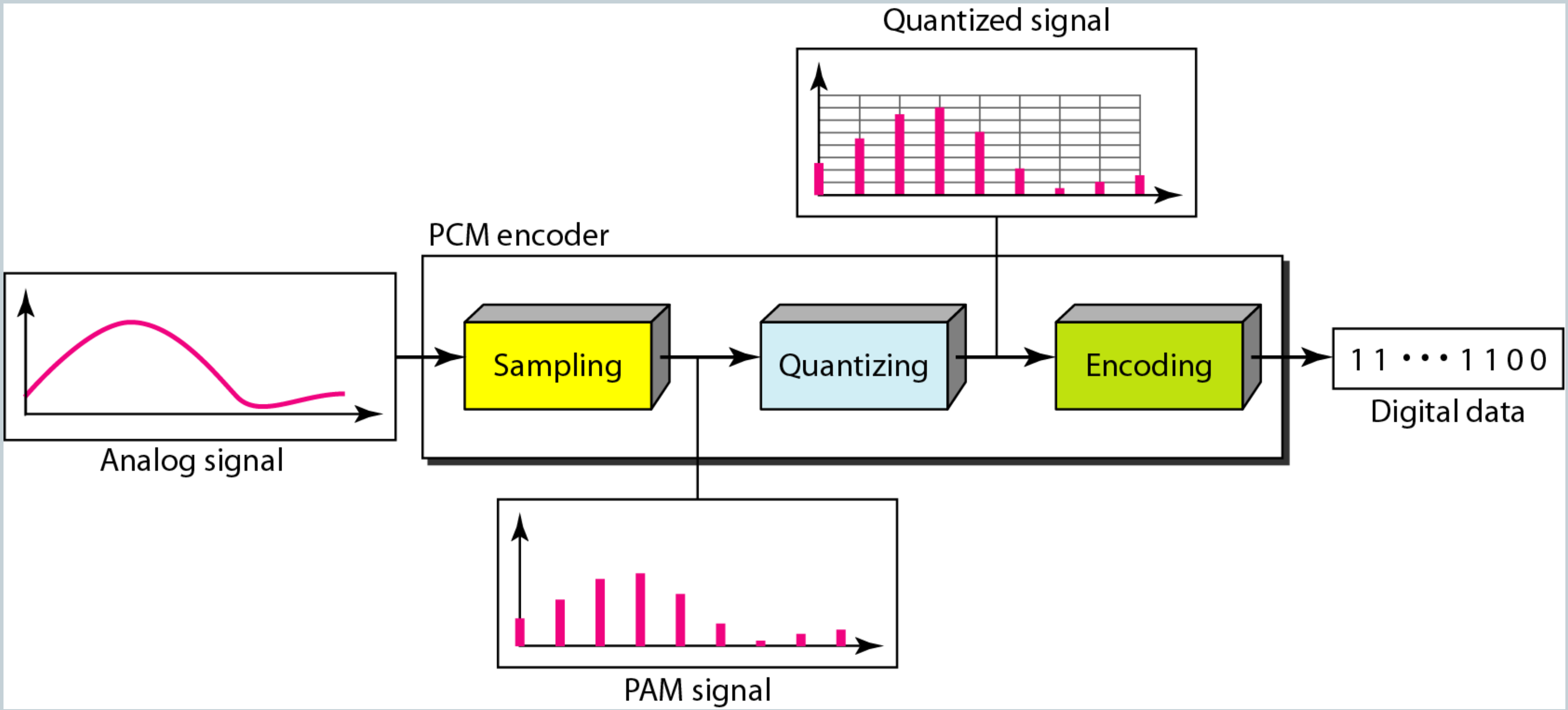
Digital Transmission

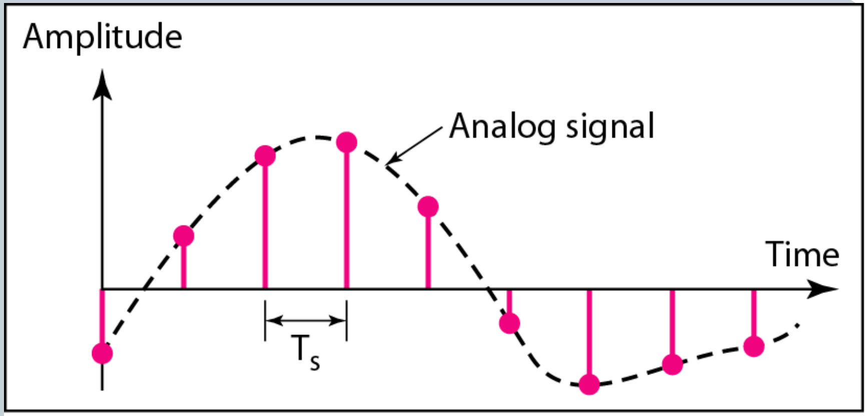
Analog-TO-Digital Conversion

- **Pulse Code Modulation (PCM)**
- **Delta Modulation (DM)**

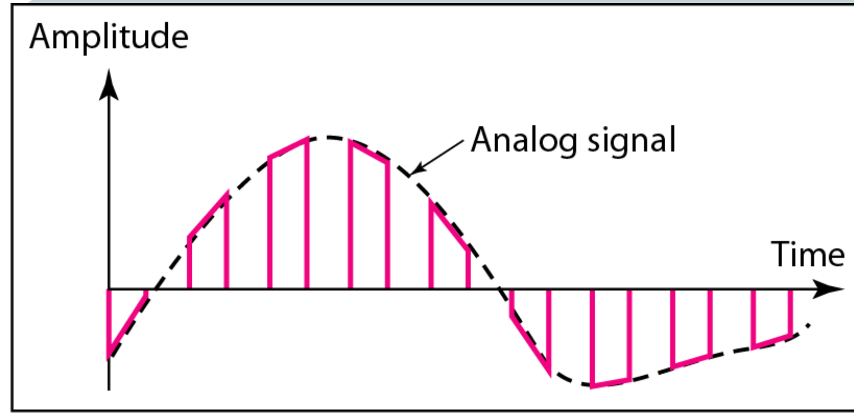
Components of PCM Encoder



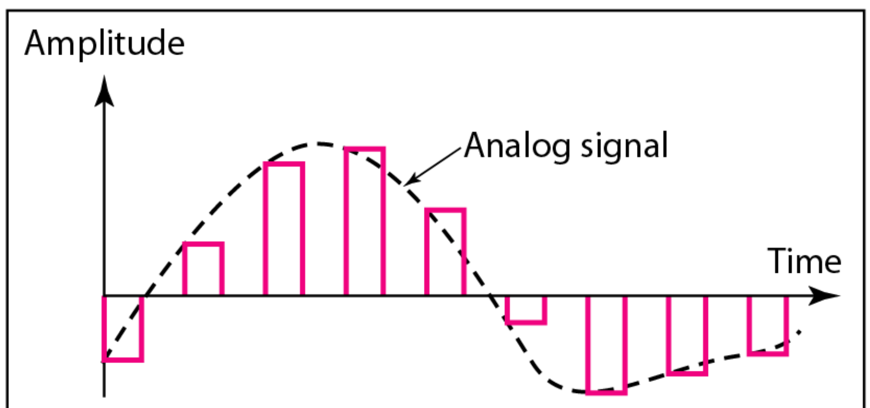
Sampling Method



a. Ideal sampling

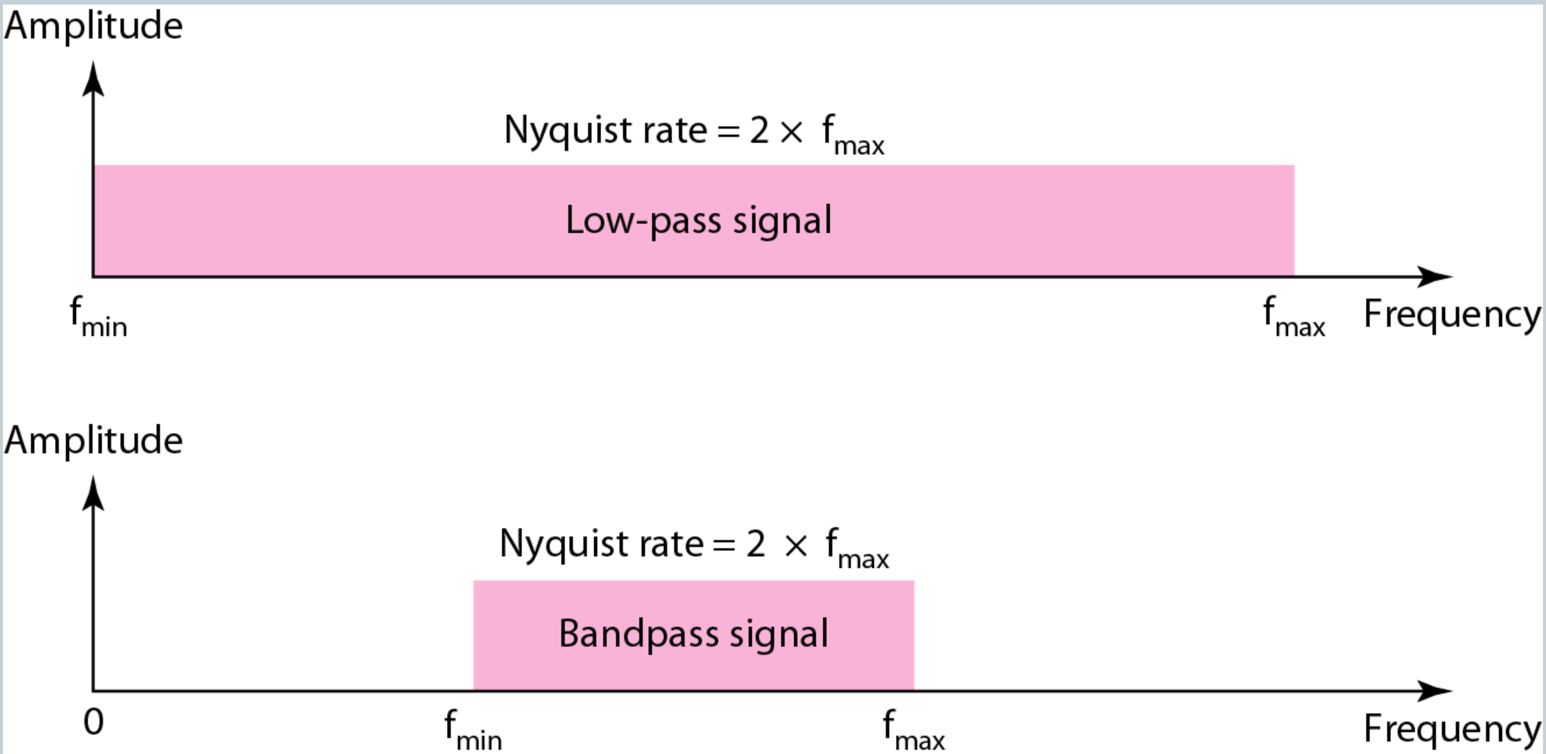


b. Natural sampling

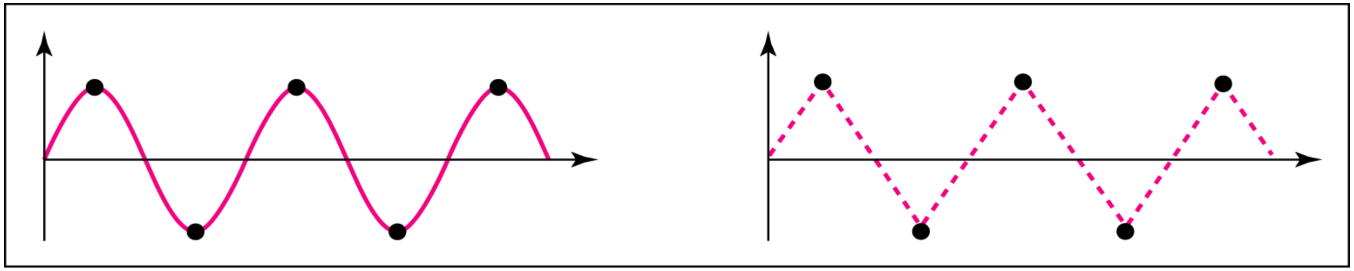


c. Flat-top sampling

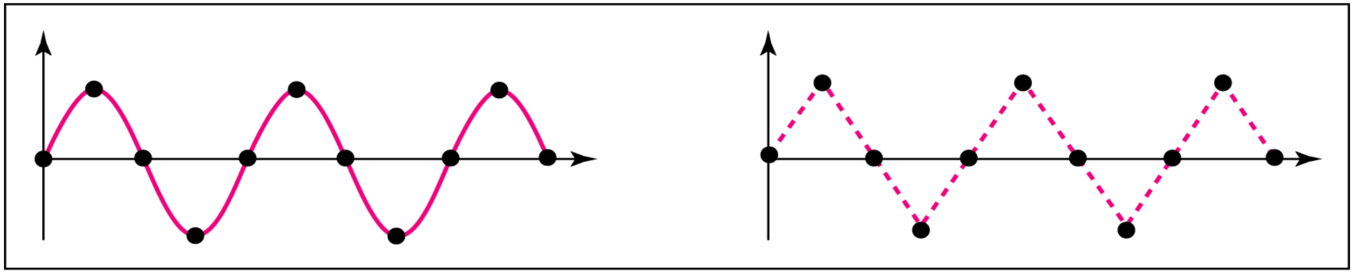
Nyquist sampling rate for low-pass and bandpass signals



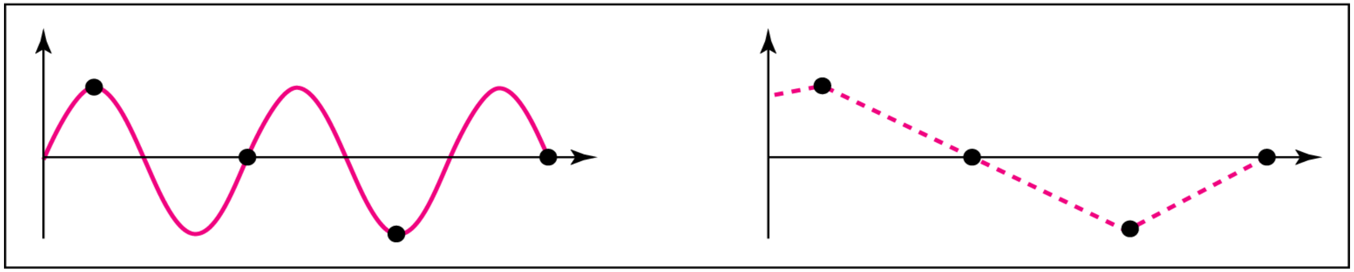
Recovery of a sampled sine wave for different sampling rates



