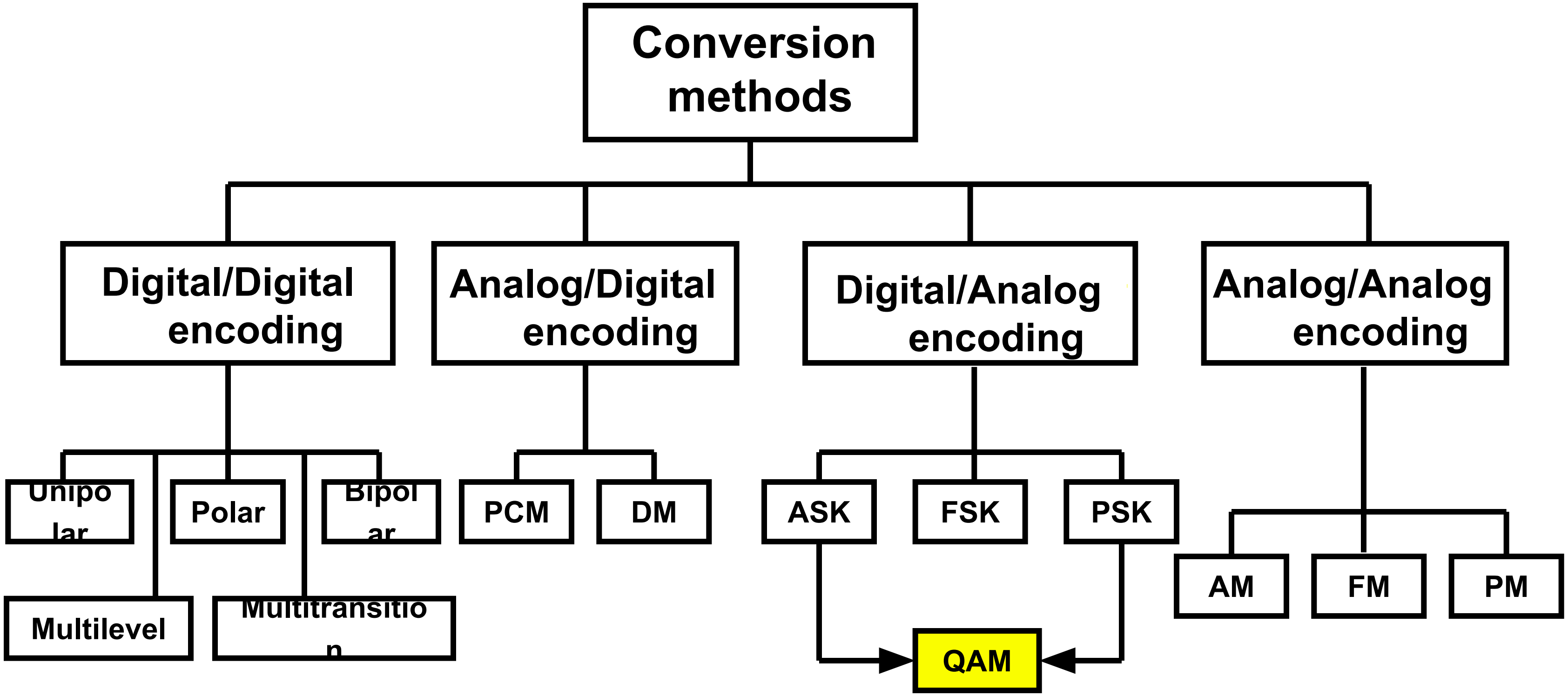
Chapter 4

Digital Transmission

Digital Transmission

- The Information needs to be converted to either a digital signal or an analog signal for transmission



4.1 DIGITAL-TO-DIGITAL CONVERSION

In this section, we see how we can represent digital data by using digital signals. The conversion involves three techniques: line coding, block coding, and scrambling. Line coding is always needed; block coding and scrambling may or may not be needed.

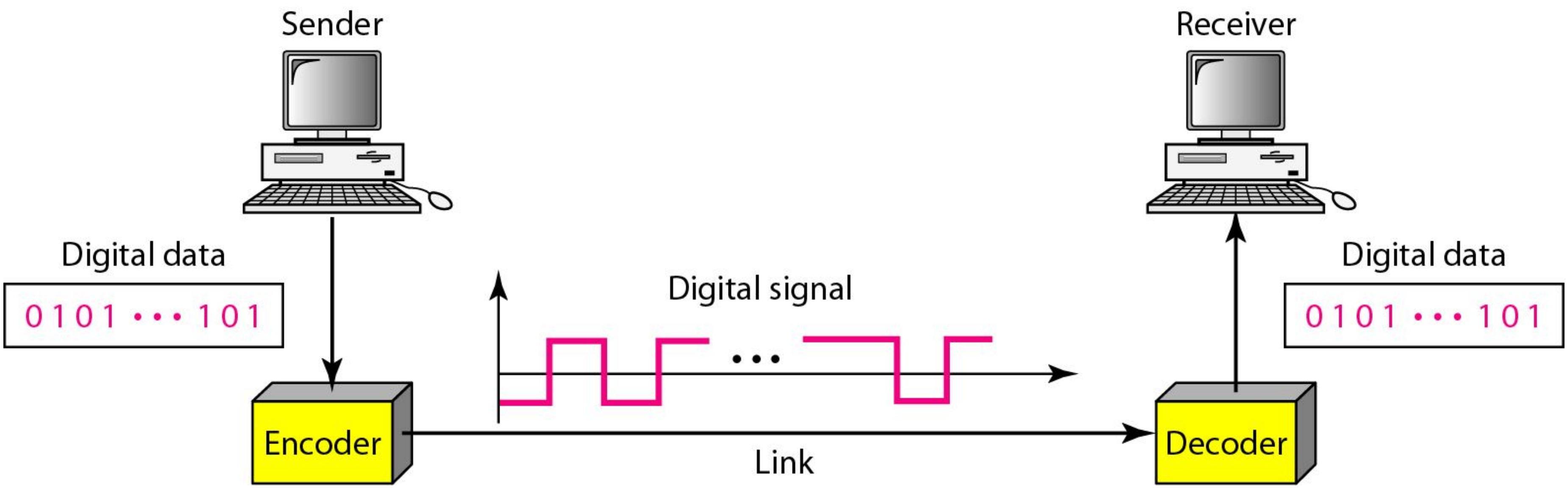
Topics discussed in this section:

Line Coding
Line Coding Schemes
Block Coding
Scrambling

Digital-to-Digital Conversion

- Converts sequence of bits to a digital signal

Figure 4.1 ***Line coding and decoding***



Characteristics of Line Coding

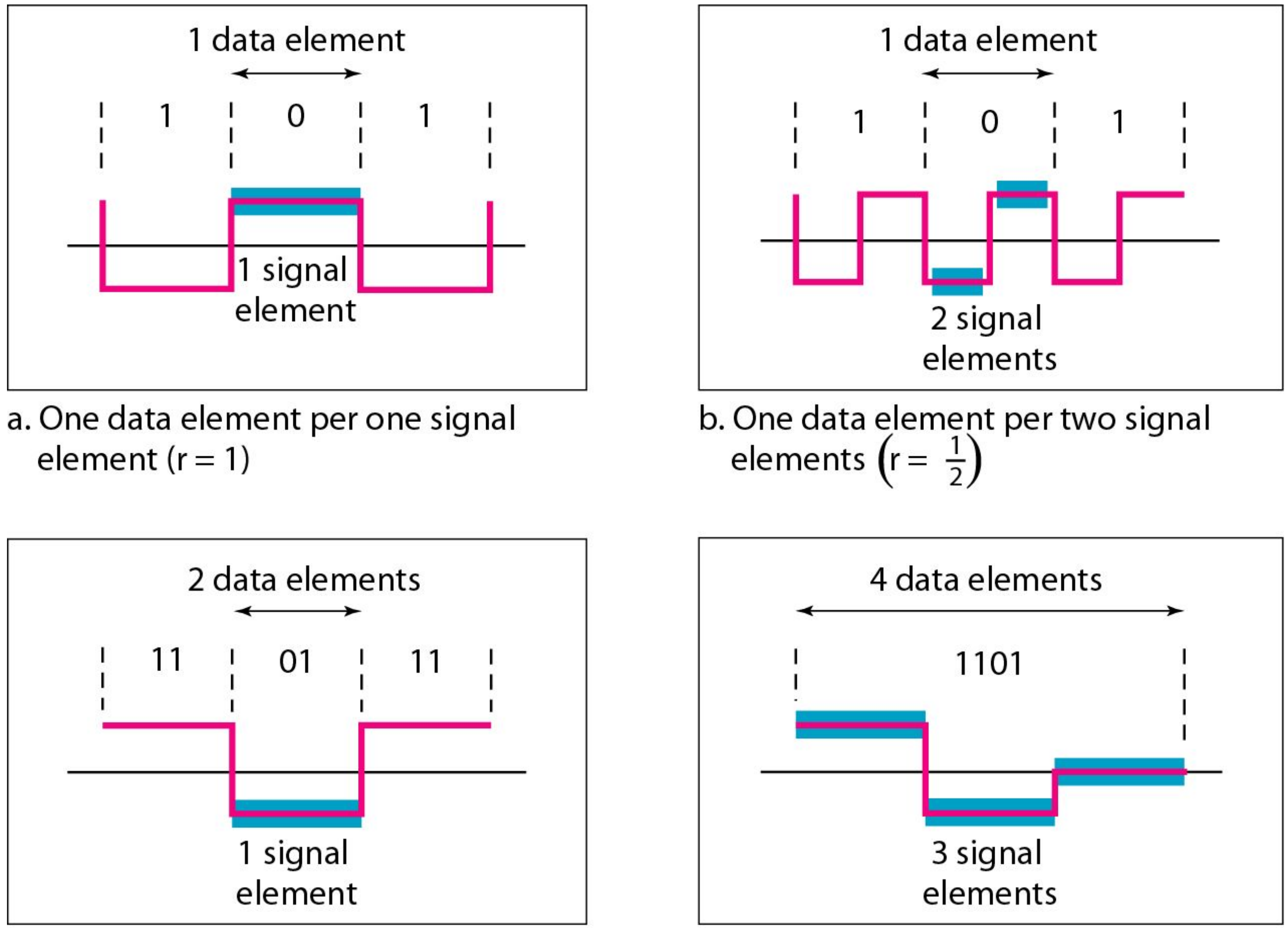
- Signal element vs. data element
- Data rate vs. bit rate
- dc components
- Self-synchronization

Data element versus Signal element

- **Data element – the smallest entity that can represent a piece of information : this is the bit.**
- **Signal element – carries data element. A signal element is the shortest unit of a digital signal.**
- **Data elements are being carried; signal elements are the carriers.**

Data element versus Signal element

Figure 4.2 ***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 versus Signal Rate

- Data rate (bit rate) : the No. of data elements sent in 1s.(bps)
- Signal rate (pulse rate, modulation rate or baud rate) :

  - the number of signal elements sent in 1s.(baud)
- Relationship between Data rate Vs Signal rate

$$S = c \times N \times 1/r \quad \text{(baud)}$$

where S : No. of signal element, (baud)

c : case factor,

N : Data rate (bps),

r : No. of data elements carried by each signal element.