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

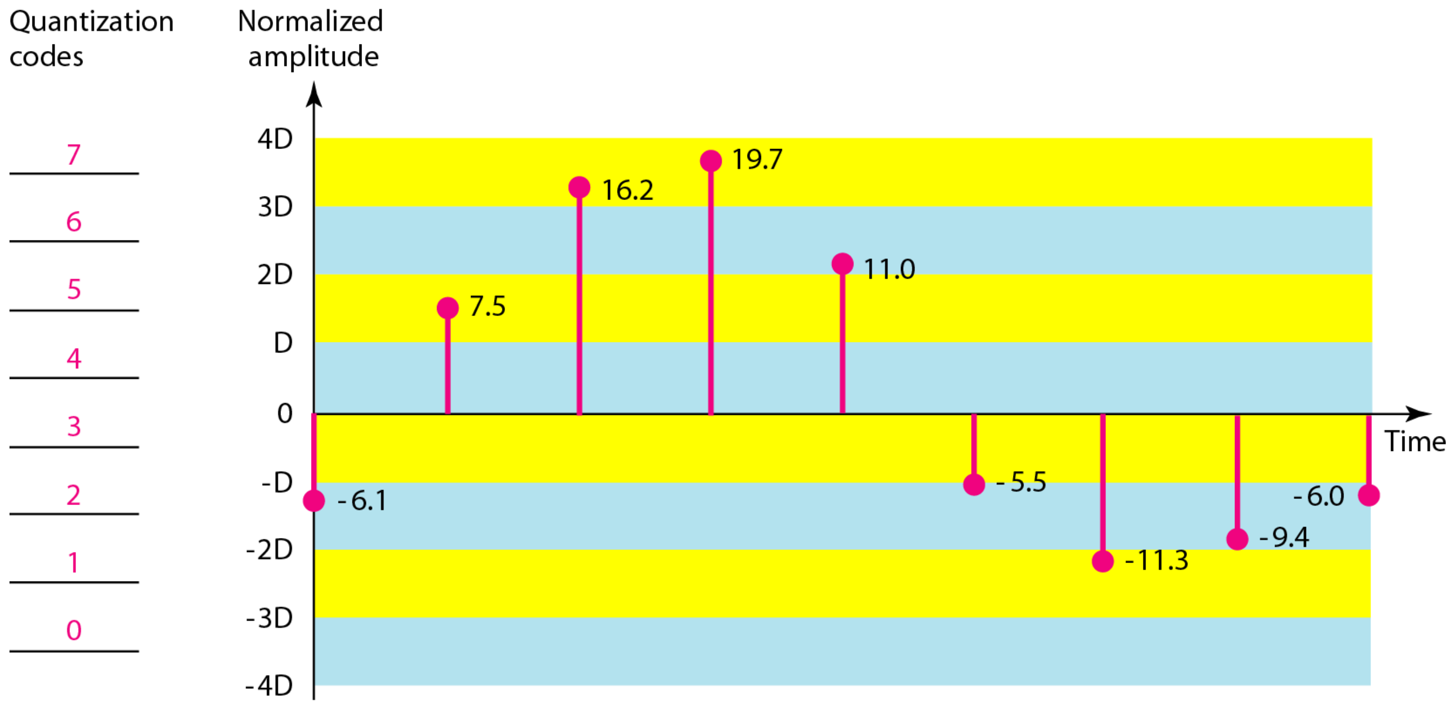


b. Oversampling: $f_s = 4\ f$



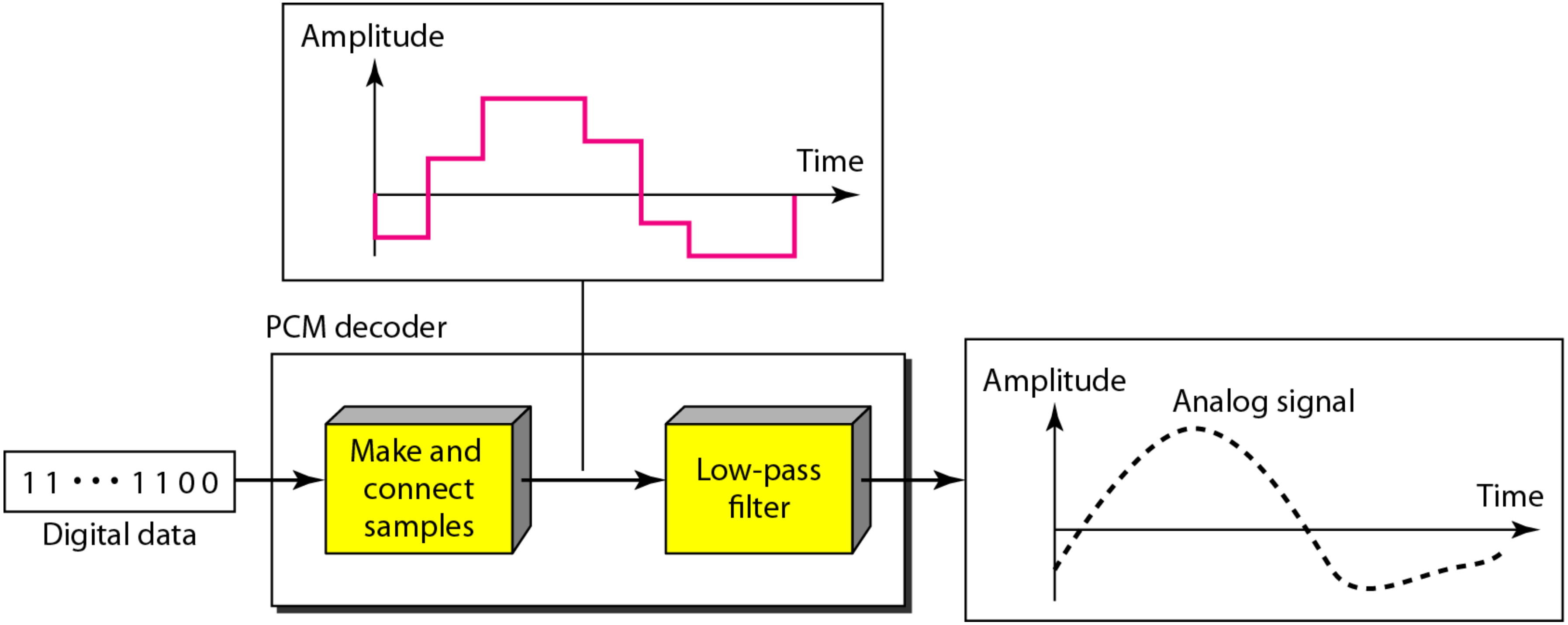
c. Undersampling: $f_s = f$

Quantization and encoding of a sampled signal

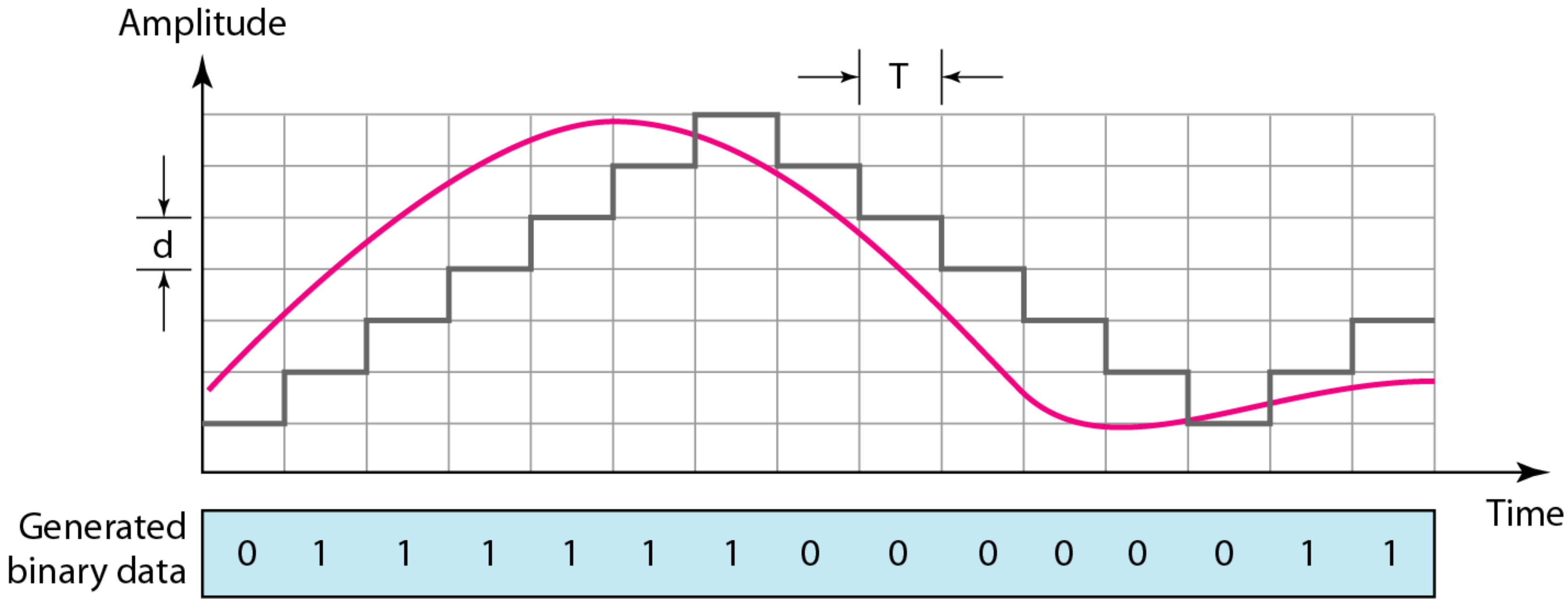


Normalized PAM values	-1.22	1.50	3.24	3.94	2.20	-1.10	-2.26	-1.88	-1.20
Normalized quantized values	-1.50	1.50	3.50	3.50	2.50	-1.50	-2.50	-1.50	-1.50
Normalized error	-0.38	0	+0.26	-0.44	+0.30	-0.40	-0.24	+0.38	-0.30
Quantization code	2	5	7	7	6	2	1	2	2
Encoded words	010	101	111	111	110	010	001	010	010

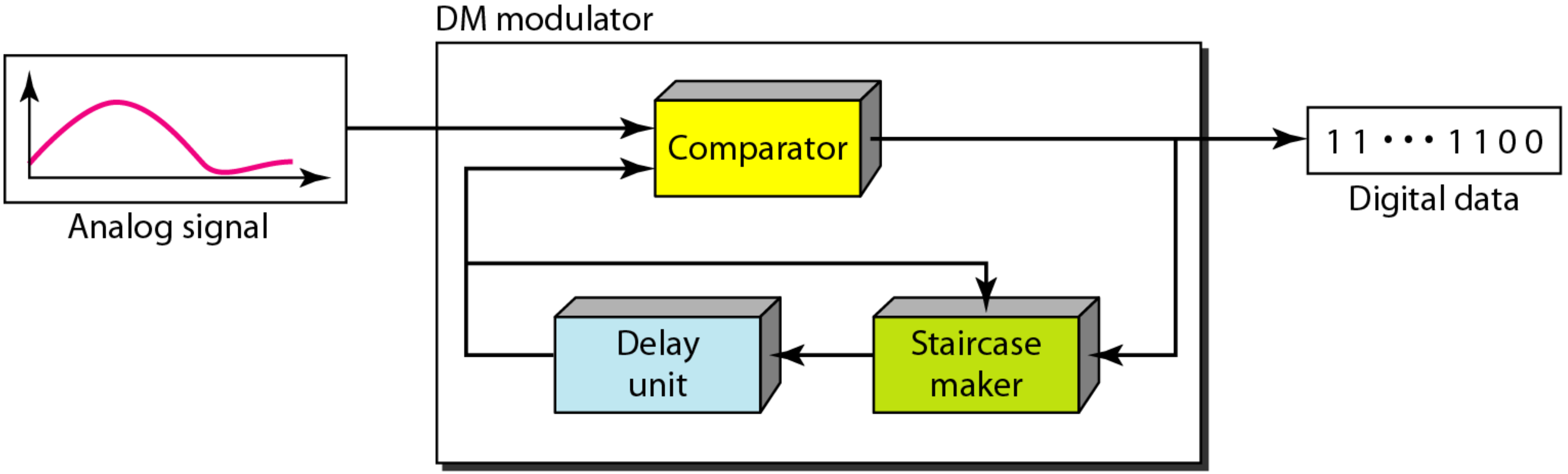
Components of a PCM decoder



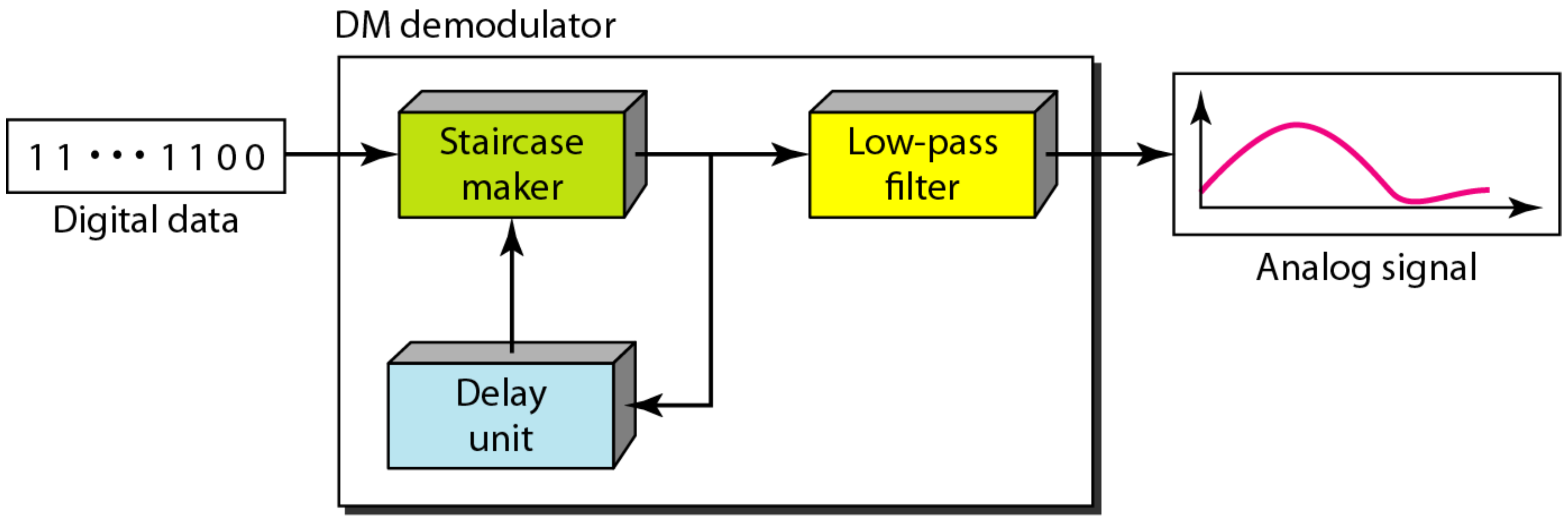
The process of delta modulation



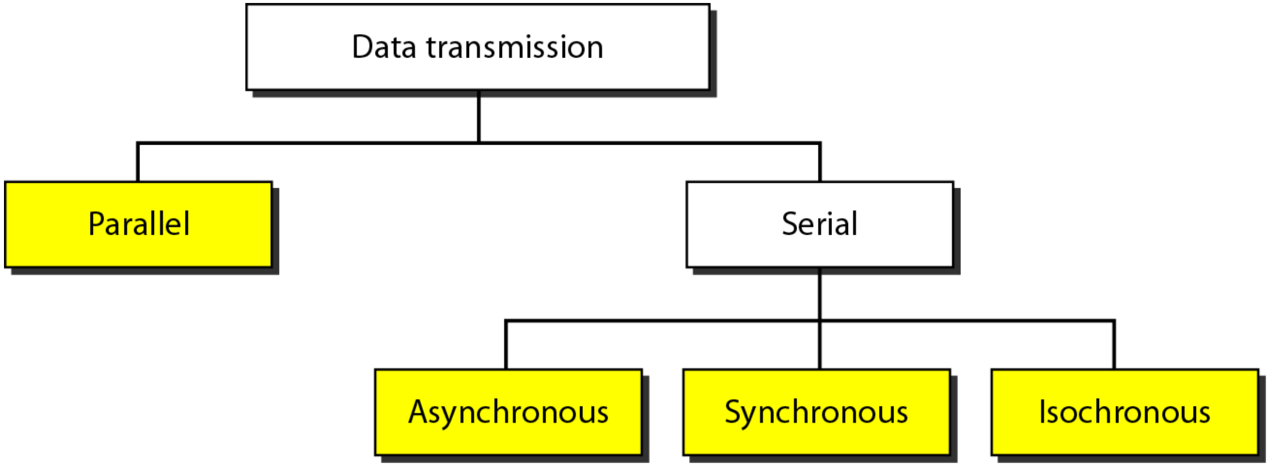
Delta modulation components



Delta demodulation components



TRANSMISSION MODES



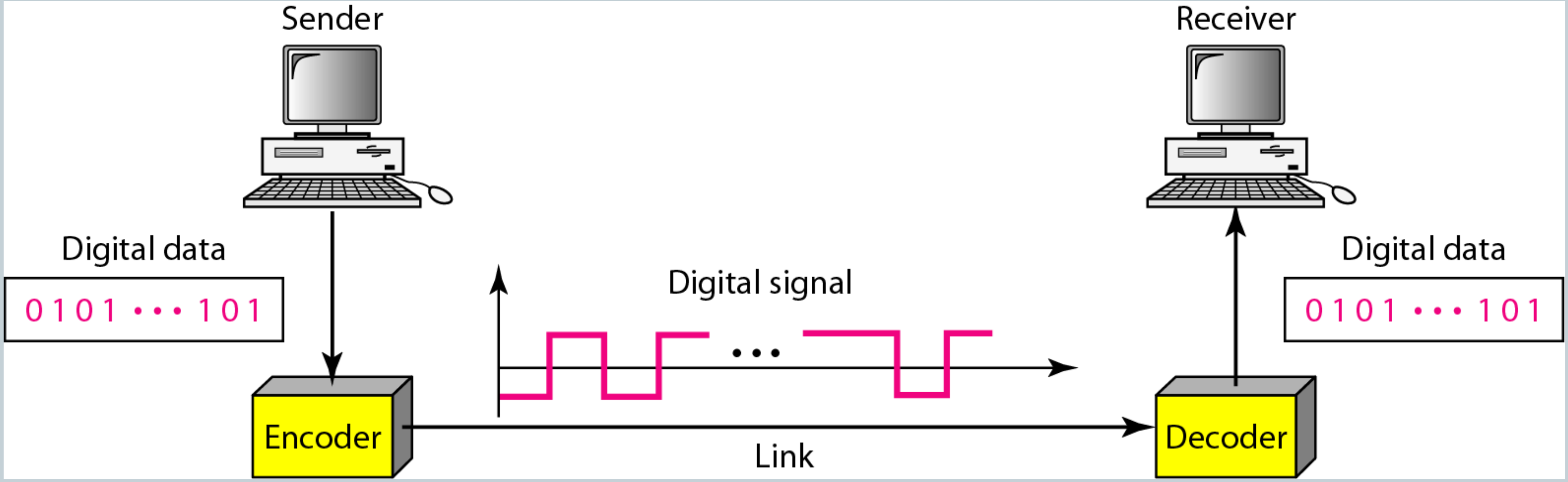
- Advantage of parellel transmission?
- Advantage of serial transmission?

DIGITAL-TO-DIGITAL CONVERSION

- **Line Coding**
  - **Line Coding Schemes**
- **Block Coding**
- **Scrambling**

Line coding is always needed; block coding and scrambling may or may not be needed.

Line coding and decoding



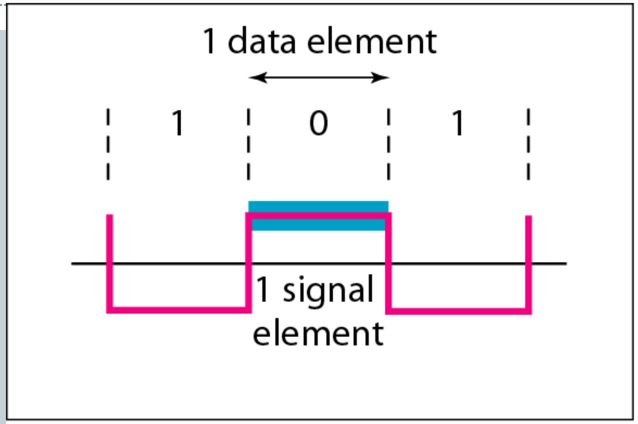
Signal element versus data element

- Data element: the smallest entity that can represent a piece of information: bit
- Signal element: is the shortest unit (timewise) of a digital signal.

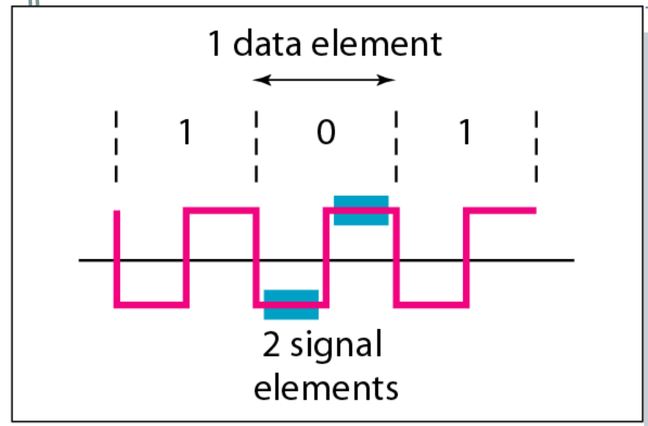
Data element is what are need to send: Signal elements are what we are sent.

Data element are being carried; signal elements are the carriers.

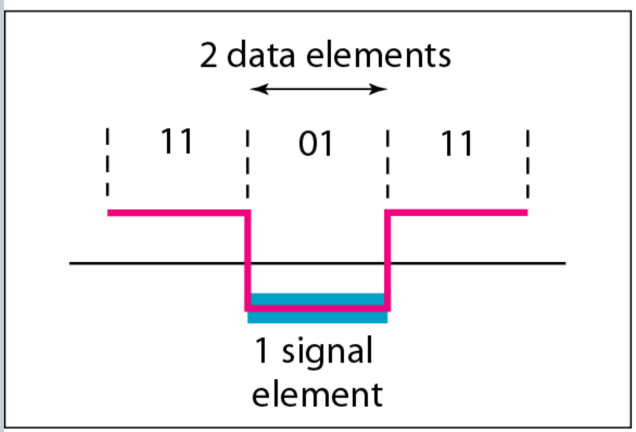
Signal element versus data element



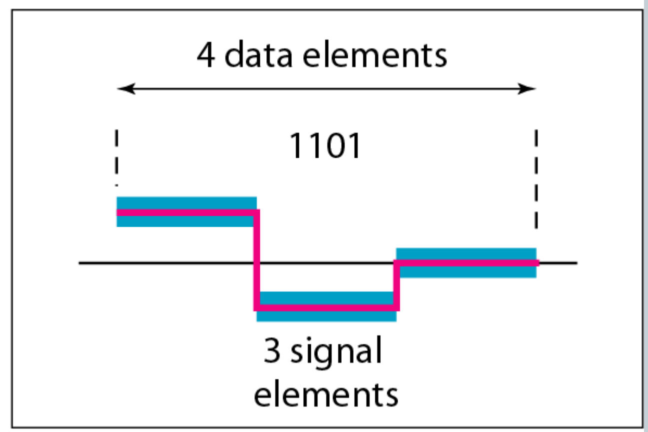
a. One data element per one signal element (r = 1)



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 $\left(r = \frac{4}{3}\right)$

Data Rate VS Signal Rate

- Data rate: the number of data elements (bits) sent in 1s (bps)
  - Called bit rate (sometimes)
- Signal rate: the number of signal elements sent in 1 s(baud)
  - Called pulse rate, modulation rate or the baud rate

$$S = c \times N \times \frac{1}{r}$$

C = case factor
N = data rate (bps)
S = the number of signal element

Bandwidth and Max Data Rate

- From previously, so we have

$$B_{min} = S$$

- From Nyquist formula, the maximum data rate of a channel is Nmax = 2 × $B \times log_2 L$ Then, the maximum data rate

$$\boxed{N_{max} = \frac{1}{c} \times B \times r = 2 \times B \times \log_2 L}$$

Characteristic Line Coding

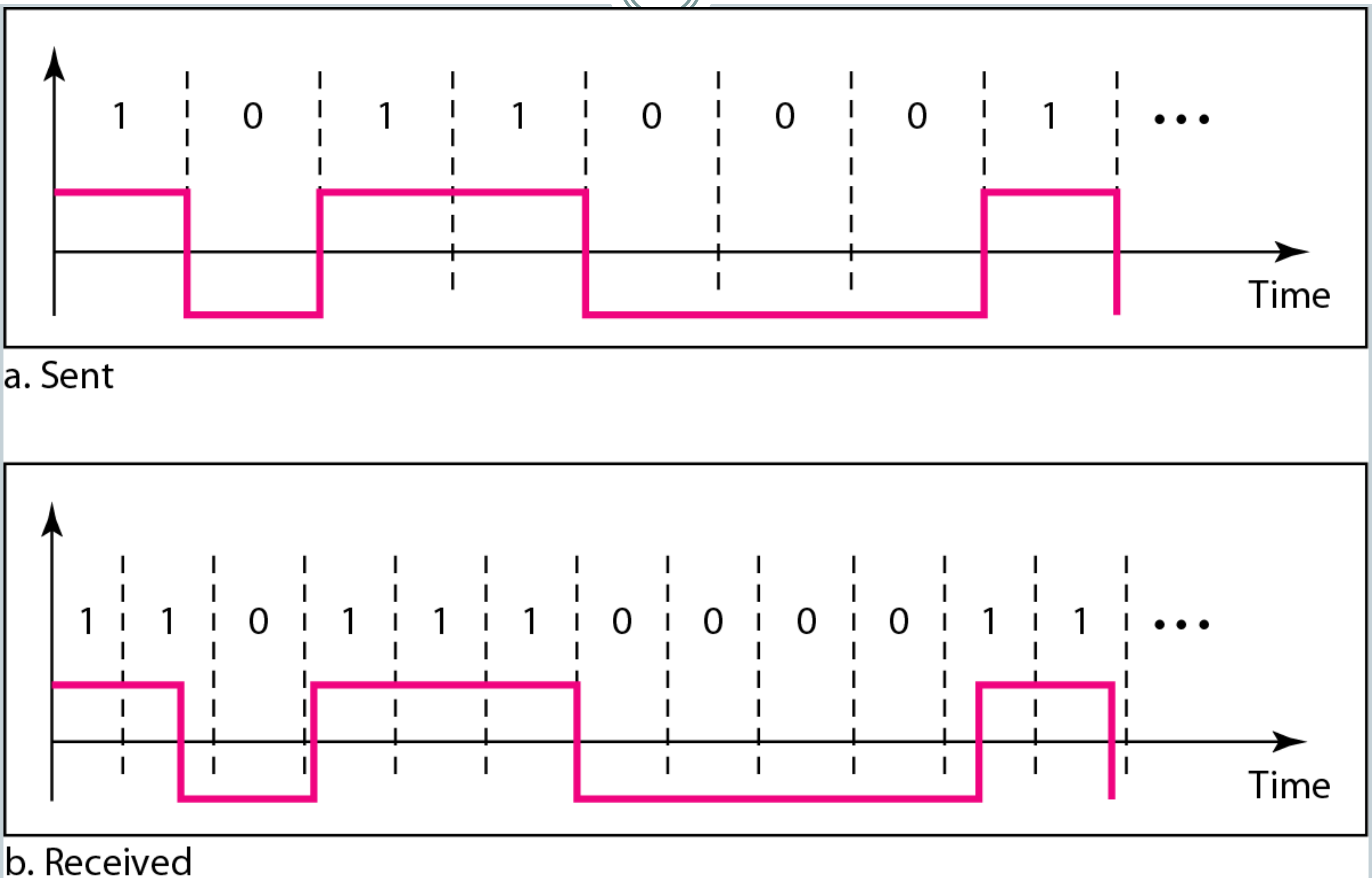
- **Bandwidth: the actual bandwidth of a digital signal is infinite, the effective bandwidth is finite**
- **Baseline wandering: in decoding a digital signal, the receiver calculates a running average of the received signal power. This average is called *the baseline*.**

  long string 0s or 1s cause drift in the baseline (Baseline Wandering)

Characteristic Line Coding

- DC component: when the digital signal is constant for a while, the spectrum creates very low frequencies, this frequencies around zero called *DC component*.
- Self-synchronization: To corrently interpret the signals received from the sender, the receiver's bit interval must correspond exactly to the sender's bit intervals.

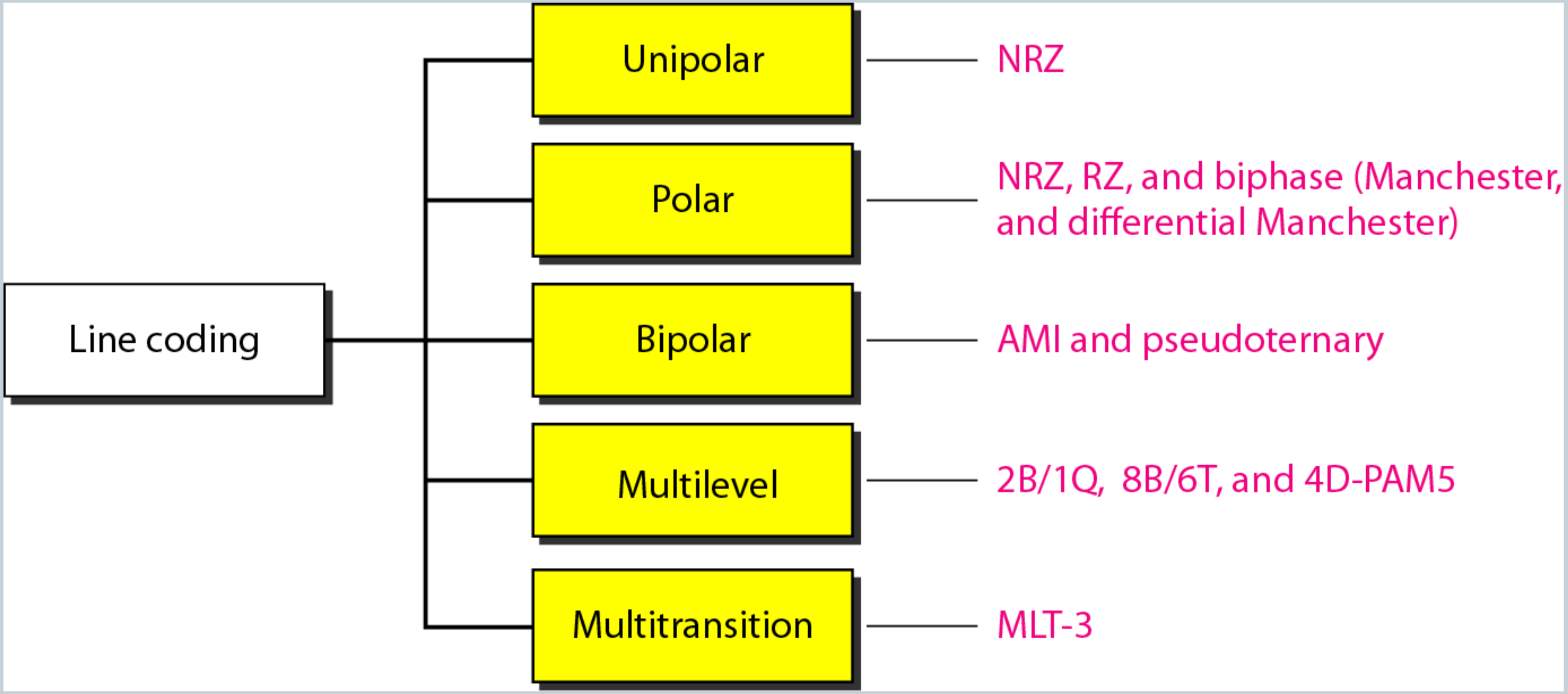
Effect of Lack of Synchronization



Characteristic Line Coding

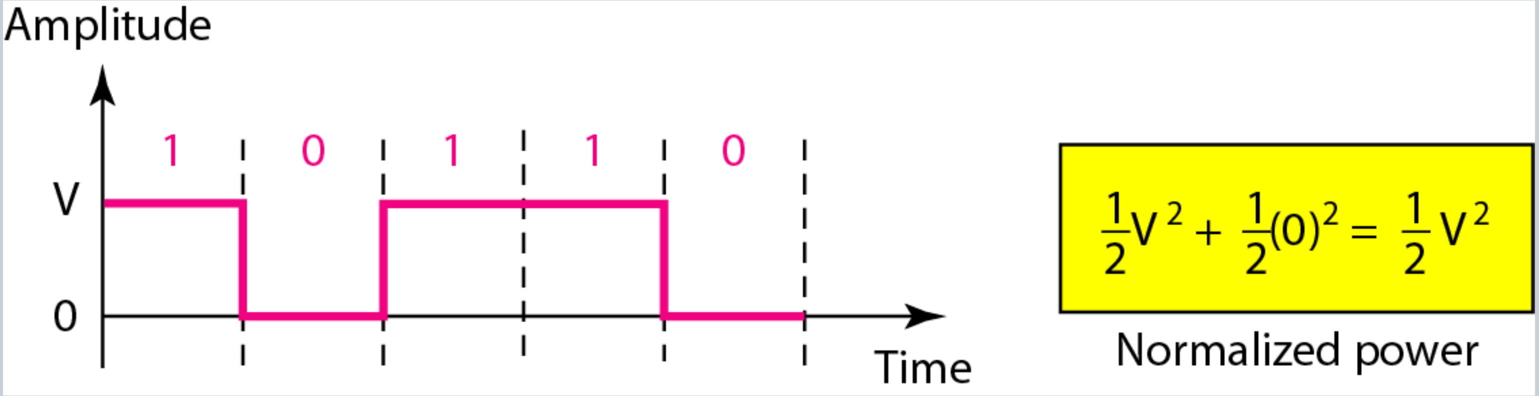
- Built-in Error Detection
- Immunity to Noise and Interference
- Complexity

Line Coding Schemes



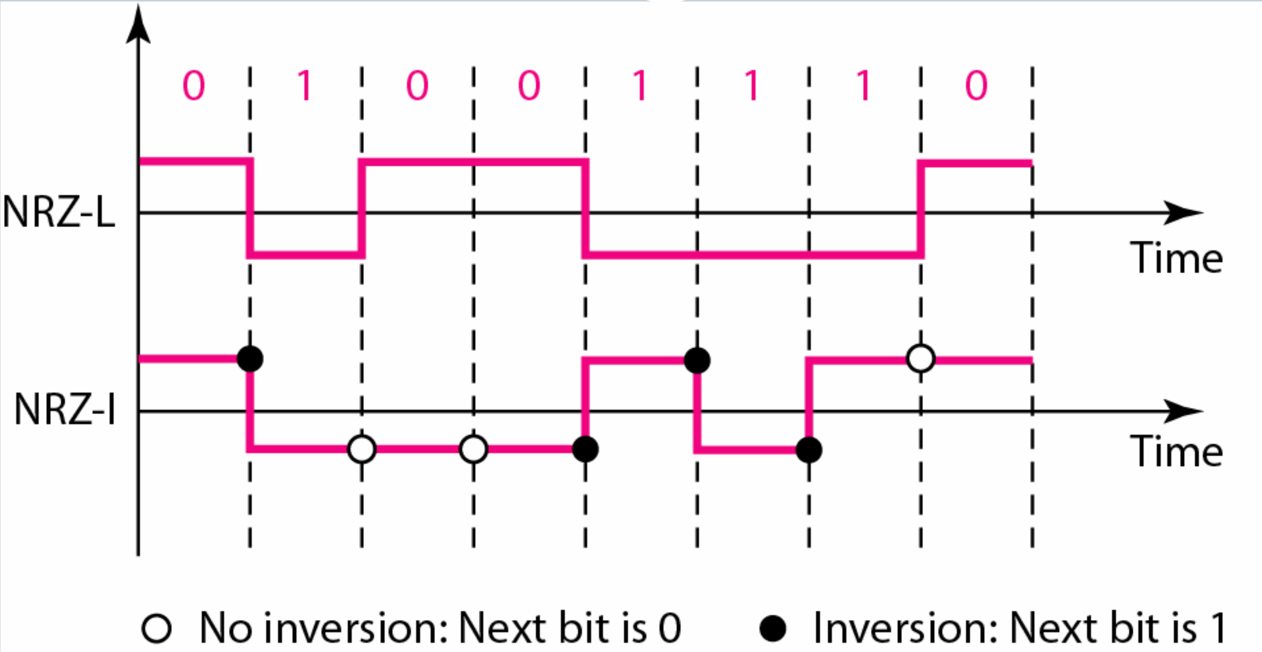
Unipolar

- Ex: Non-Return-to Zero (the signal does not return to zero at the middle of the bit)