Example 4.1

A signal is carrying data in which one data element is encoded as one signal element (r = 1). If the bit rate is 100 kbps, what is the average value of the baud rate if c is between 0 and 1?

Solution

We assume that the average value of c is 1/2 . The baud rate is then

$$S = c \times N \times \frac{1}{r} = \frac{1}{2} \times 100{,}000 \times \frac{1}{1} = 50{,}000 = 50 \text{ kbaud}$$

Bandwidth

Note

Although the actual bandwidth of a digital signal is infinite, the effective bandwidth is finite.

* A digital signal that carries information is nonperiodic. So, bandwidth of nonperiodic signal is continuous with an infinite range theoretically.

Min. Bandwidth & Max. Data rate

- The baud rate determines the required bandwidth for a digital signal.
- Minimum bandwidth

$$B_{minimum} = c \times N \times 1/r$$

- Maximum Data rate

$$N_{maximum} = (1/c) \times B \times r$$

Example 4.2

The maximum data rate of a channel (see Chapter 3) is $N_{max} = 2 \times B \times \log_2 L$ (defined by the Nyquist formula). Does this agree with the previous formula for N_{max}?

Solution

A signal with L levels actually can carry $\log_2 L$ bits per level. If each level corresponds to one signal element and we assume the average case ($c = 1/2$), then we have

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

Baseline Wandering

- In Decoding Digital Signal running average of received signal power is used known as Baseline.
- Incoming signal is evaluated against Baseline.
- A long string of 1 or 0 can cause a drift in the baseline (Baseline Wandering)
- So the interpretation of received signal can be difficult due to this baseline wandering effect.

DC Components

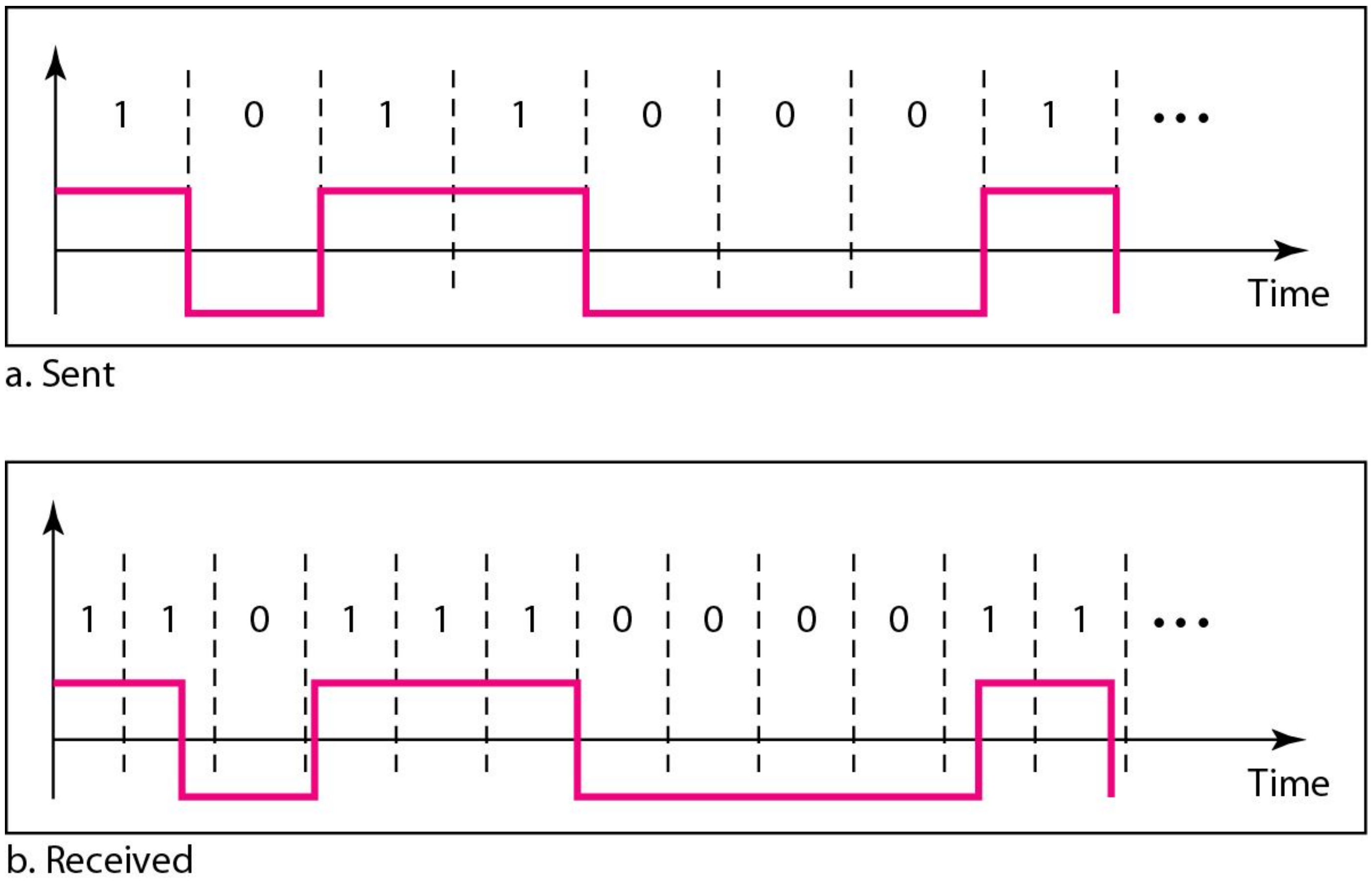
- When the voltage level in a digital signal is constant for a while, the spectrum creates very low frequencies.
  - These frequencies are around zero, called DC(direct current) components.
- Some systems (such as transformer) will not allow passage of DC component
- A telephone line cannot pass frequencies below 200Hz

Self-Synchronization

- Receiver's bit intervals must correspond exactly to the sender's bit intervals
- Self-synchronizing signal includes timing information (beginning, middle or end of the pulse)
- If the receiver's clock is out of synchronization, these alerting points can reset the clock.

Self-Synchronization

Figure 4.3 *Effect of lack of synchronization*



Example 4.3

In a digital transmission, the receiver clock is 0.1 percent faster than the sender clock. How many extra bits per second does the receiver receive if the data rate is 1 kbps? How many if the data rate is 1 Mbps?

Solution

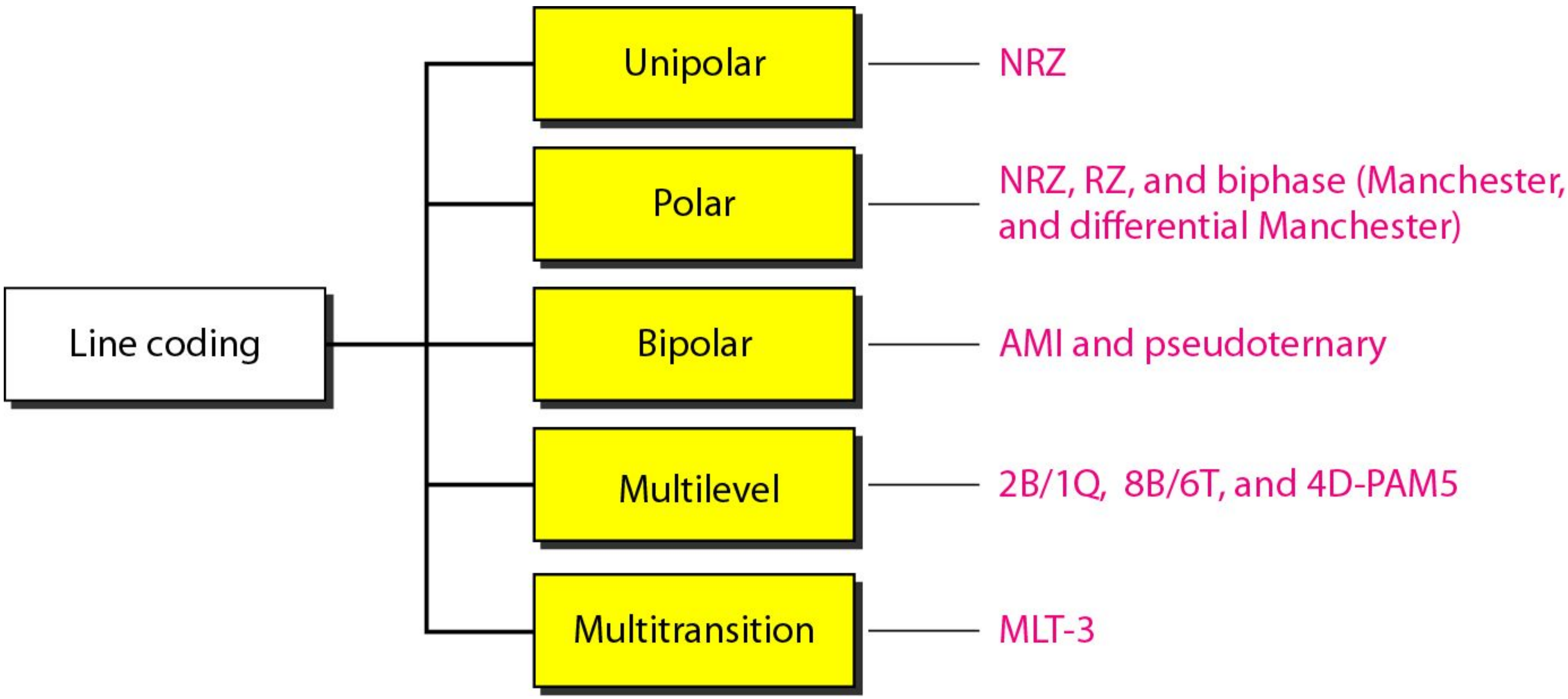
At 1 kbps, the receiver receives 1001 bps instead of 1000 bps.

1000 bits sent	1001 bits received	1 extra bps

At 1 Mbps, the receiver receives 1,001,000 bps instead of 1,000,000 bps.

1,000,000 bits sent	1,001,000 bits received	1000 extra bps

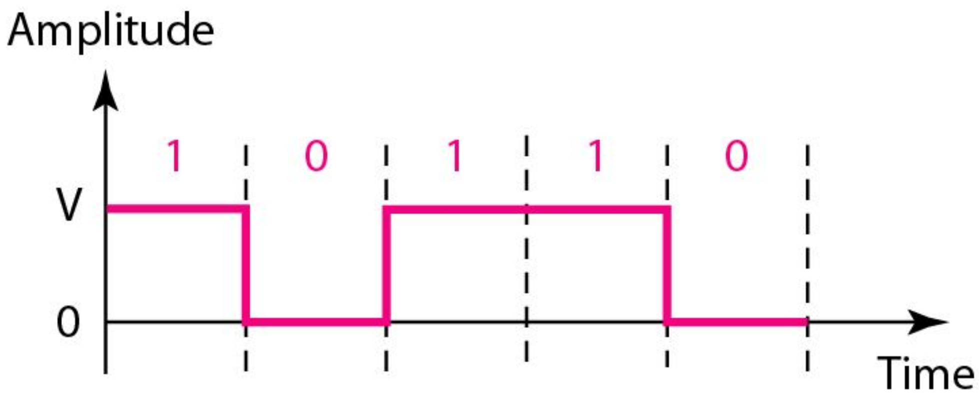
Line Coding Schemes



Line Coding Schemes

Figure 4.5 ***Unipolar NRZ scheme***

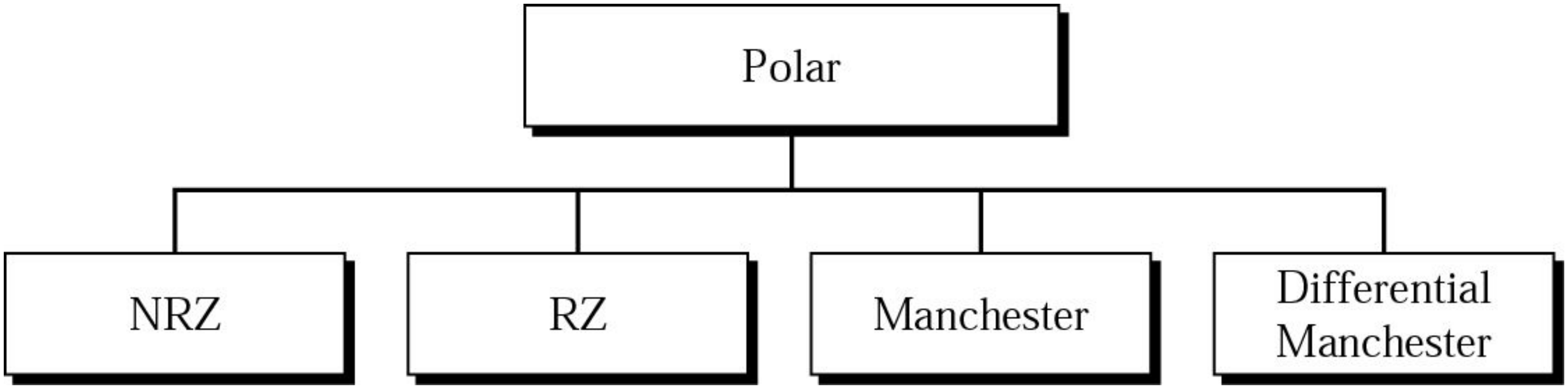
- **Unipolar encoding uses only one voltage level.**



$$\frac{1}{2}V^2 + \frac{1}{2}(0)^2 = \frac{1}{2}V^2$$

Normalized power

Variations of Polar Schemes



Polar Schemes

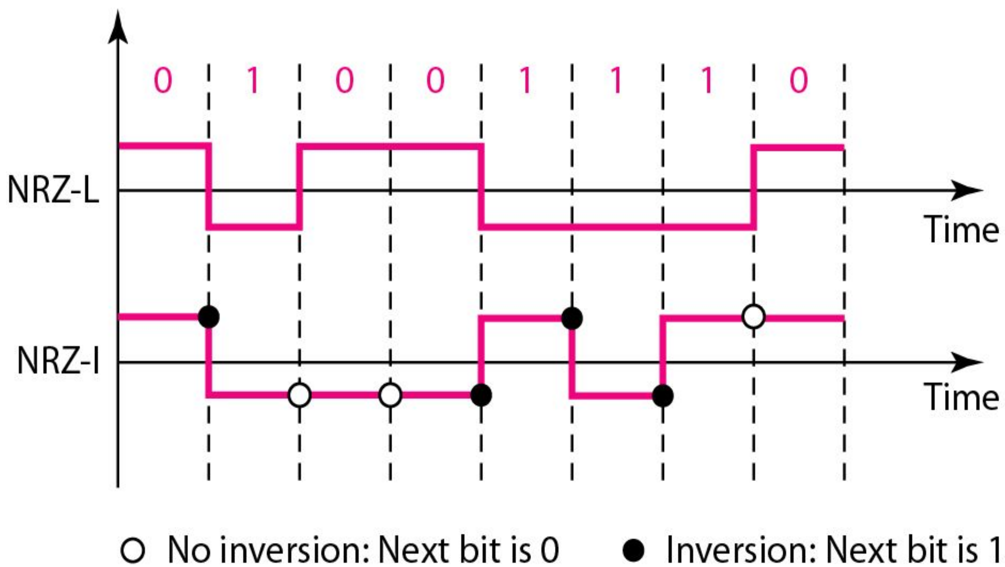
- Polar encoding uses two voltage levels (positive and negative).

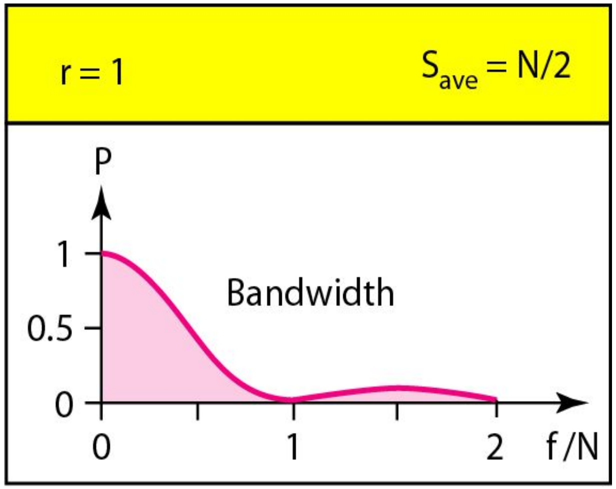
NRZ-L and NRZ-I

- In Non-return to Zero-level (NRZ-L) the level of the signal is dependent upon the state of the bit.
- In Non-return to Zero-Invert (NRZ-I) the signal is inverted if a 1 is encountered.

Figure 4.6 *Polar NRZ-L and NRZ-I schemes*

r: average baud rate
s: signal rate





Note

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.

Note

NRZ-L and NRZ-I both have an average signal rate of N/2 Bd.

Note

NRZ-L and NRZ-I both have a DC component problem.

Example 4.4

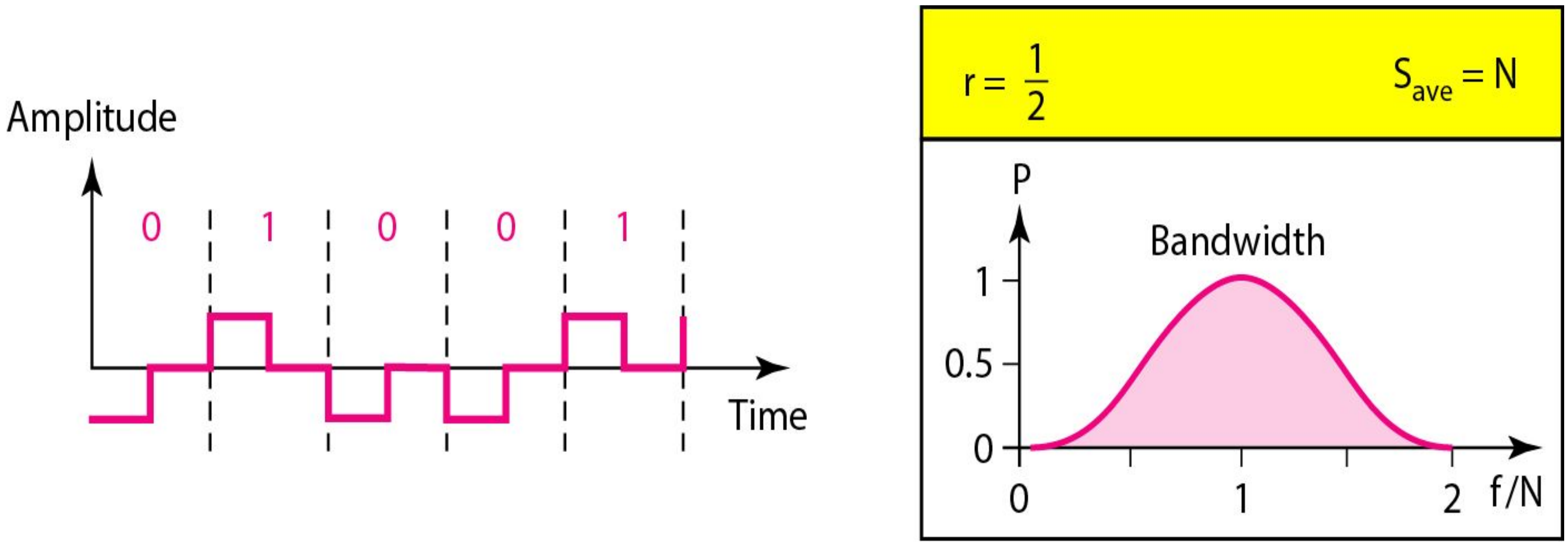
A system is using NRZ-I to transfer 1 Mbps data. What are the average signal rate and minimum bandwidth?