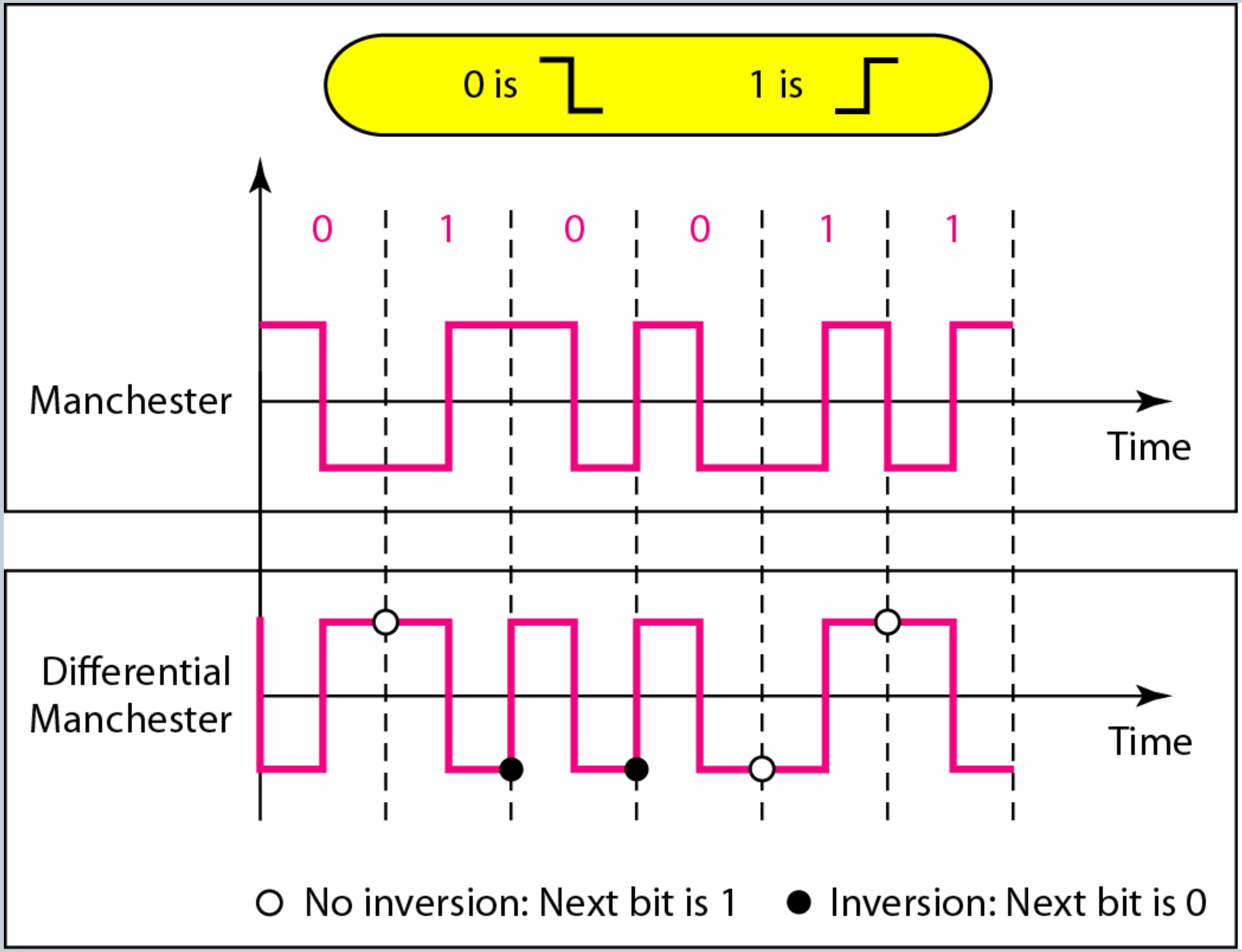
- Normalized power: power needed to send 1 bit per unit line resistance

Polar Scheme



- **In NRZ-L the level of the voltage determines the value of the bit.**
- **In NRZ-I the inversion or the lack of inversion determines the value of the bit.**

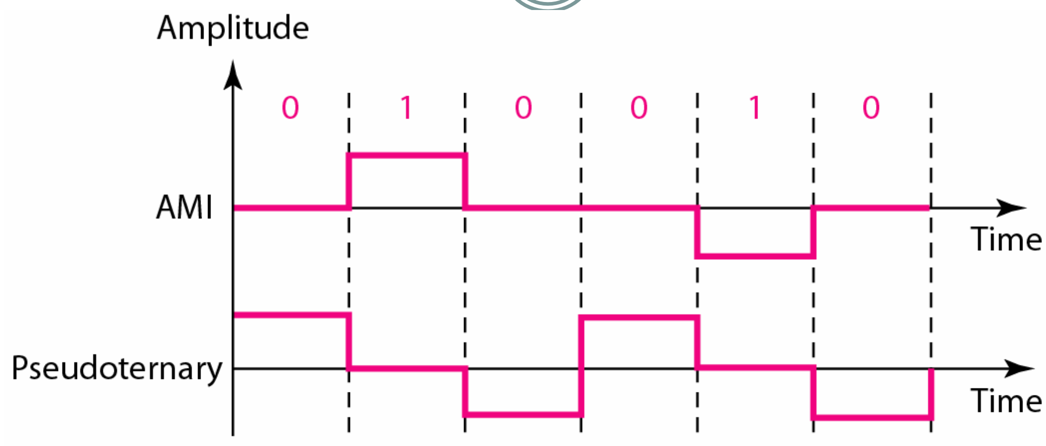
Polar Biphase: Manchester and differential Manchester schemes



Polar Biphase: Manchester and differential Manchester schemes

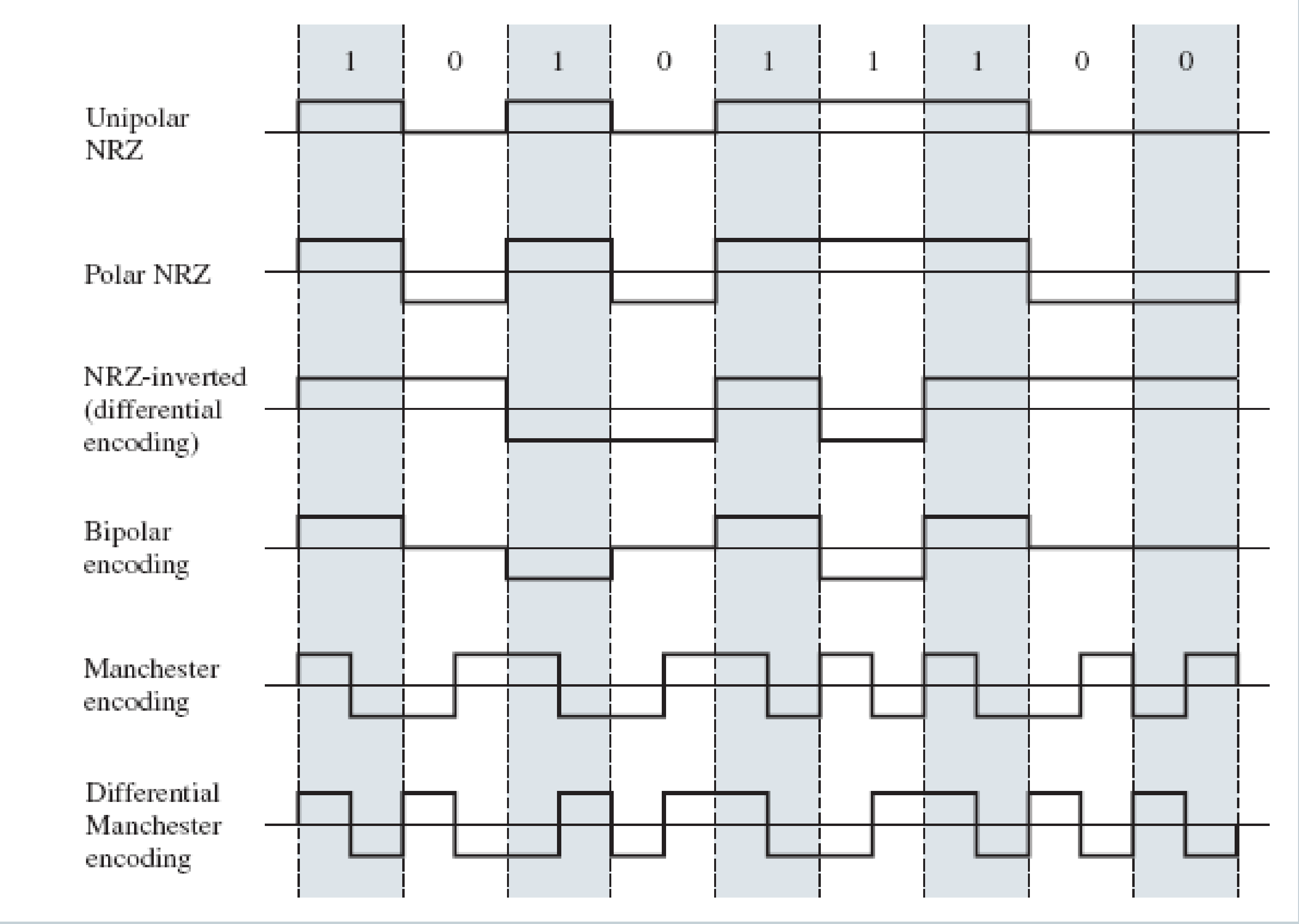
- **In Manchester and differential Manchester encoding, the transition at the middle of the bit is used for synchronization.**
  - **No dc component**
  - **Drawback: the signal rate for Manchester and differential Manchester is double**

Bipolar Scheme



- AMI (Alternate Mark Inversion): Alternate 1 inversion, A neutral zero voltage represent binary 0.
- Pseudoternary: 1 bit is encoded as a zero voltage and the 0 bit is encoded as alternating positive and negative voltages.

Compare Among Line Coding



Multilevel Scheme (*m*B*n*L)

- Carefully designed to prevent baseline wandering, to provide synchronization, and to detect error
  - The first two letters define the data pattern
  - The second two define the signal pattern

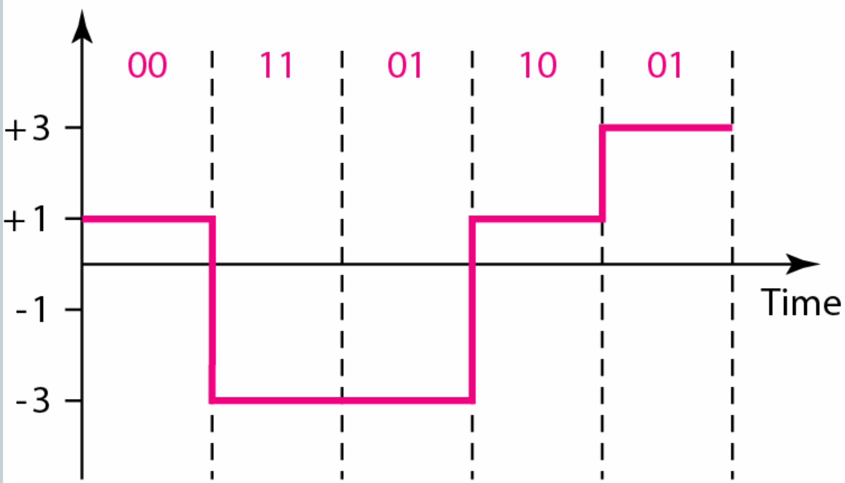
Multilevel Scheme (mBnL)

- *M* is the length of the binary pattern
- *B* means binary data
- *n* the length of the signal pattern
- *L* the number of the levels in the signal
  - *B* = binary (L = 2)
  - *T* = ternery (L = 3)
  - *Q* = Quaternary) (L = 4)

Multilevel Scheme (*m*B*n*L)

- Normally, in *m*B*n*L schemes, a pattern of *m* data elements is encoded as a pattern of *n* signal elements in which $2^m \leq L^n$

Multilevel: 2B1Q scheme



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

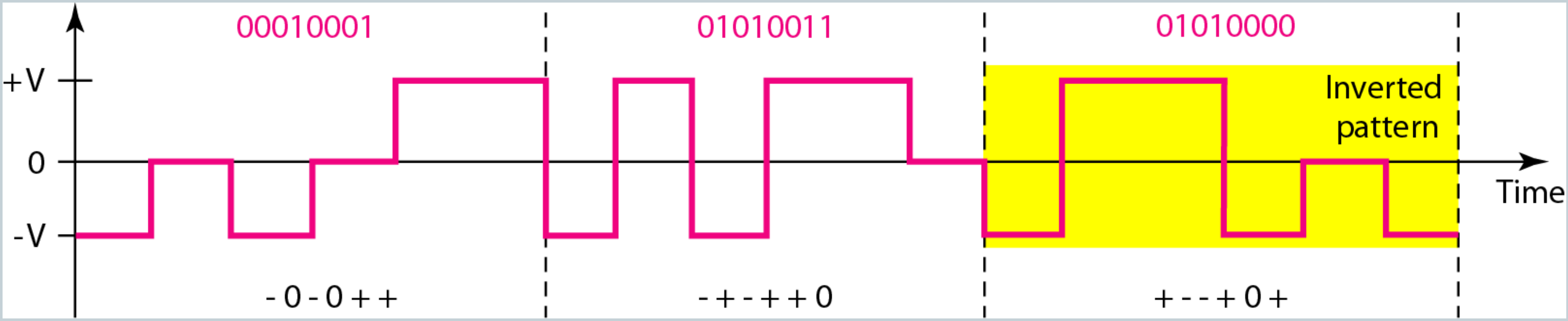
Transition table

- Send data 2 times faster than by using NRZ-L
- The receiver has to discern four different thresholds
- Used in DSL (Digital Subscriber Line)

Multilevel: 8B6T scheme

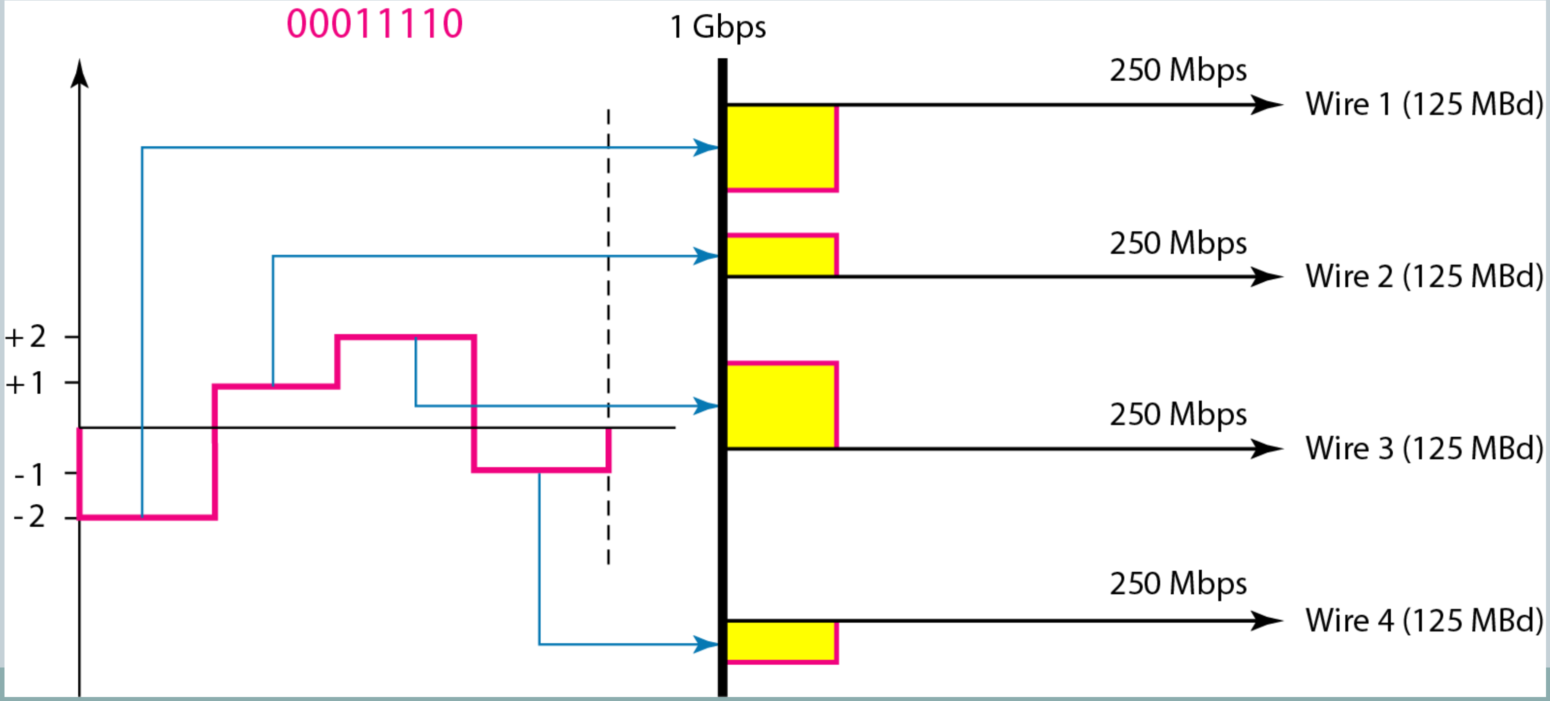
- 8B6T (Eight binary, six ternary)
- Used with 100base-4T cable
- Encode 8 bits as a pattern of 6 signal elements, where signal has three levels (ternary).
  - 2^8 = 256 data pattern -> 3^6 = 729 different signal
- 473 Redundent signal elements provide
  - Synchronization
  - Error detection
  - and part of DC balance