Solution

The average signal rate is S = N/2 = 500 kbaud. The minimum bandwidth for this average baud rate is B_{min} = S = 500 kHz.

RZ (Return-to-zero)

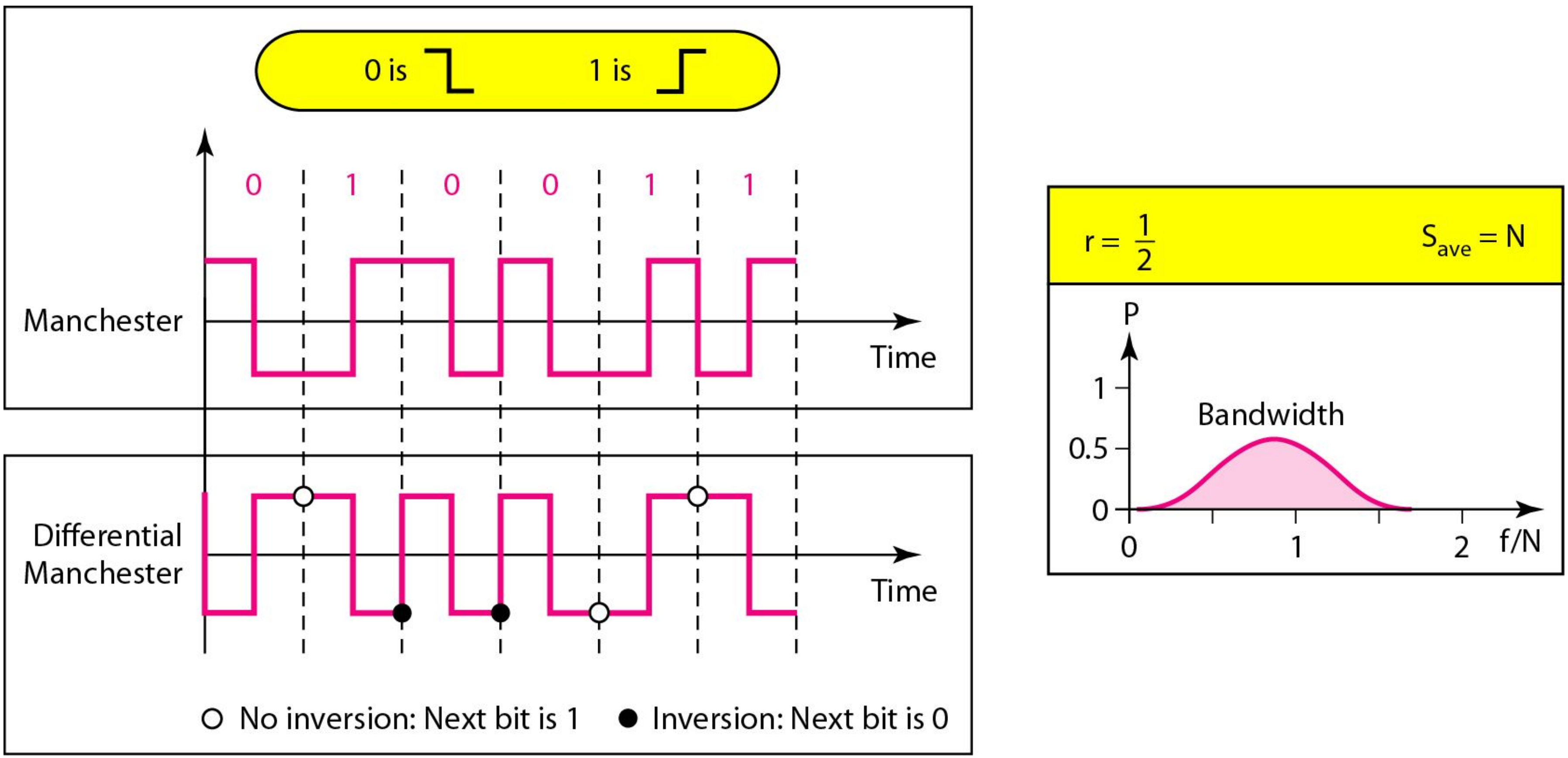
Figure 4.7 ***Polar RZ scheme***



A good encoded digital signal must contain a provision for synchronization.

Biphase: Manchester & Differential Manchester

Figure 4.8 *Polar biphase: Manchester and differential Manchester schemes*



Biphase: Manchester & Differential Manchester

In Manchester and differential Manchester encoding, the transition at the middle of the bit is used for synchronization.

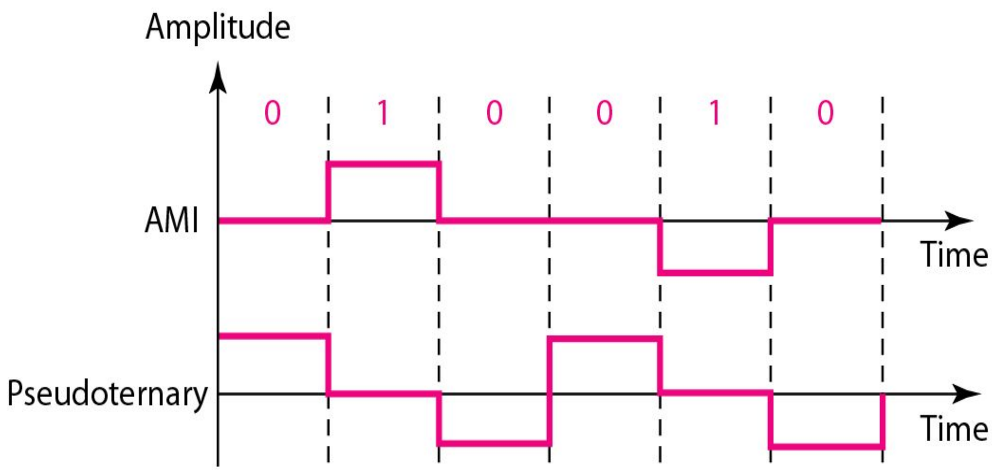
The minimum bandwidth of Manchester and differential Manchester is 2 times that of NRZ.

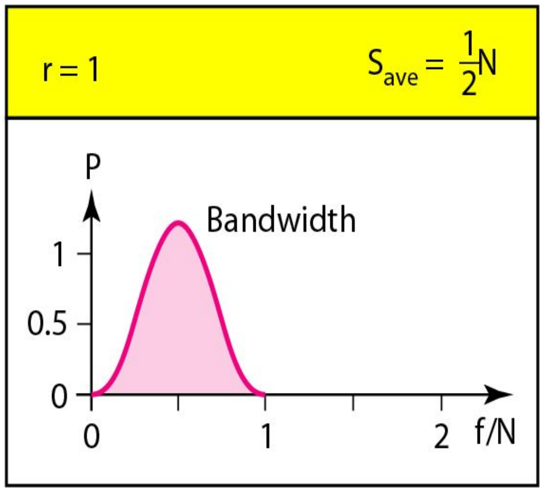
Bipolar Schemes

- In bipolar encoding, we use three levels:

  - positive, zero, and negative.

- ***Bipolar schemes: AMI (Alternate Mark Inversion) and pseudoternary***





Multilevel Schemes

- The desire to increase the data speed or decrease the required bandwidth has resulted in the creation of many scheme.
- The goal is to increase the number of bits per baud by encoding a pattern of m data elements into a pattern of n signal elements.

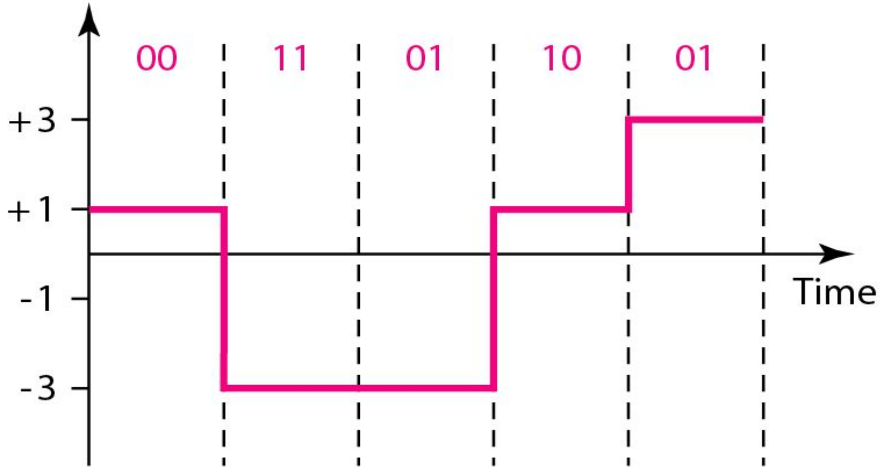
In *m*B*n*L schemes, a pattern of *m* data elements is encoded as a pattern of *n* signal elements in which $2^m \leq L^n$.

Multilevel Schemes (cont'd)

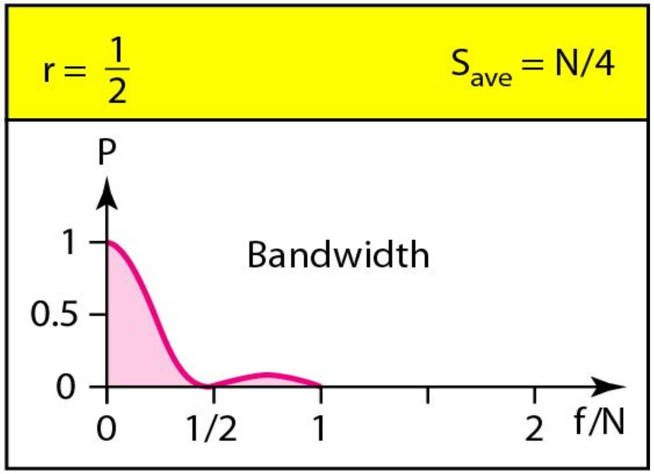
Figure 4.10 ***Multilevel: 2B1Q scheme***

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

Transition table

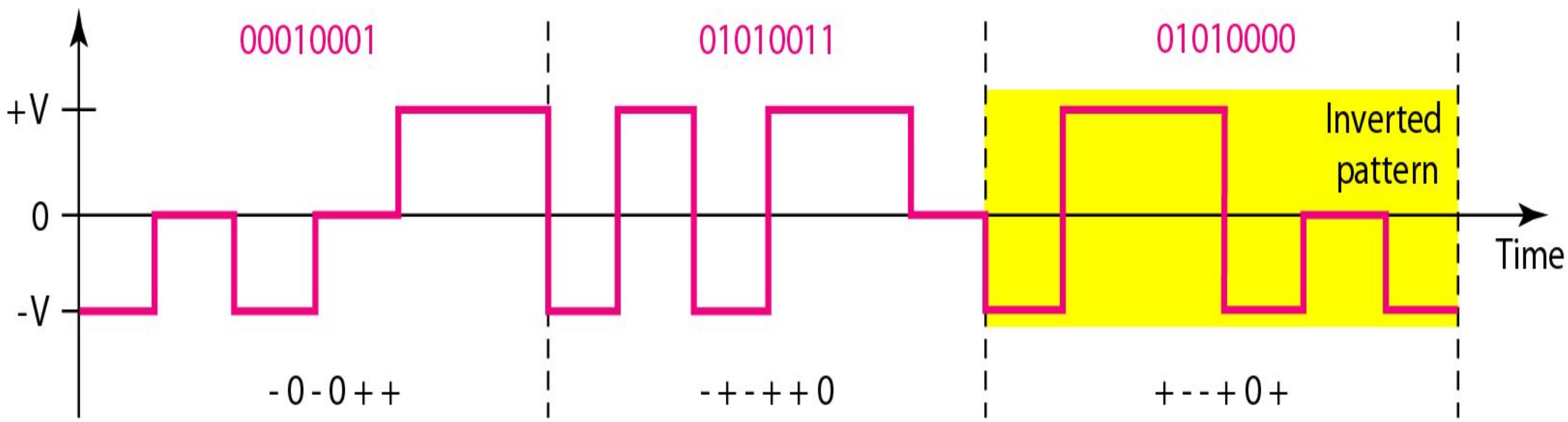


Assuming positive original level



Multilevel Schemes (cont'd)

Figure 4.11 ***Multilevel: 8B6T scheme***



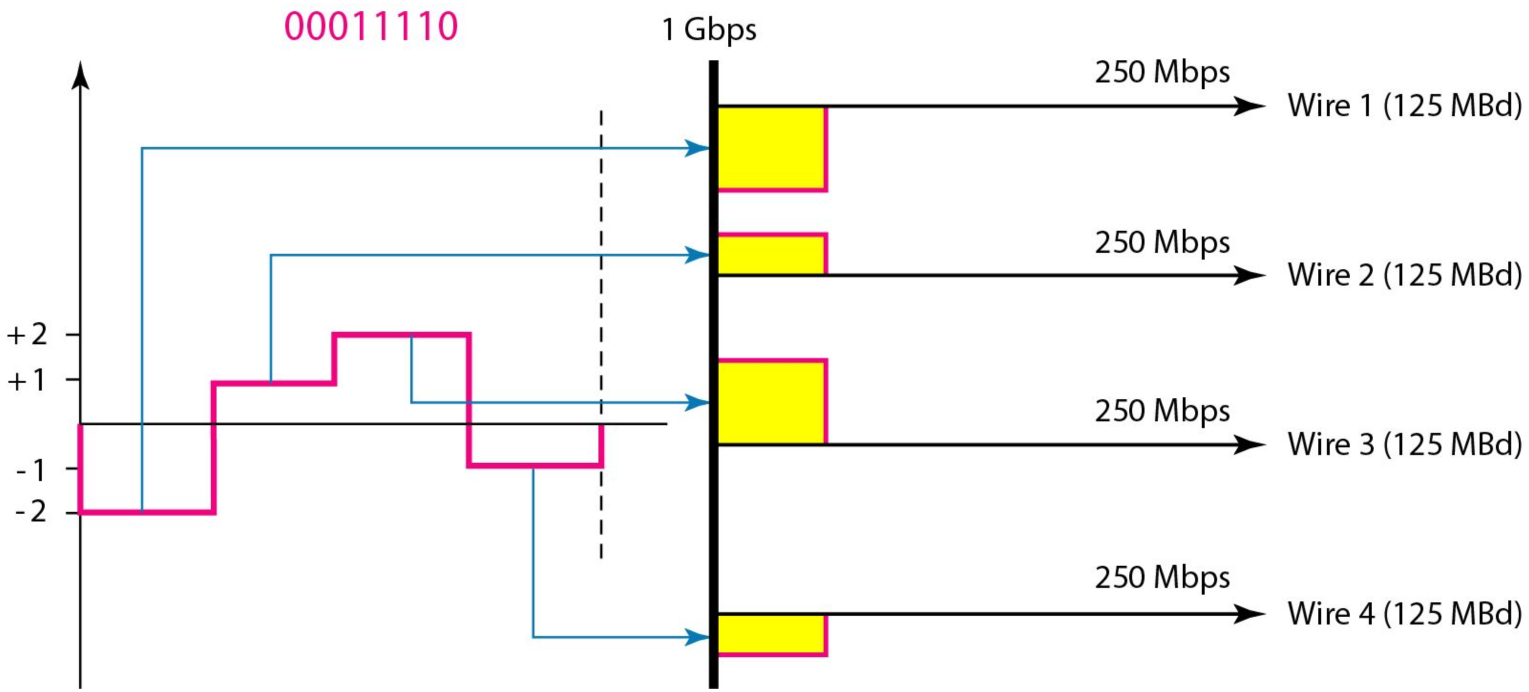
- **8 bit code = 2^8 = 256**
- **6 bit ternary = 3^6 = 729**

Multilevel Schemes (cont'd)

Portion of 8B6T Code Table

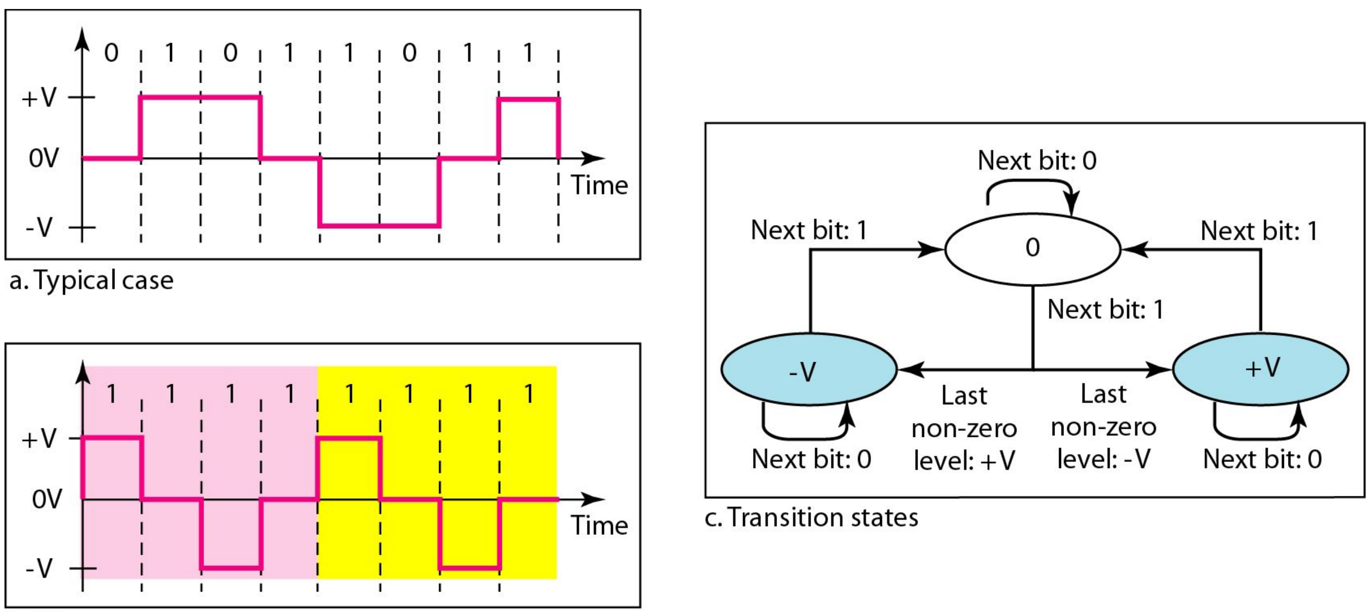
Data octet	6T code group	Data octet	6T code group	Data octet	6T code group	Data octet	6T code group
00	+-00+-	10	+0+--0	20	00-++-	30	+-00-+
01	0+-+-0	11	++0-0-	21	--+00+	31	0+--+0
02	+-0+-0	12	+0+-0-	22	++-0+-	32	+-0-+0
03	-0++-0	13	0++-0-	23	++-0-+	33	-0+-+0
04	-0+0+-	14	0++--0	24	00+0-+	34	-0+0-+
05	0+--0+	15	++00--	25	00+0+-	35	0+-+0-
06	+-0-0+	16	+0+0--	26	00-00+	36	+-0+0-
07	-0+-0+	17	0++0--	27	--+++-	37	-0++0-
08	-+00+-	18	0+-0+-	28	-0-++0	38	-+00-+
09	0-++-0	19	0+-0-+	29	--0+0+	39	0-+-+0
0A	-+0+-0	1A	0+-++-	2A	-0-+0+	3A	-+0-+0
0B	+0-+-0	1B	0+-00+	2B	0--+0+	3B	+0--+0
0C	+0-0+-	1C	0-+00+	2C	0--++0	3C	+0-0-+
0D	0-+-0+	1D	0-+++-	2D	--00++	3D	0-++0-
0E	-+0-0+	1E	0-+0-+	2E	-0-0++	3E	-+0+0-
0F	+0--0+	1F	0-+0+-	2F	0--0++	3F	+0-+0-

4D-PAM5: for Gigabit LAN
4 Dimensional 5 Level Pulse Amplitude Modulation



Multiline Transmission: MLT-3

- The signal rate for MLT-3 is one-fourth the bit rate
- MLT-3 when we need to send 100Mbps on a copper wire that cannot support more than 32MHz



a. Typical case

b. Worse case

c. Transition states

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

4.2 Block Coding

- We need redundancy to endure synchronization and to provide some kind of inherent error detecting.
- Block coding can give us redundancy to endure Synchronization and improve the performance of line coding.