Multilevel: 8B6T scheme



Multilevel: 4D-PAM5 scheme

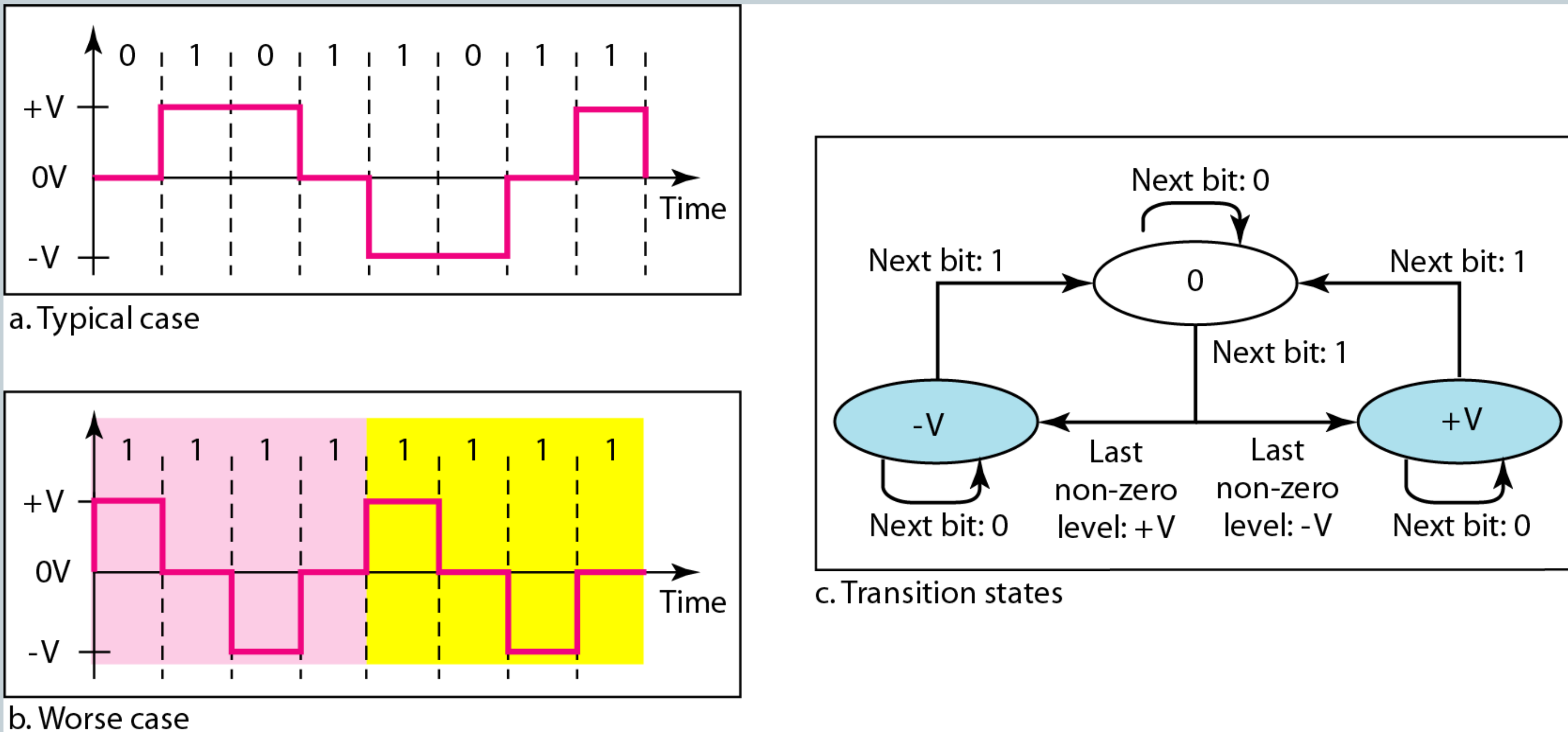
- Design to send data over four channels (four wires).
- Use to send 1 Gbps data over four copper cables that can handles 125 Mbaud



Multitransition: MLT-3 scheme

- Uses three levels (+V, 0 and –V) and three transition rules to move between the levels
  1. If the next bit is 0, there is no transition
  2. If the next bit is 1 and the current level is not 0, the next level is 0
  3. If the next bit is 1 and the current level is 0, the next level is the opposite of the last nonzero level

Multitransition: MLT-3 scheme

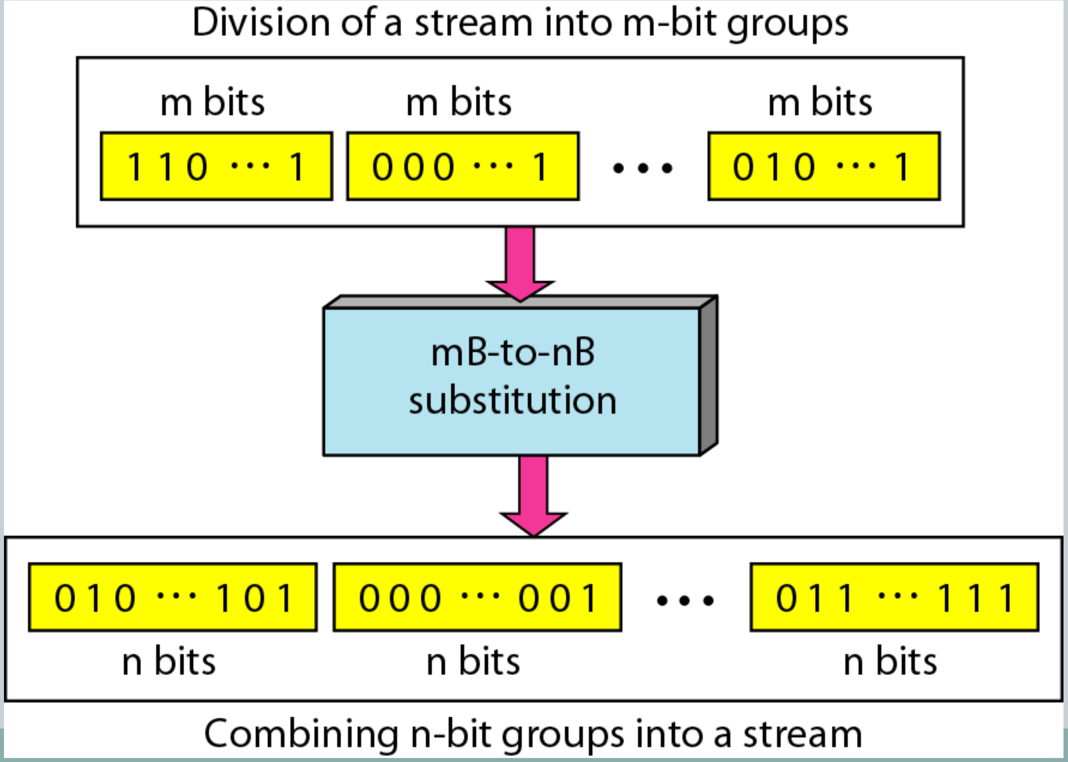


Summary of line coding schemes

Category	*Scheme*	*Bandwidth (average)*	*Characteristics*
Unipolar	NRZ	$B = N/2$	Costly, no self-synchronization if long 0s or 1s, DC
Unipolar	NRZ-L	$B = N/2$	No self-synchronization if long 0s or 1s, DC
	NRZ-I	$B = N/2$	No self-synchronization for long 0s, DC
	Biphase	$B = N$	Self-synchronization, no DC, high bandwidth
Bipolar	AMI	$B = N/2$	No self-synchronization for long 0s, DC
Multilevel	2B1Q	$B = N/4$	No self-synchronization for long same double bits
	8B6T	$B = 3N/4$	Self-synchronization, no DC
	4D-PAM5	$B = N/8$	Self-synchronization, no DC
Multiline	MLT-3	$B = N/3$	No self-synchronization for long 0s

Block Coding Concept

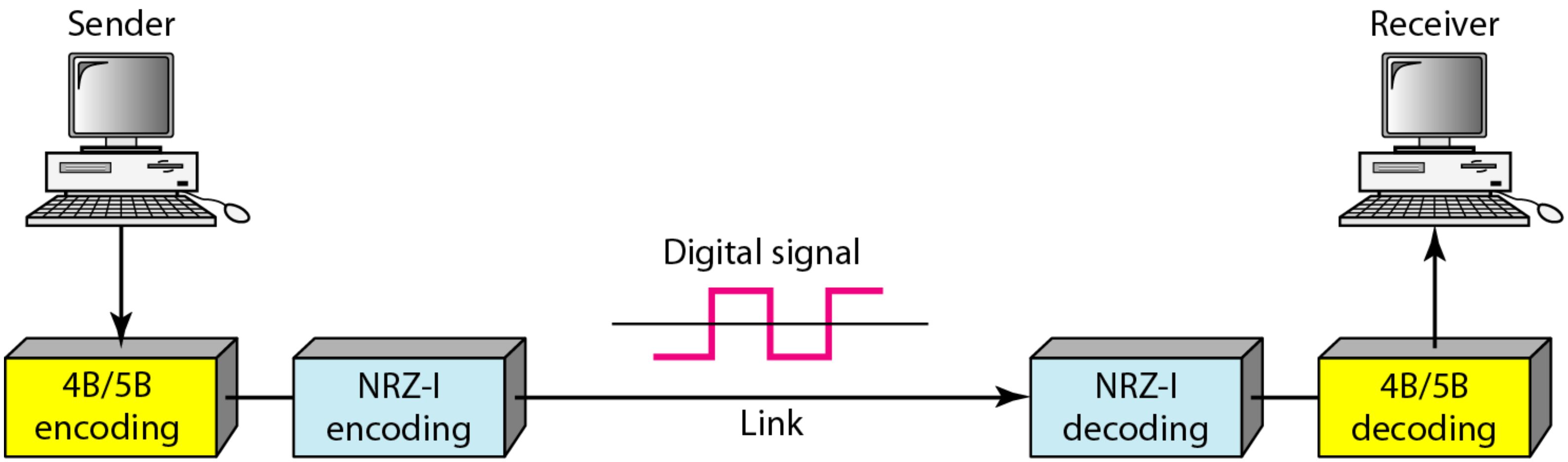
- **Block coding is normally referred to as *m*B/*n*B coding; it replaces each *m*-bit group with an *n*-bit group.**



Four Binary/Five Binary (4B/5B)

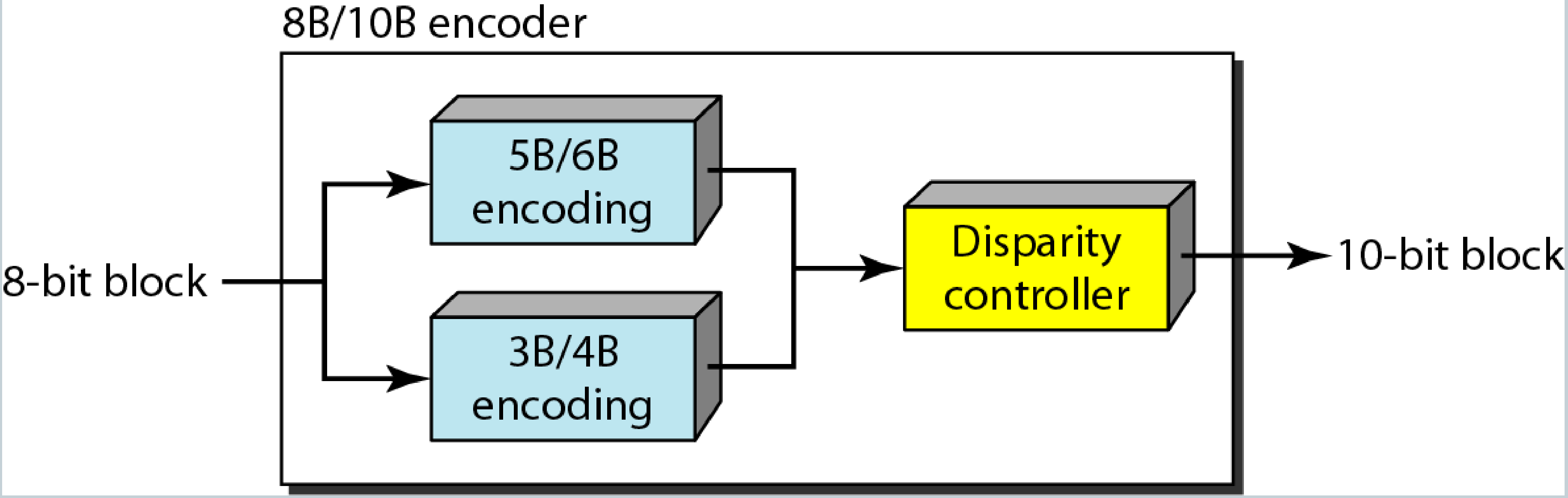
- Design to used in combination with NRZ-I
- NRZ-I
  - Benefit: Good signal rate
  - Weakness: Synchronization problem (long 0 can make it lose synchronization)
- Solution: change the bit stream prior to encoding with NRZ-I

Four Binary/Five Binary (4B/5B)

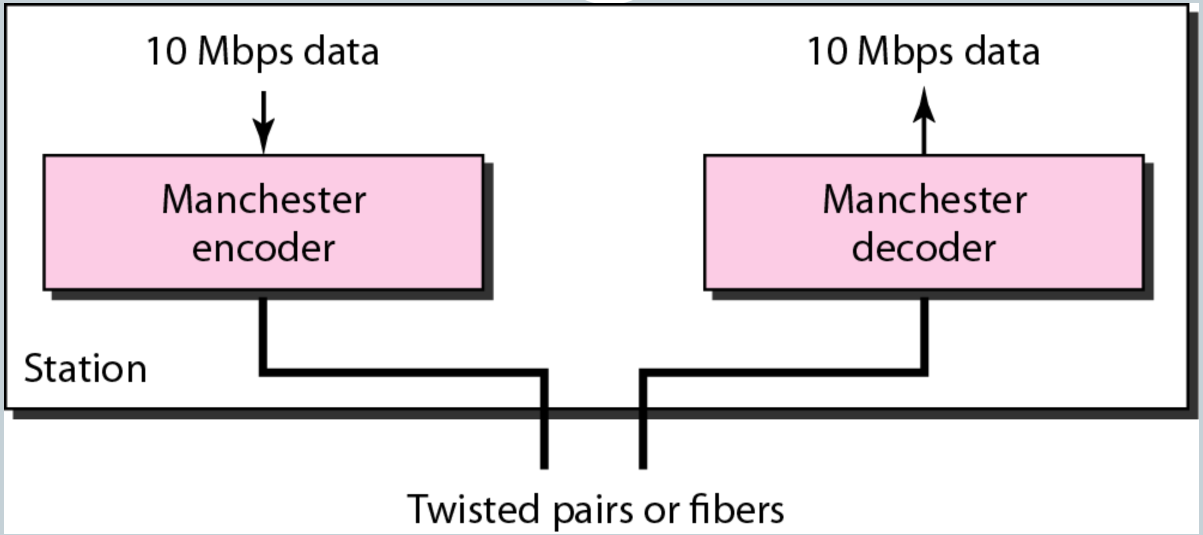


- Unused sequence are used for control sequence
- Not solve DC component problem
  - May use biphase or bipolar encoding, if DC component requires to eliminate

8B/10B Block Encoding

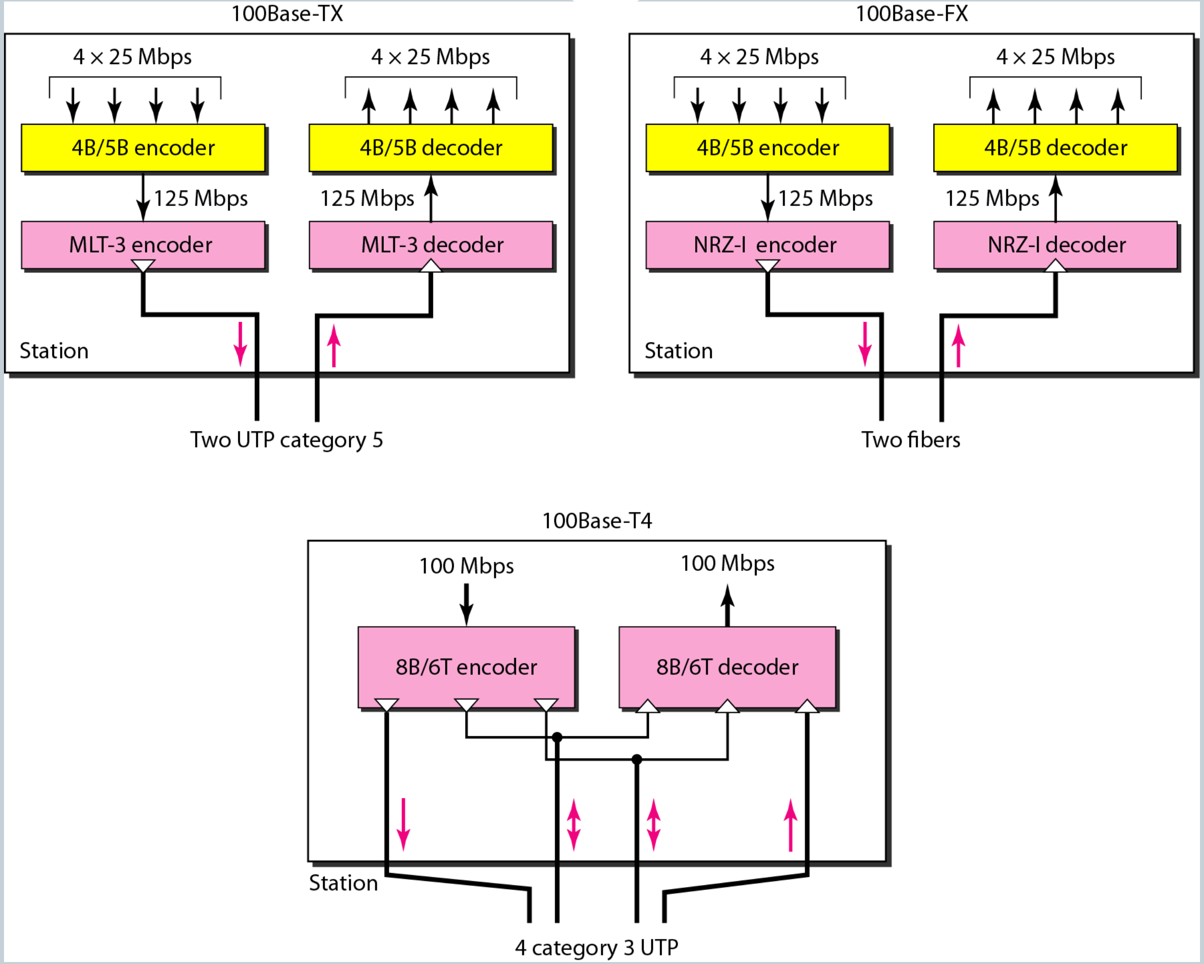


Encoding in a Standard Ethernet Implementation



Characteristics	*10Base5*	*10Base2*	*10Base-T*	*10Base-F*
Media	Thick coaxial cable	Thin coaxial cable	2 UTP	2 Fiber
Maximum length	500 m	185 m	100 m	2000 m
Line encoding	Manchester	Manchester	Manchester	Manchester