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

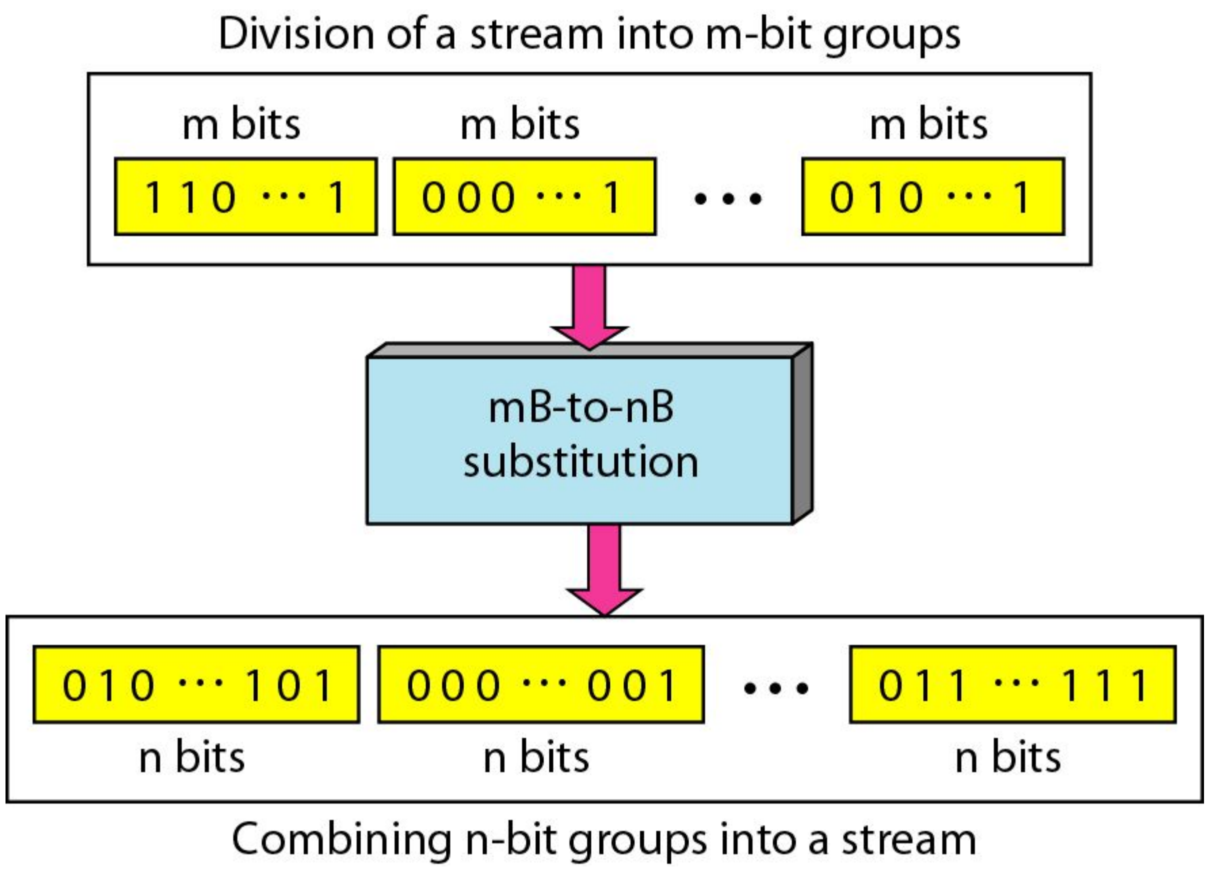
Block Coding (cont'd)

Steps in transmission

- Step 1: Division
  - divide sequence of bits into groups of m bits
- Step 2: Substitution
  - substitute an m-bit code for an n-bit group
- Step 3: Line Coding
  - create the signal

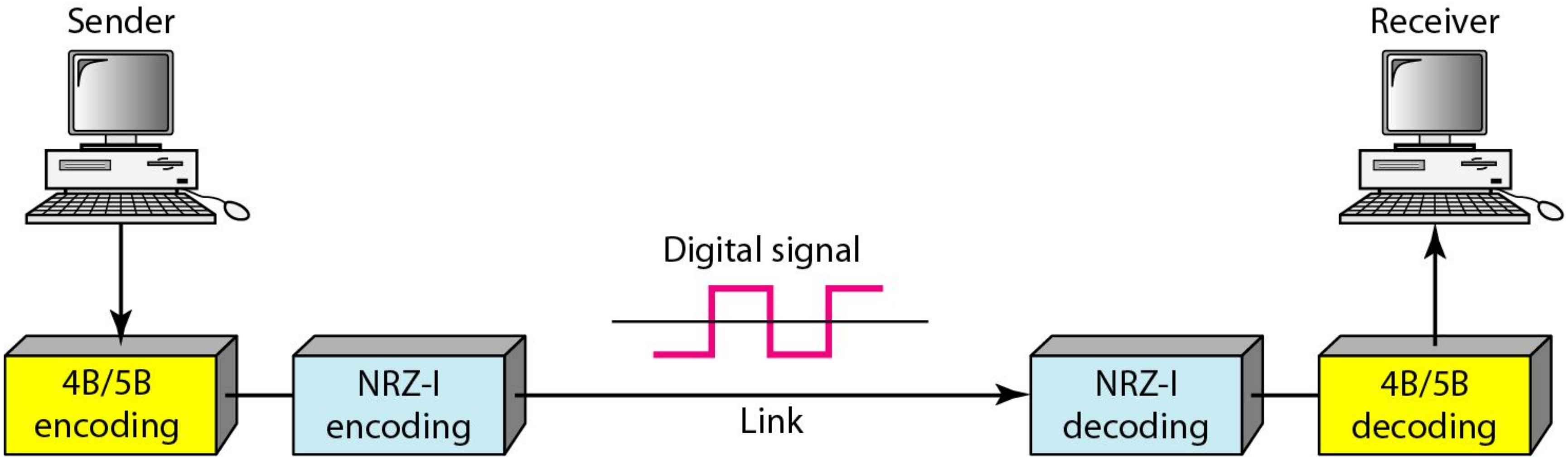
Block Coding (cont'd)

Figure 4.14 *Block coding concept*



Block Coding (cont'd)

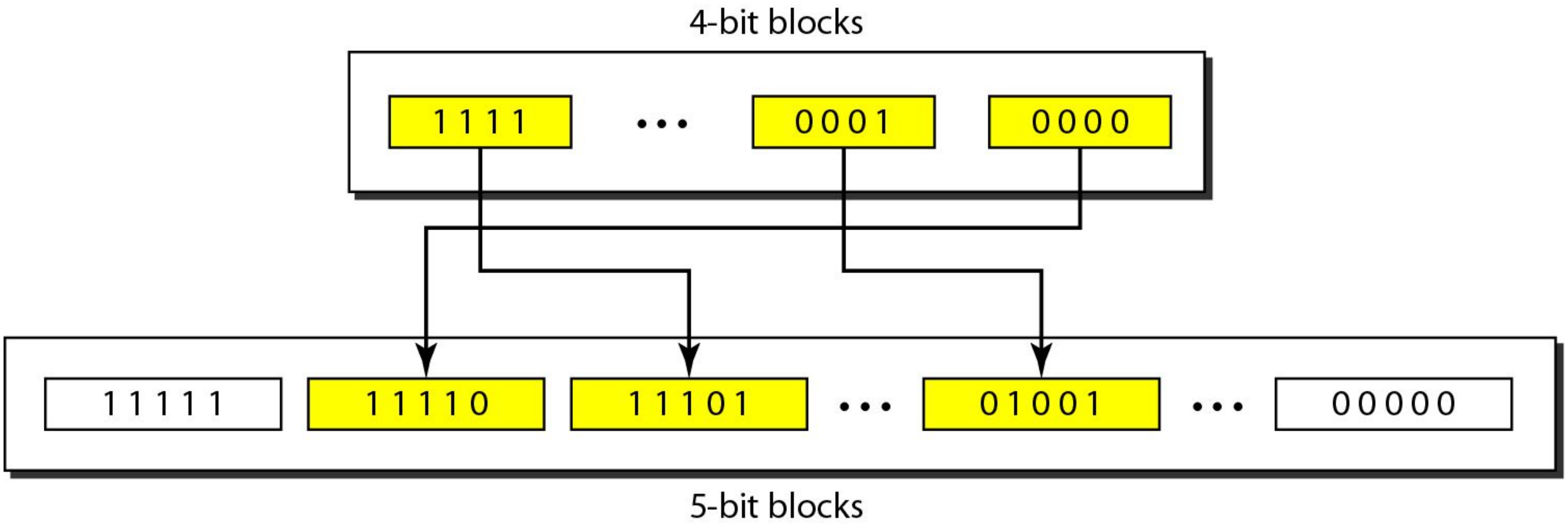
Figure 4.15 ***Using block coding 4B/5B with NRZ-I line coding scheme***



Ex) 100Base-FX

Block Coding (cont'd)

Figure 4.16 ***Substitution in 4B/5B block coding***



Block Coding (cont'd)

Table 4.2 ***4B/5B mapping codes***

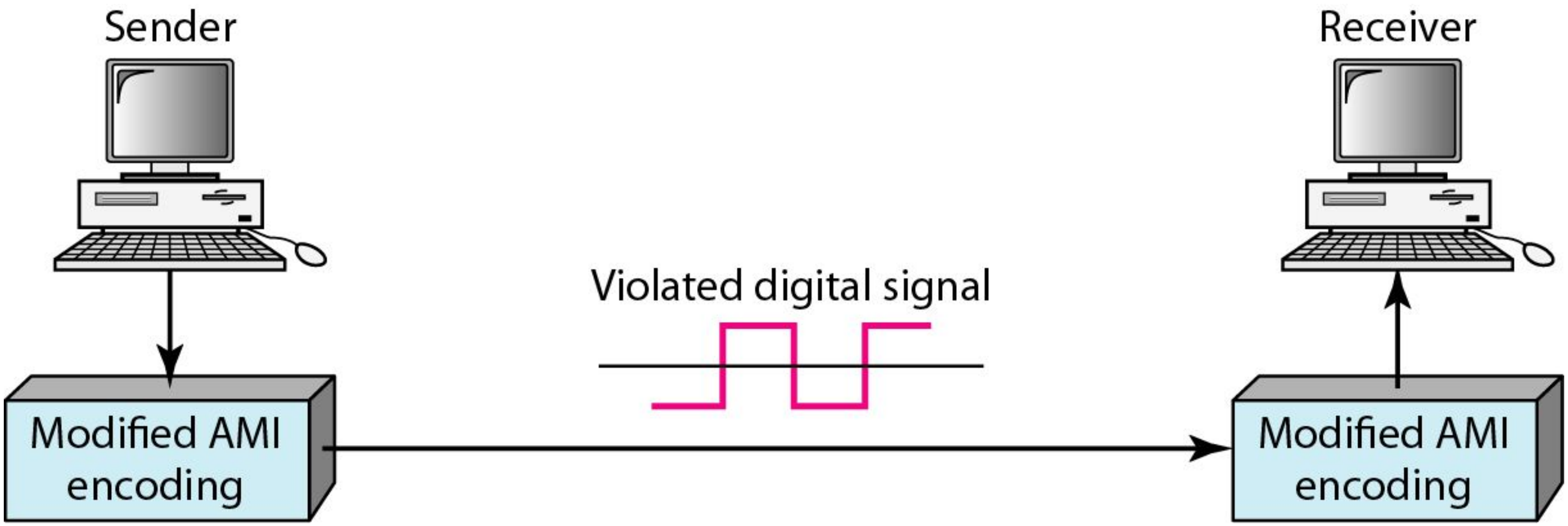
Data Sequence	*Encoded Sequence*	*Control Sequence*	*Encoded Sequence*
0000	11110	Q (Quiet)	00000
0001	01001	I (Idle)	11111
0010	10100	H (Halt)	00100
0011	10101	J (Start delimiter)	11000
0100	01010	K (Start delimiter)	10001
0101	01011	T (End delimiter)	01101
0110	01110	S (Set)	11001
0111	01111	R (Reset)	00111
1000	10010		
1001	10011		
1010	10110		
1011	10111		
1100	11010		
1101	11011		
1110	11100		
1111	11101		

Scrambling

- Biphase and the other scheme are not suitable for long-distance communication because of their wide bandwidth requirement and DC component.
- Scrambling substitutes long zero-level pulses with a combination of other levels to provide synchronization.
- Two common scrambling techniques are B8ZS and HDB3.

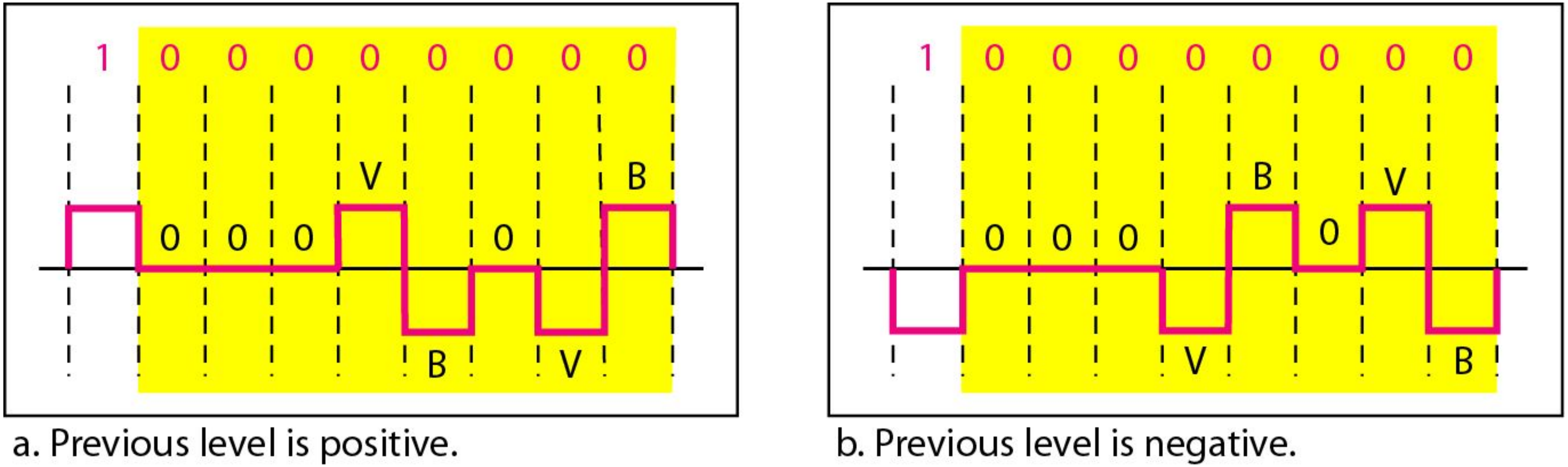
Scrambling (cont'd)

Figure 4.18 *AMI used with scrambling*



Scrambling (cont'd)

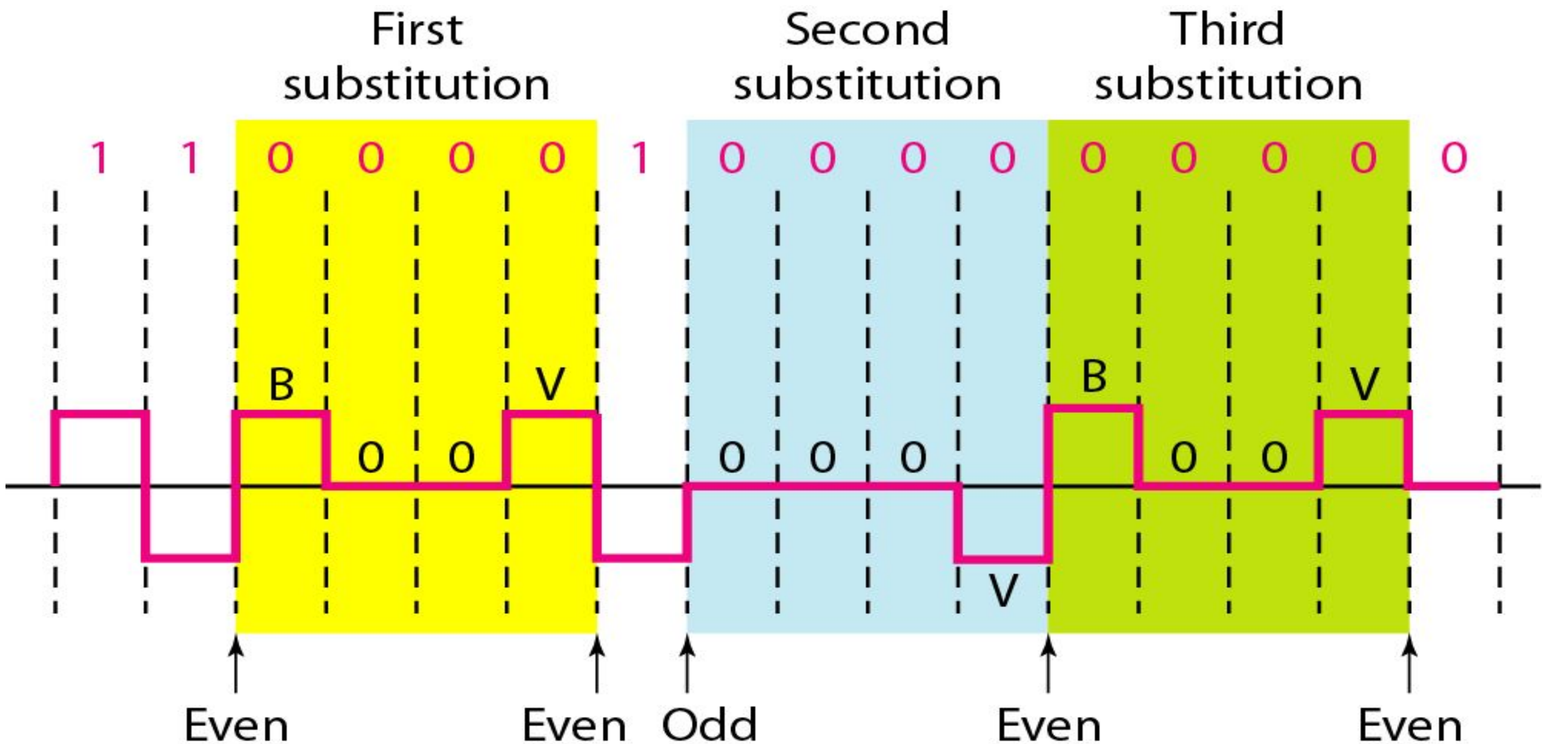
Figure 4.19 ***Two cases of B8ZS scrambling technique***



B8ZS substitutes eight consecutive zeros with 000VB0VB.

Scrambling (cont'd)

Figure 4.20 ***Different situations in HDB3 scrambling technique***



HDB3 substitutes four consecutive zeros with 000V or B00V depending on the number of nonzero pulses after the last substitution.

4.2 ANALOG-TO-DIGITAL CONVERSION

We have seen in Chapter 3 that a digital signal is superior to an analog signal. The tendency today is to change an analog signal to digital data. In this section we describe two techniques, pulse code modulation and delta modulation.