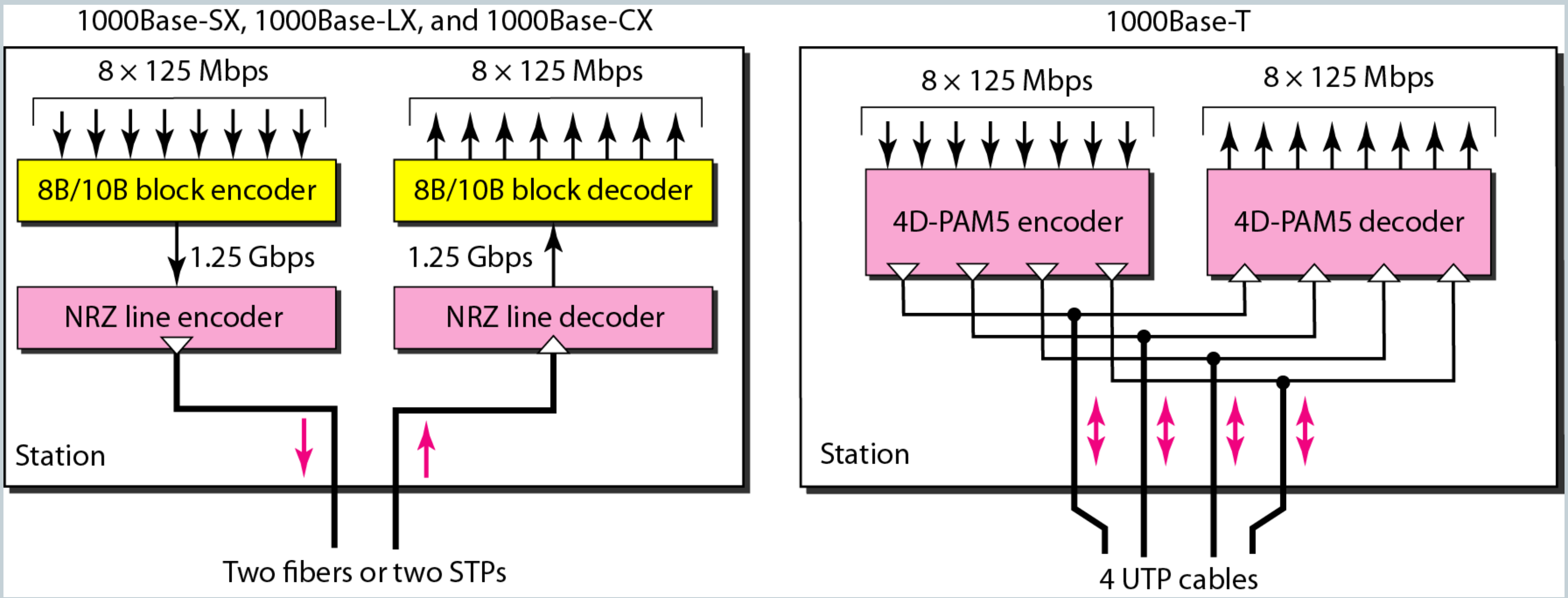
Encoding for Fast Ethernet Implementation



Encoding for Fast Ethernet Implementation

Characteristics	*100Base-TX*	*100Base-FX*	*100Base-T4*
Media	Cat 5 UTP or STP	Fiber	Cat 4 UTP
Number of wires	2	2	4
Maximum length	100 m	100 m	100 m
Block encoding	4B/5B	4B/5B	
Line encoding	MLT-3	NRZ-I	8B/6T

Encoding in Gigabit Ethernet Implementations



Encoding in Gigabit Ethernet Implementations

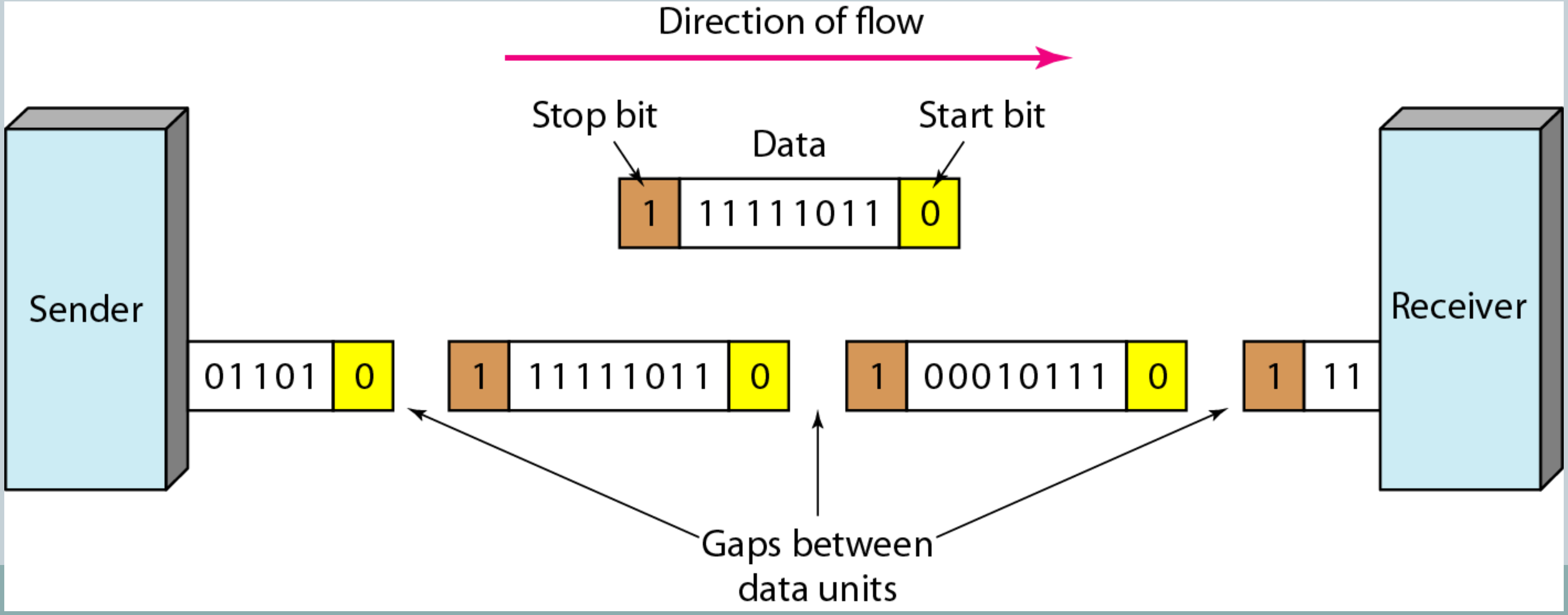
Characteristics	*1000Base-SX*	*1000Base-LX*	*1000Base-CX*	*1000Base-T*
Media	Fiber short-wave	Fiber long-wave	STP	Cat 5 UTP
Number of wires	2	2	2	4
Maximum length	550 m	5000 m	25 m	100 m
Block encoding	8B/10B	8B/10B	8B/10B	
Line encoding	NRZ	NRZ	NRZ	4D-PAM5

Types of Serial Transmission

- Asynchronous Transmission: timing of signal is unimportant
  - Information is received and translated by agreed upon patterns
  - Patterns are based on grouping the bit stream into bytes. The sending system handles each group independently, relaying it to link whenever ready.

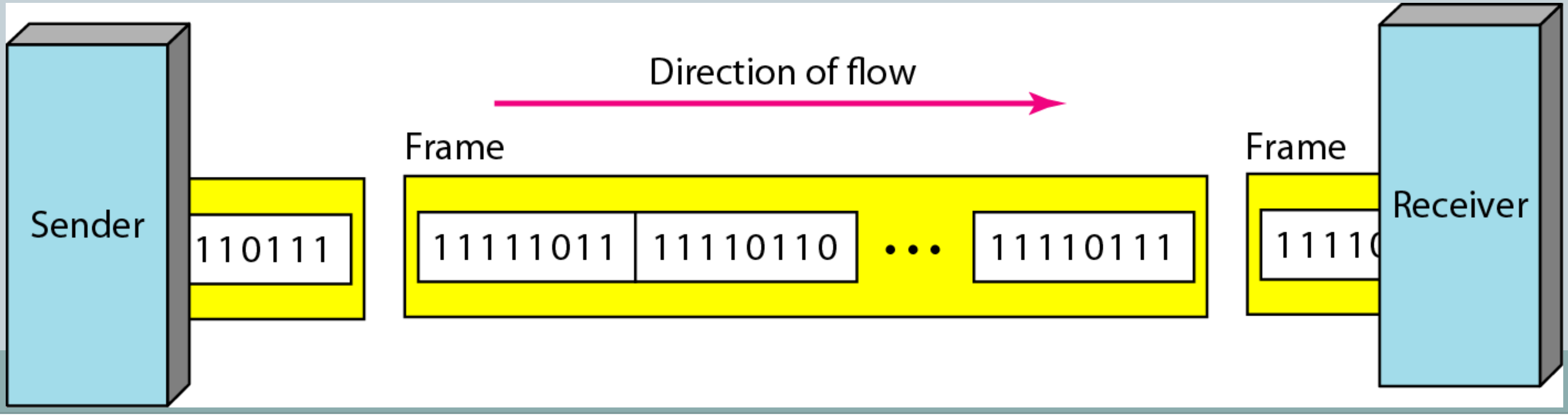
Types of Serial Transmission

- In asynchronous transmission, we send 1 start bit (0) at the beginning and 1 or more stop bits (1s) at the end of each byte. There may be a gap between each byte.



Types of Serial Transmission

- Synchronous transmission: the bit stream is combined into longer “frames,” which may contain multiple bytes.
  - In synchronous transmission, we send bits one after another without start or stop bits or gaps. It is the responsibility of the receiver to group the bits
  - The advantage of synchronous transmission is speed



Types of Serial Transmission

- Isochronous transmission: synchronous over the entire stream. This guarantees that the data arrive at a fixed rate.
  - Example in real-time audio and video, in which uneven delays between frames are not acceptable, synchronous transmission fails.

DATA RATE LIMITS

- A very important consideration in data communications is how fast we can send data, in bits per second, over a channel. Data rate depends on three factors:

1. The bandwidth available
2. The level of the signals we use
3. The quality of the channel (the level of noise)

Nyquist Theorem

- As early as 1924, an AT&T engineer, Henry Nyquist, realized that even a perfect channel has a finite transmission capacity. He derived an equation expressing the maximum data rate for a finite bandwidth noiseless channel.

$$C = 2B \log_2 M$$

  - M = number of discrete signal or voltage levels

- Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels. The maximum bit rate can be calculated as

$$\boxed{\text{BitRate} = 2 \times 3000 \times \log_2 2 = 6000 \text{ bps}}$$

- Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). The maximum bit rate can be calculated as

$$\text{BitRate} = 2 \times 3000 \times \log_2 4 = 12{,}000 \text{ bps}$$

- We need to send 265 kbps over a noiseless channel with a bandwidth of 20 kHz. How many signal levels do we need?
- So,

$$265{,}000 = 2 \times 20{,}000 \times \log_2 L$$

$$\log_2 L = 6.625 \qquad L = 2^{6.625} = 98.7 \text{ levels}$$

Since this result is not a power of 2, we need to either increase the number of levels or reduce the bit rate. If we have 128 levels, the bit rate is 280 kbps. If we have 64 levels, the bit rate is 240 kbps.

- In 1948, Claude Shannon carried Nyquist's work further and extended it to the case of a channel subject to random (that is, thermodynamic) noise (Shannon, 1948).

Shannon Capacity Formula

- Equation:

$$C = B \log_2 \left(1 + \mathrm{SNR}\right)$$

- Represents theoretical maximum that can be achieved
- In practice, only much lower rates achieved
  - Formula assumes white noise (thermal noise)
  - Impulse noise is not accounted for
  - Attenuation distortion or delay distortion not accounted for

- Consider an extremely noisy channel in which the value of the signal-to-noise ratio is almost zero. In other words, the noise is so strong that the signal is faint. For this channel the capacity C is calculated as

$$\boxed{C = B \log_2 (1 + \text{SNR}) = B \log_2 (1 + 0) = B \log_2 1 = B \times 0 = 0}$$

- This means that the capacity of this channel is zero regardless of the bandwidth. In other words, we cannot receive any data through this channel.

- 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?

$$C = B \log_2(1 + \text{SNR}) = 10^6 \log_2(1 + 63) = 10^6 \log_2 64 = 6 \text{ Mbps}$$

- The Shannon formula gives us 6 Mbps, the upper limit. For better performance we choose something lower, 4 Mbps, for example. Then we use the Nyquist formula to find the number of signal levels

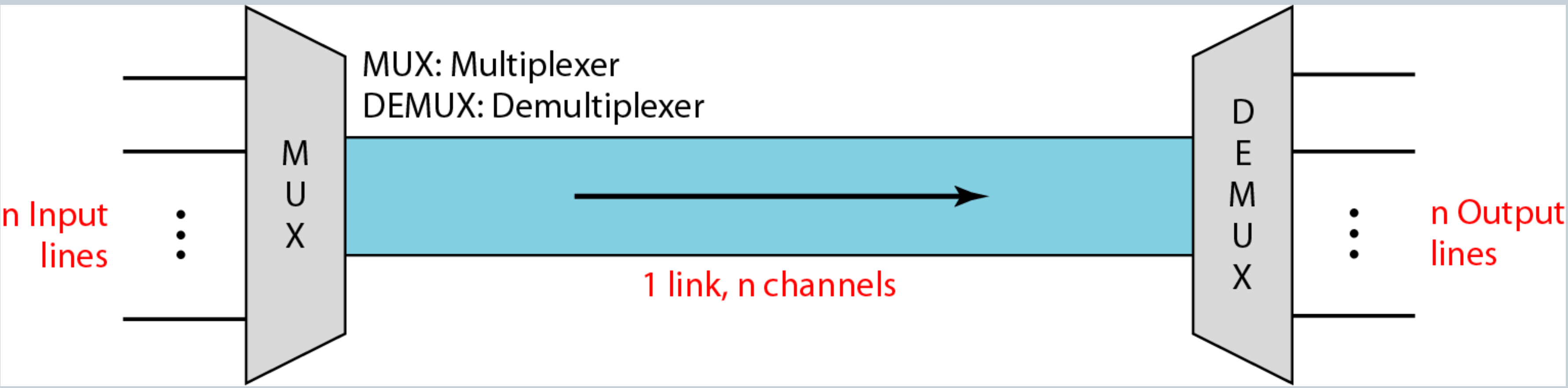
$$4 \text{ Mbps} = 2 \times 1 \text{ MHz} \times \log_2 L \quad \longrightarrow \quad L = 4$$

Bandwidth utilization: Multiplexing & Spreading

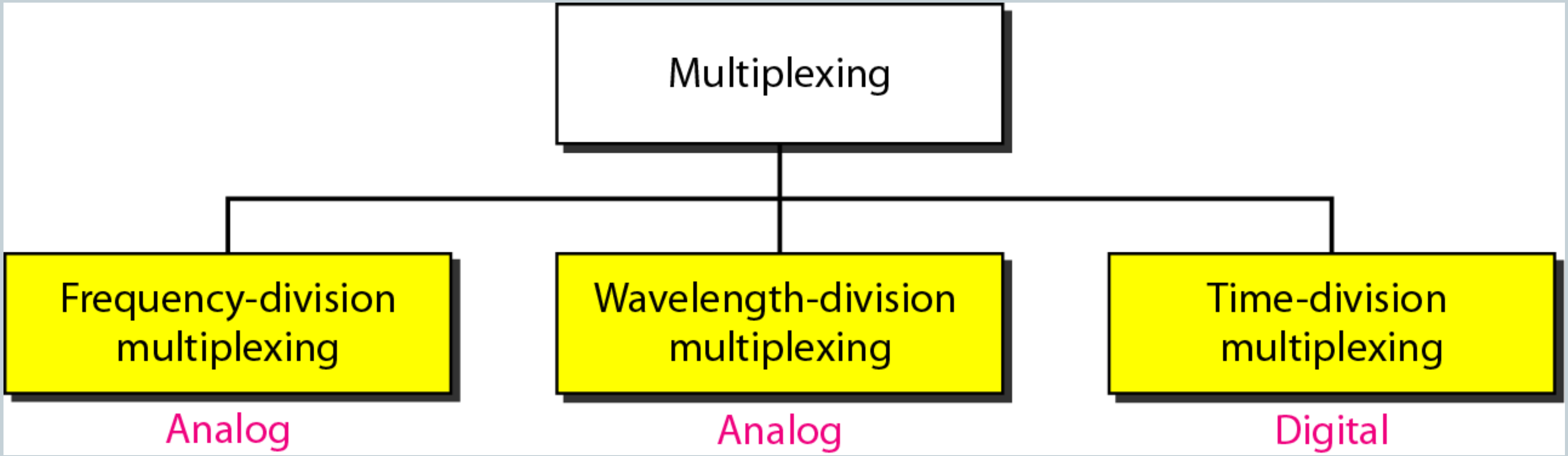
- Bandwidth utilization is the wise use of available bandwidth to achieve specific goals.

- Efficiency can be achieved by multiplexing; privacy and anti-jamming can be achieved by spreading

Multiplexing



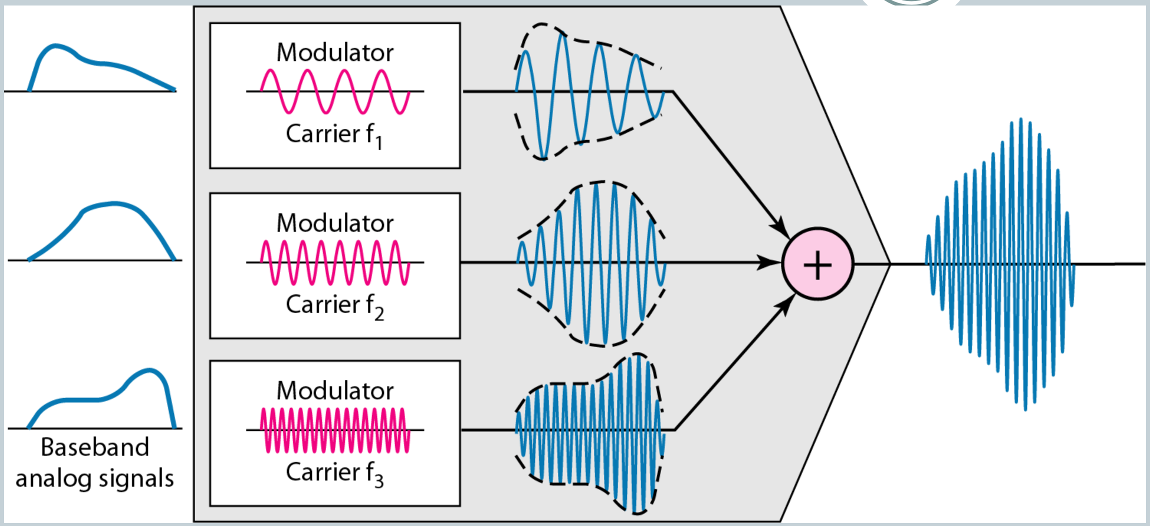
Categories of multiplexing



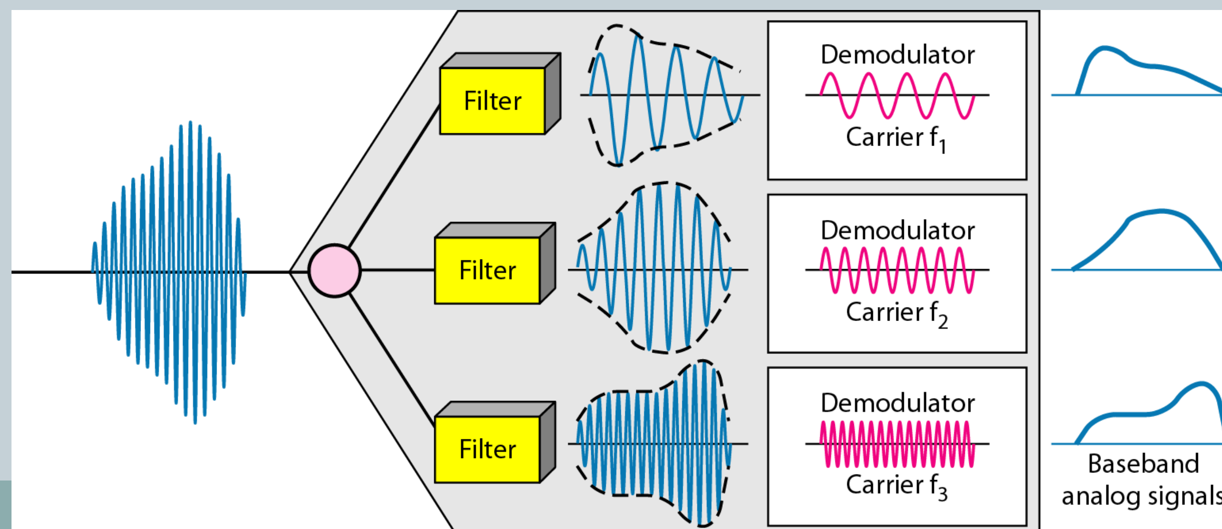
FDM

FDM is an analog multiplexing technique that combines analog signals

FDM process



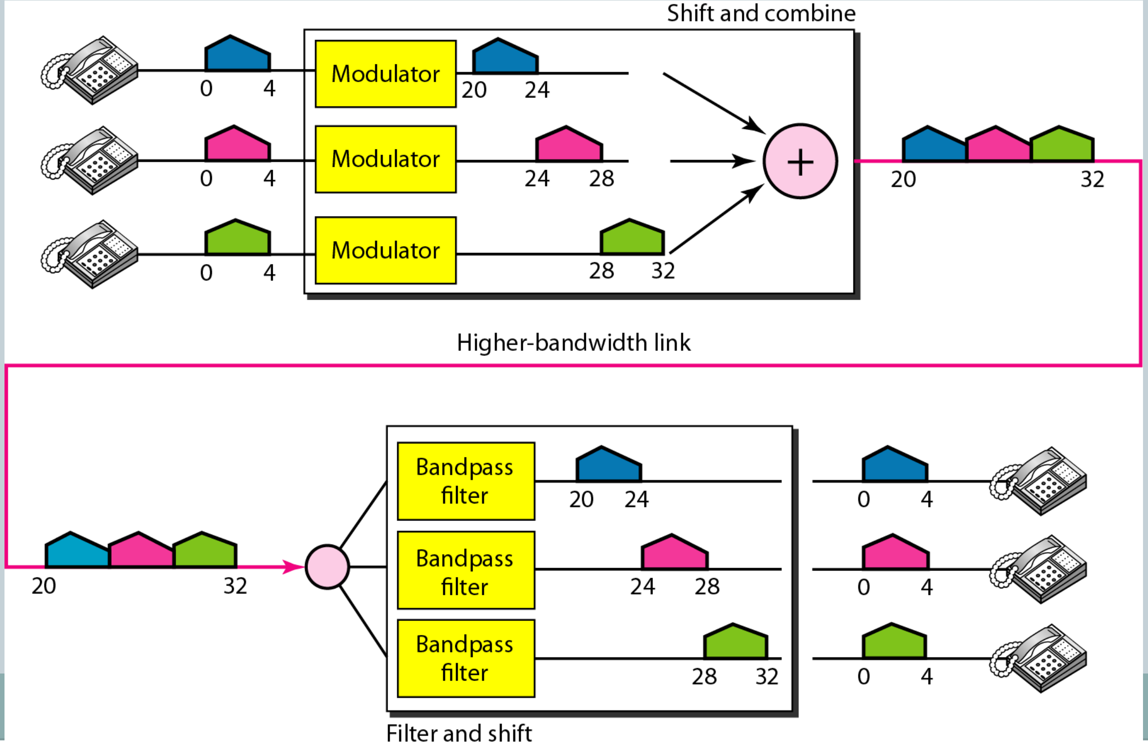
Modulator
Carrier f1
Modulator
Carrier f2
Modulator
Carrier f3
Baseband
analog signals



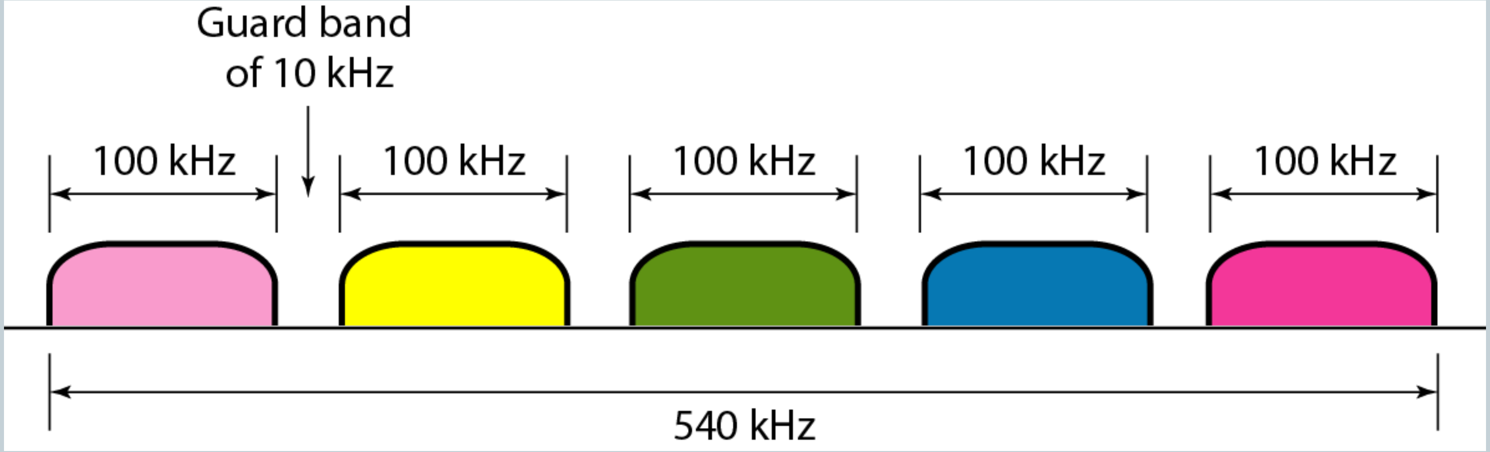
Filter
Filter
Filter
Demodulator
Carrier f1
Demodulator
Carrier f2
Demodulator
Carrier f3
Baseband
analog signals

Example

- Assume that a voice channel occupies a bandwidth of 4 kHz. We need to combine three voice channels into a link with a bandwidth of 12 kHz, from 20 to 32 kHz. Show the configuration, using the frequency domain. Assume there are no guard bands

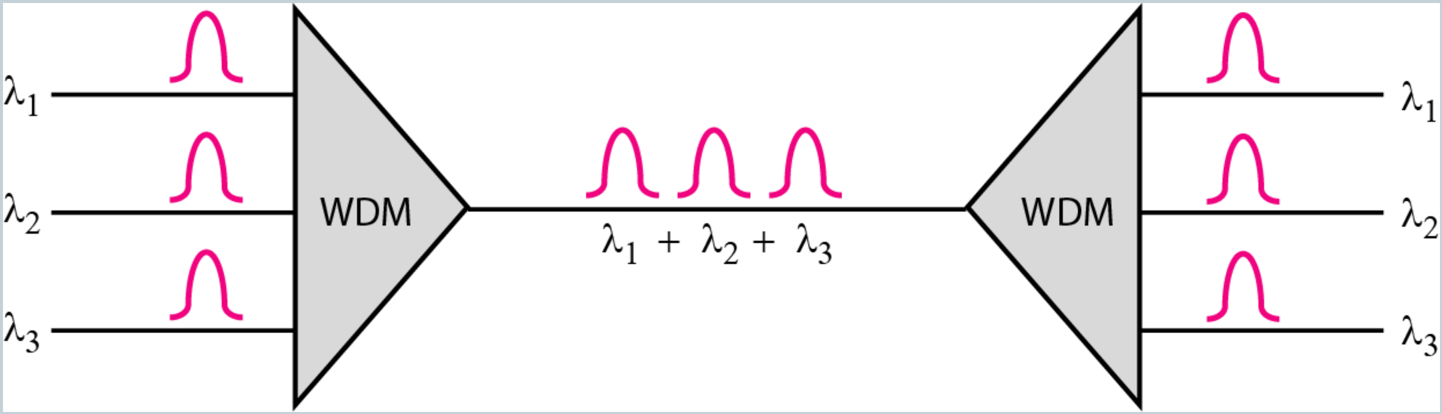


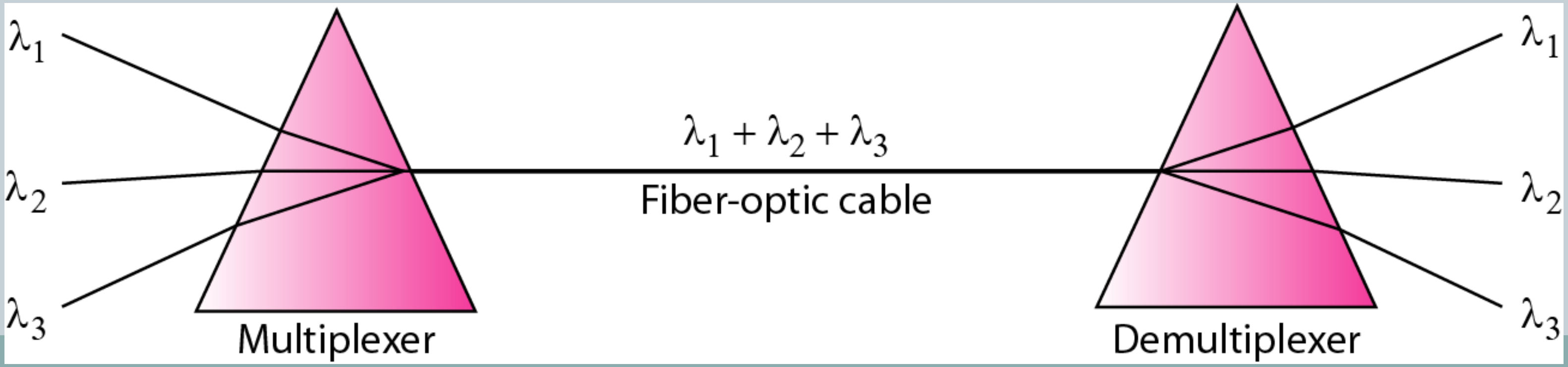
- Five channels, each with a 100-kHz bandwidth, are to be multiplexed together. What is the minimum bandwidth of the link if there is a need for a guard band of 10 kHz between the channels to prevent interference?



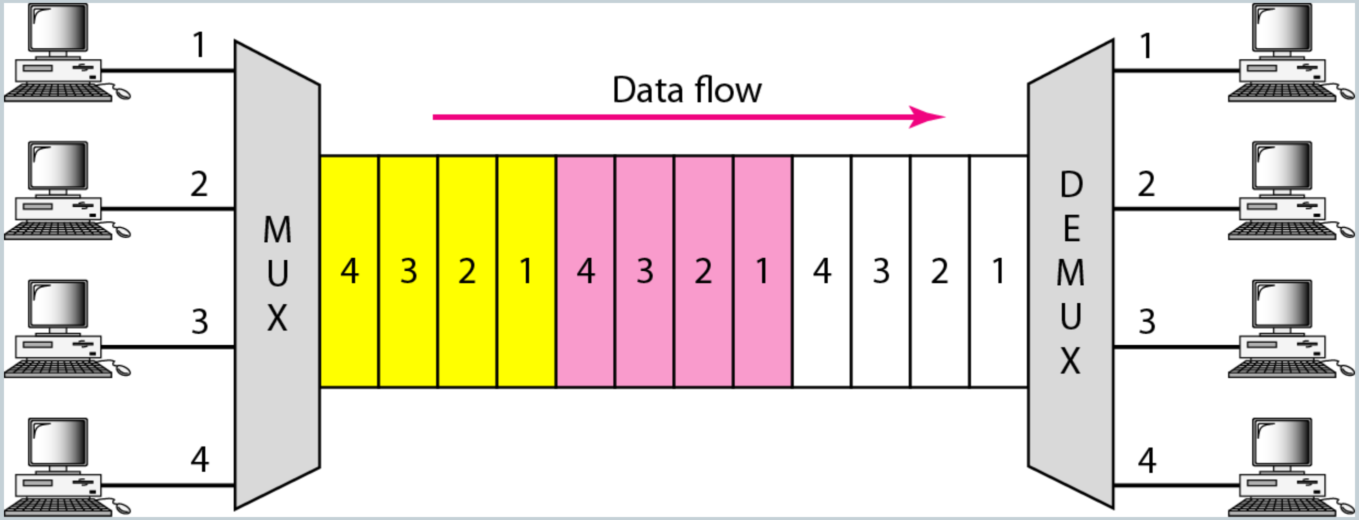
Wavelength-division multiplexing

- WDM is an analog multiplexing technique to combine optical signals



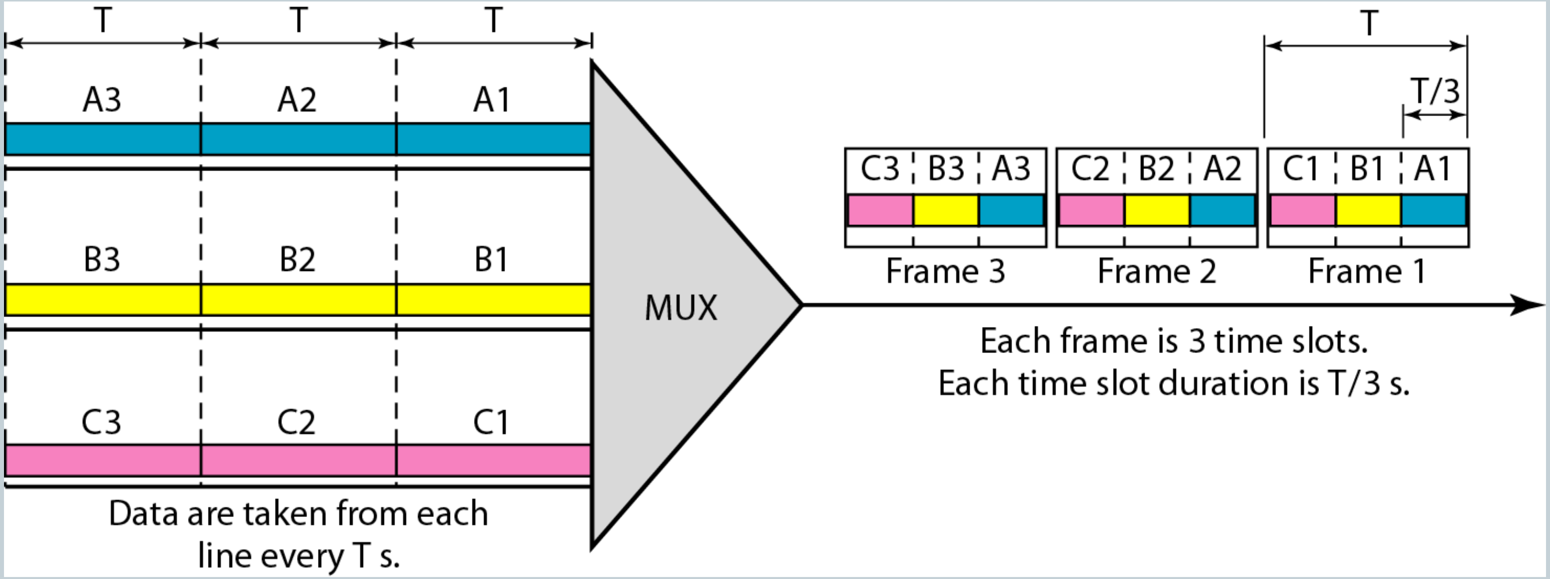


- TDM is a digital multiplexing technique for combining several low-rate channels into one high-rate one.



Synchronous time-division multiplexing

- In synchronous TDM, the data rate of the link is *n* times faster, and the unit duration is *n* times shorter.



Example

- Four 1-kbps connections are multiplexed together. A unit is 1 bit. Find (a) the duration of 1 bit before multiplexing, (b) the transmission rate of the link, (c) the duration of a time slot, and (d) the duration of a frame.

  a. The duration of 1 bit before multiplexing is 1 / 1 kbps, or 0.001 s (1 ms).

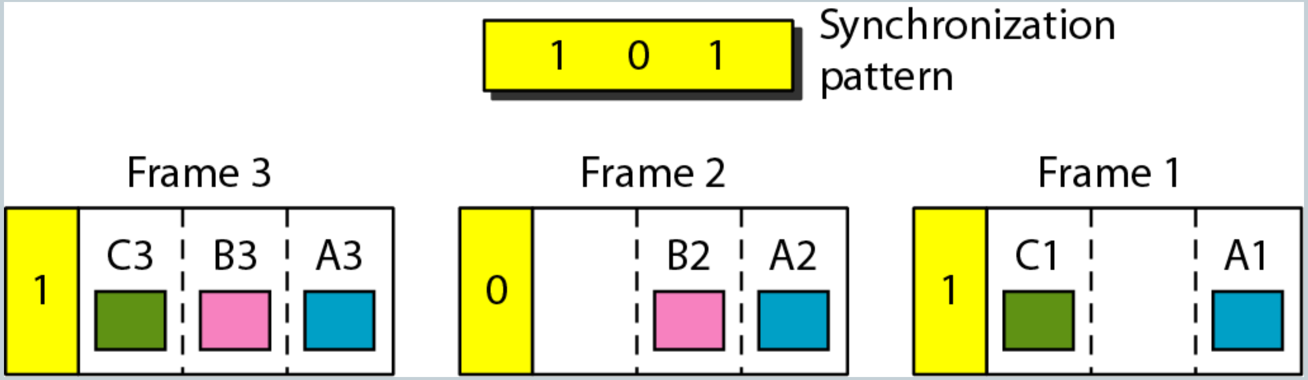
  b. The rate of the link is 4 times the rate of a connection, or 4 kbps.

c. The duration of each time slot is one-fourth of the duration of each bit before multiplexing, or 1/4 ms or 250 μs. Note that we can also calculate this from the data rate of the link, 4 kbps. The bit duration is the inverse of the data rate, or 1/4 kbps or 250 μs.

d. The duration of a frame is always the same as the duration of a unit before multiplexing, or 1 ms. We can also calculate this in another way. Each frame in this case has four time slots. So the duration of a frame is 4 times 250 μs, or 1 ms.

Example

- We have four sources, each creating 250 characters per second. If the interleaved unit is a character and 1 synchronizing bit is added to each frame, find (a) the data rate of each source, (b) the duration of each character in each source, (c) the frame rate, (d) the duration of each frame, (e) the number of bits in each frame, and (f) the data rate of the link.
- What is framing bit



Solution

- We can answer the questions as follows:

a. The data rate of each source is $250 \times 8 = 2000$ bps = 2 kbps

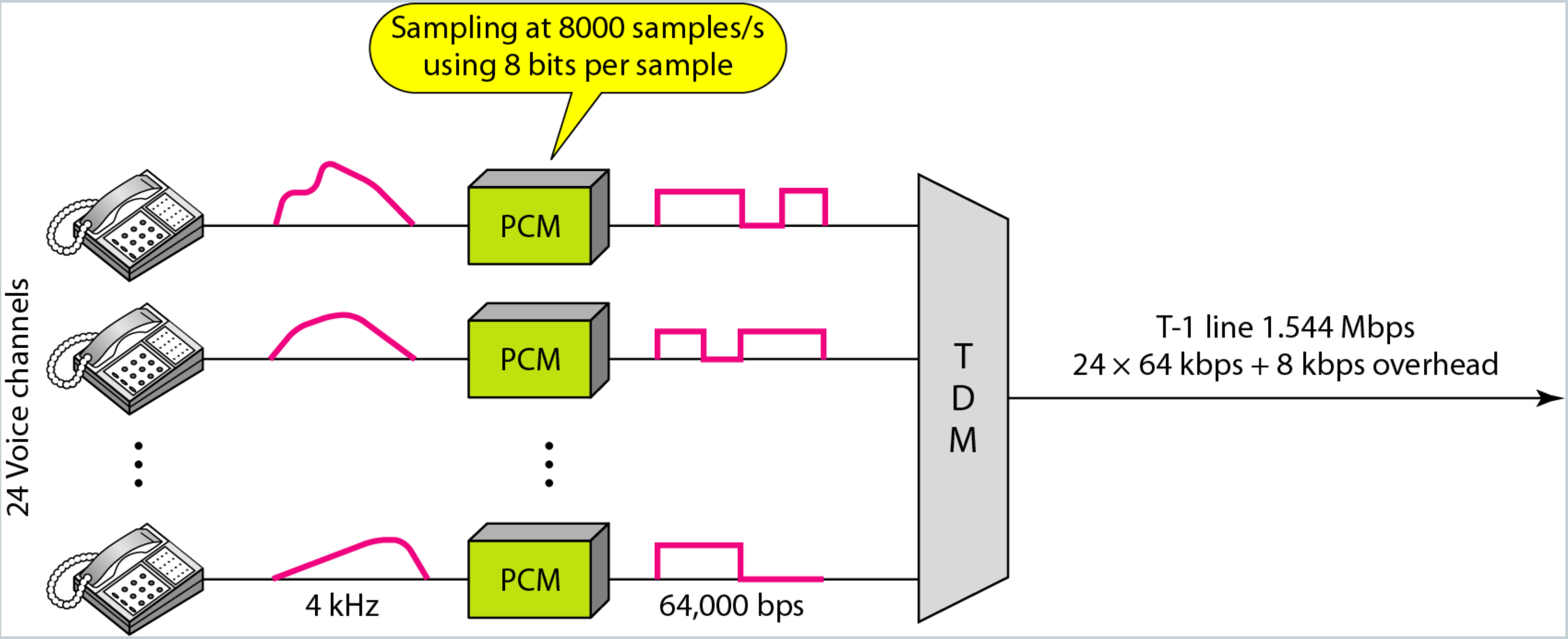
b. Each source sends 250 characters per second; therefore, the duration of a character is 1/250 s, or
4 ms.

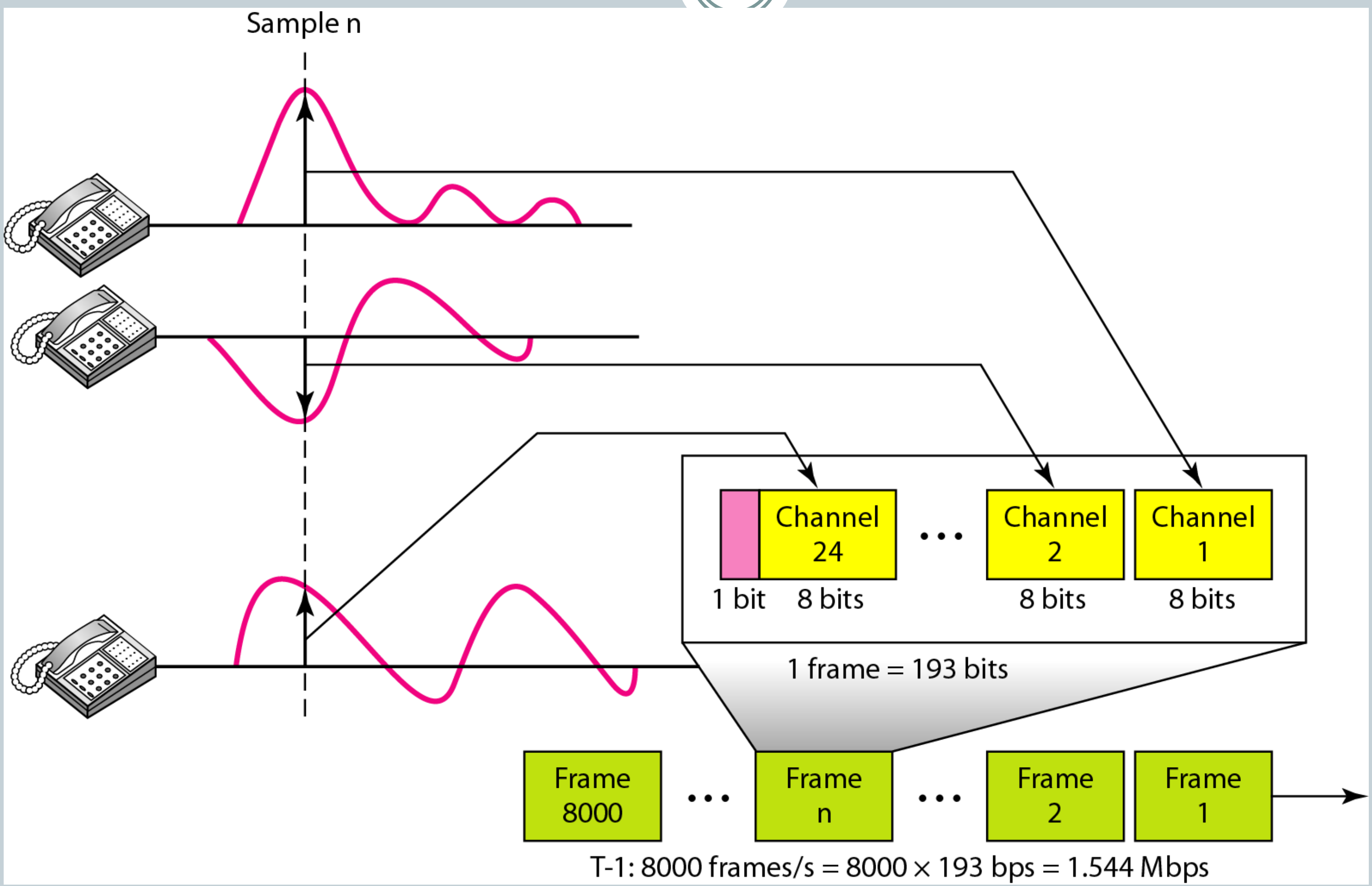
c. Each frame has one character from each source, which means the link needs to send 250 frames per second to keep the transmission rate of each source.

d. The duration of each frame is 1/250 s, or 4 ms. Note that the duration of each frame is the same as the duration of each character coming from each source.

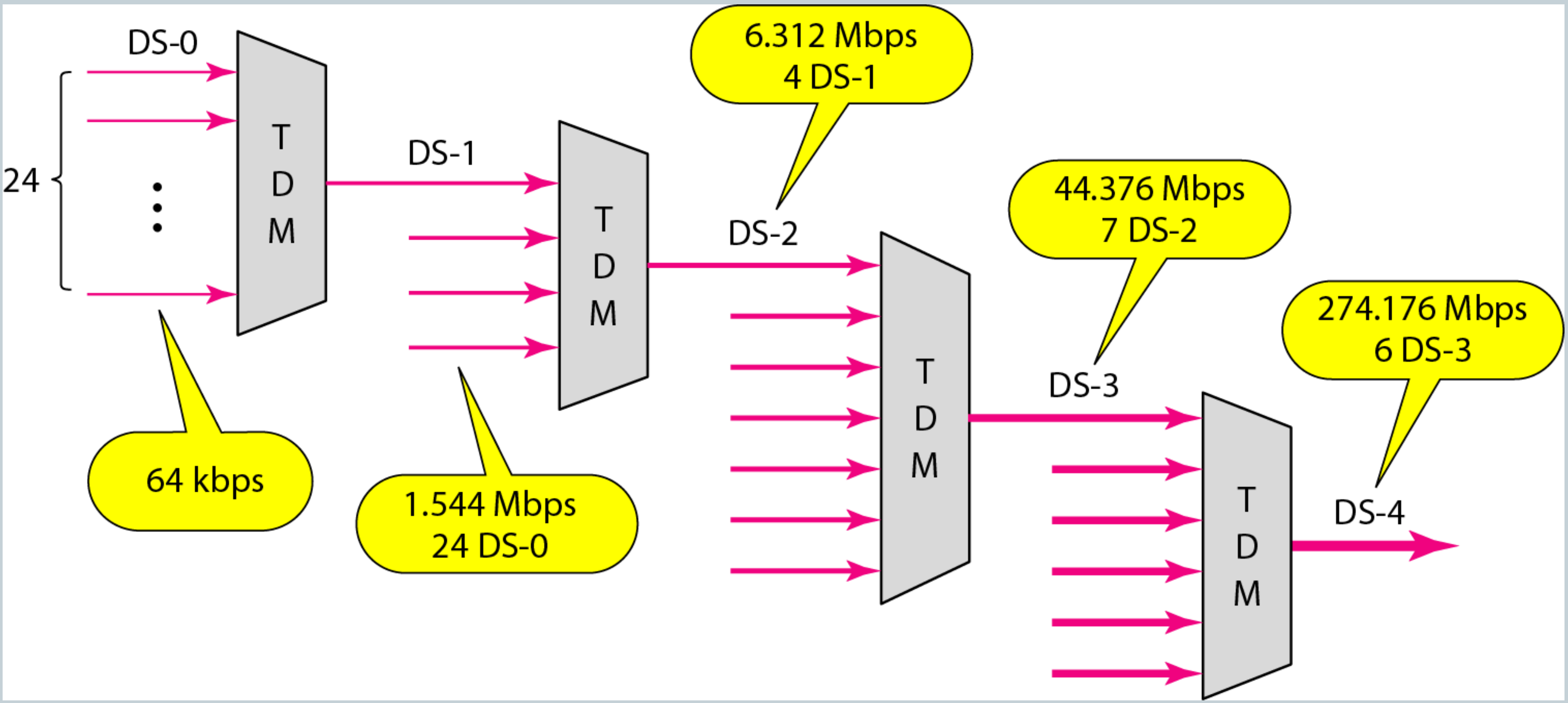
e. Each frame carries 4 characters and 1 extra synchronizing bit. This means that each frame is
$4 \times 8 + 1 = 33$ bits.

T-1 line for multiplexing telephone lines




Sample n
Channel 24
Channel 2
Channel 1
1 bit
8 bits
8 bits
8 bits
1 frame = 193 bits
Frame 8000
Frame n
Frame 2
Frame 1
T-1: 8000 frames/s = 8000 × 193 bps = 1.544 Mbps

Service	*Line*	*Rate (Mbps)*	*Voice Channels*
DS-1	T-1	1.544	24
DS-2	T-2	6.312	96
DS-3	T-3	44.736	672
DS-4	T-4	274.176	4032


DS-0
24
TDM
64 kbps
DS-1
TDM
1.544 Mbps
24 DS-0
6.312 Mbps
4 DS-1
DS-2
TDM
44.376 Mbps
7 DS-2
DS-3
TDM
274.176 Mbps
6 DS-3
DS-4