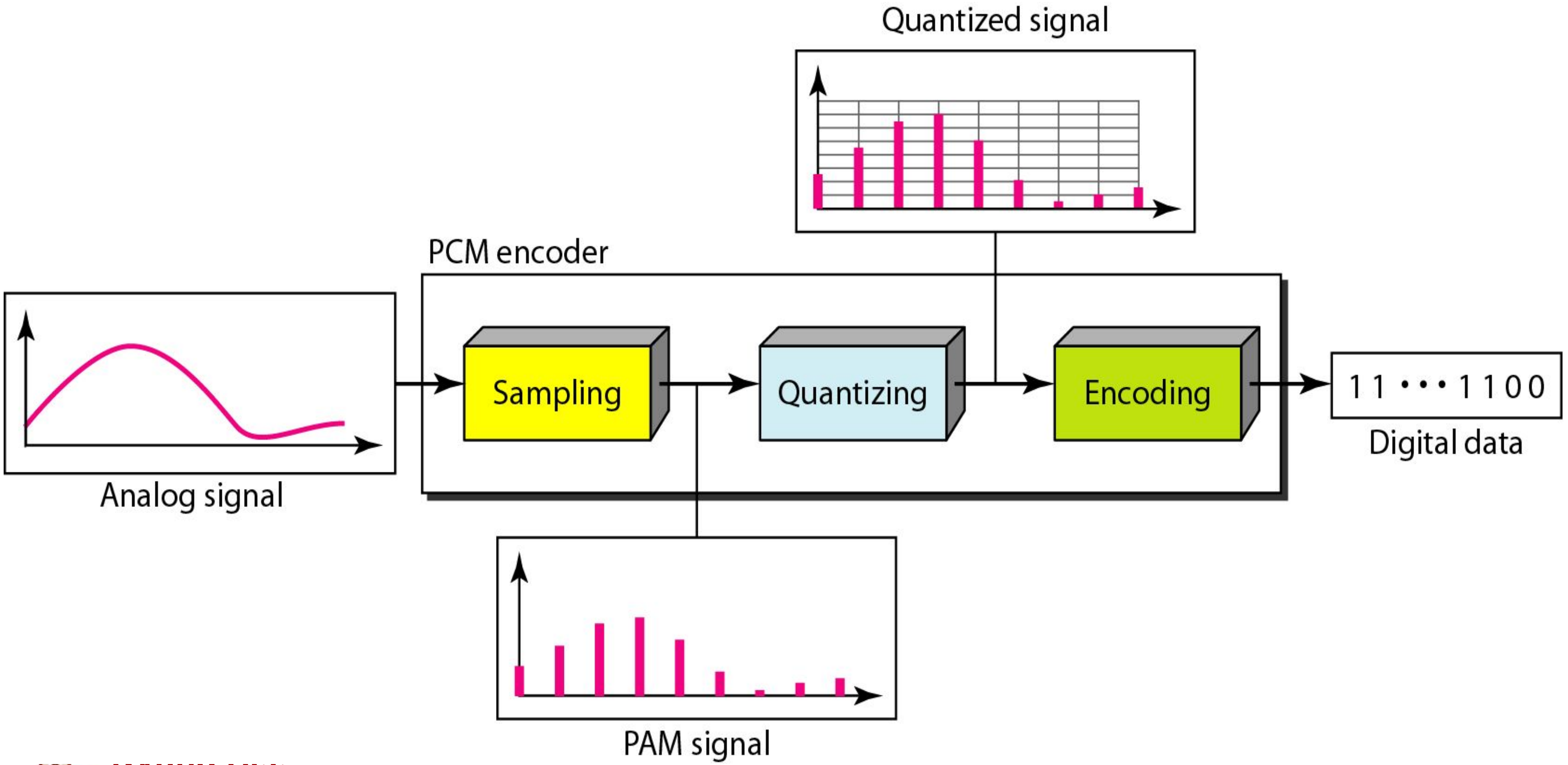
Topics discussed in this section:

Pulse Code Modulation (PCM)
Delta Modulation (DM)

Pulse Code Modulation (PCM)

- To change an analog signal to digital data (digitization) is called Pulse Code Modulation (PCM)

Figure 4.21 *Components of PCM encoder*



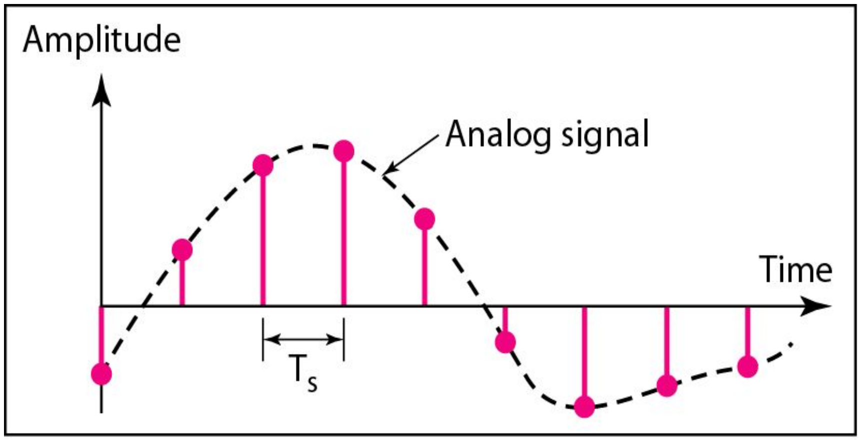
Sampling

- Pulse amplitude modulation has some applications, but it is not used by itself in data communication. However, it is the first step in another very popular conversion method called pulse code modulation.

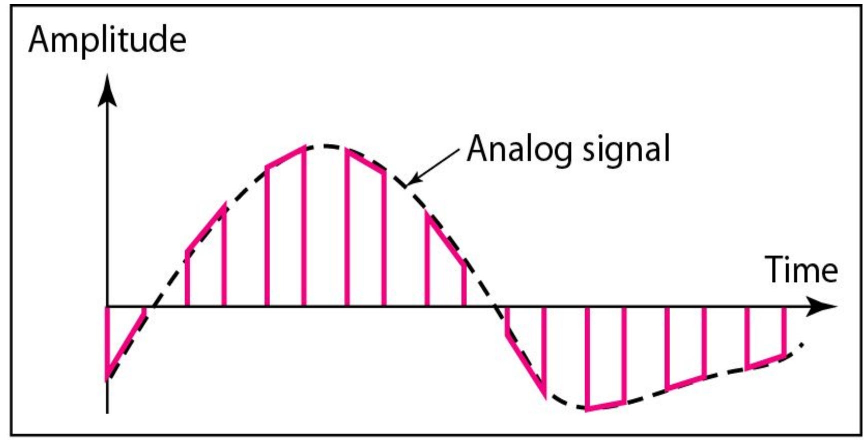
•Term *sampling* means measuring the amplitude of the signal at equal intervals.

Sampling (cont’d)

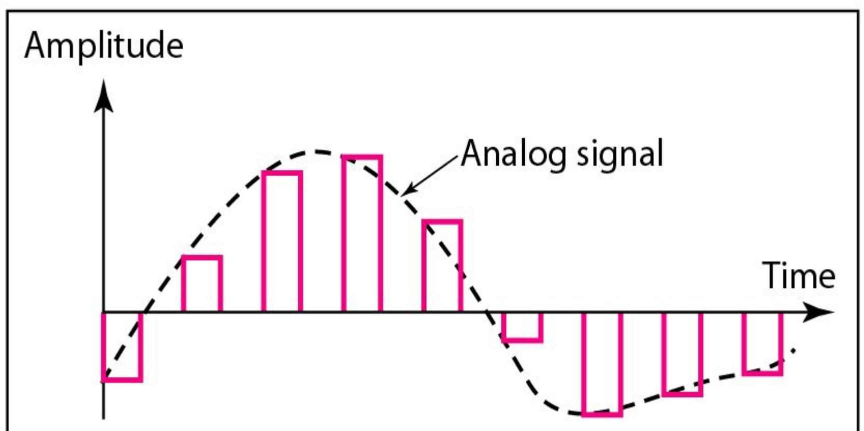
Figure 4.22 ***Three different sampling methods for PCM***



a. Ideal sampling



b. Natural sampling



c. Flat-top sampling

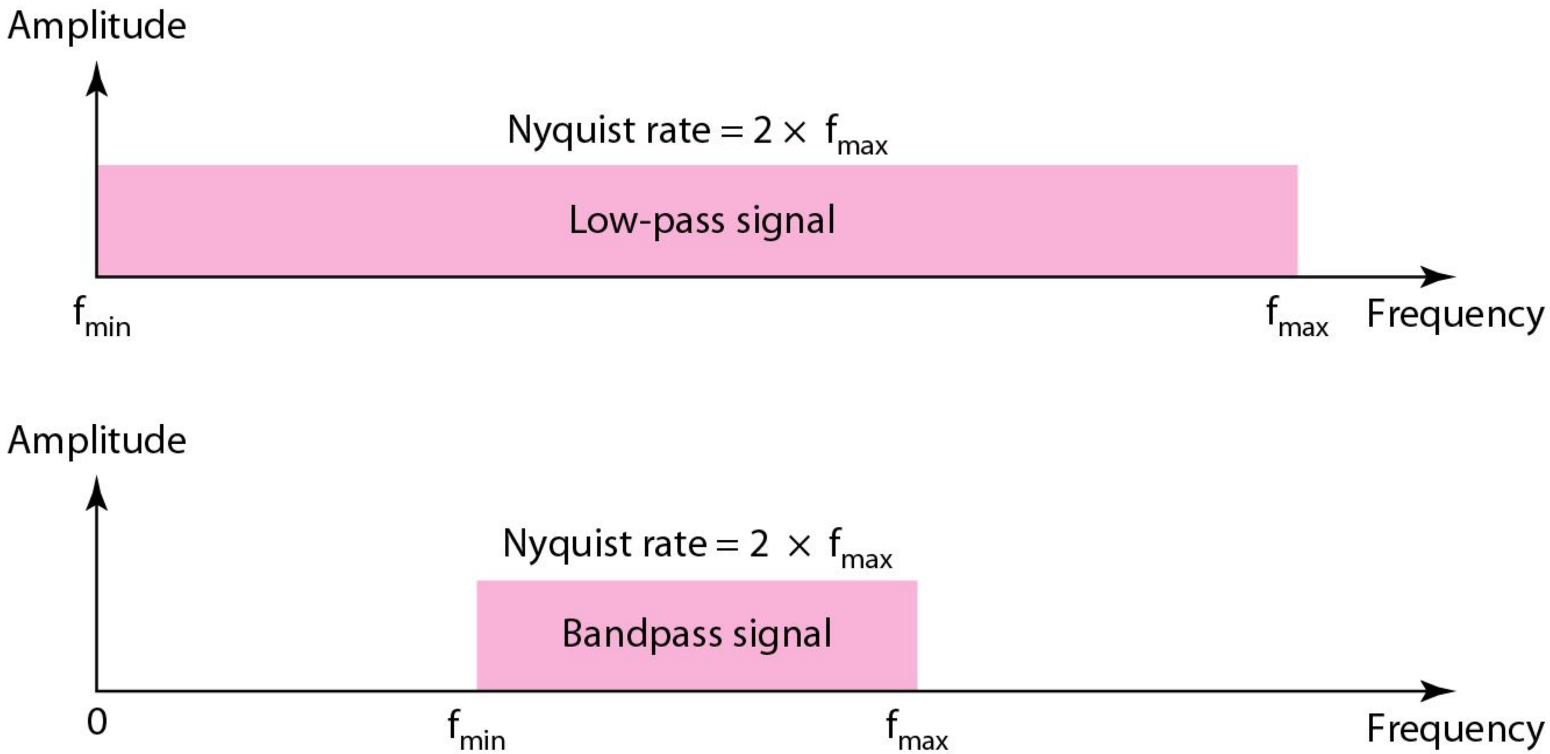
Sampling (cont'd)

Note

According to the Nyquist theorem, the sampling rate must be at least 2 times the highest frequency contained in the signal.

Sampling (cont'd)

Figure 4.23 *Nyquist sampling rate for low-pass and bandpass signals*



Sampling (cont'd)

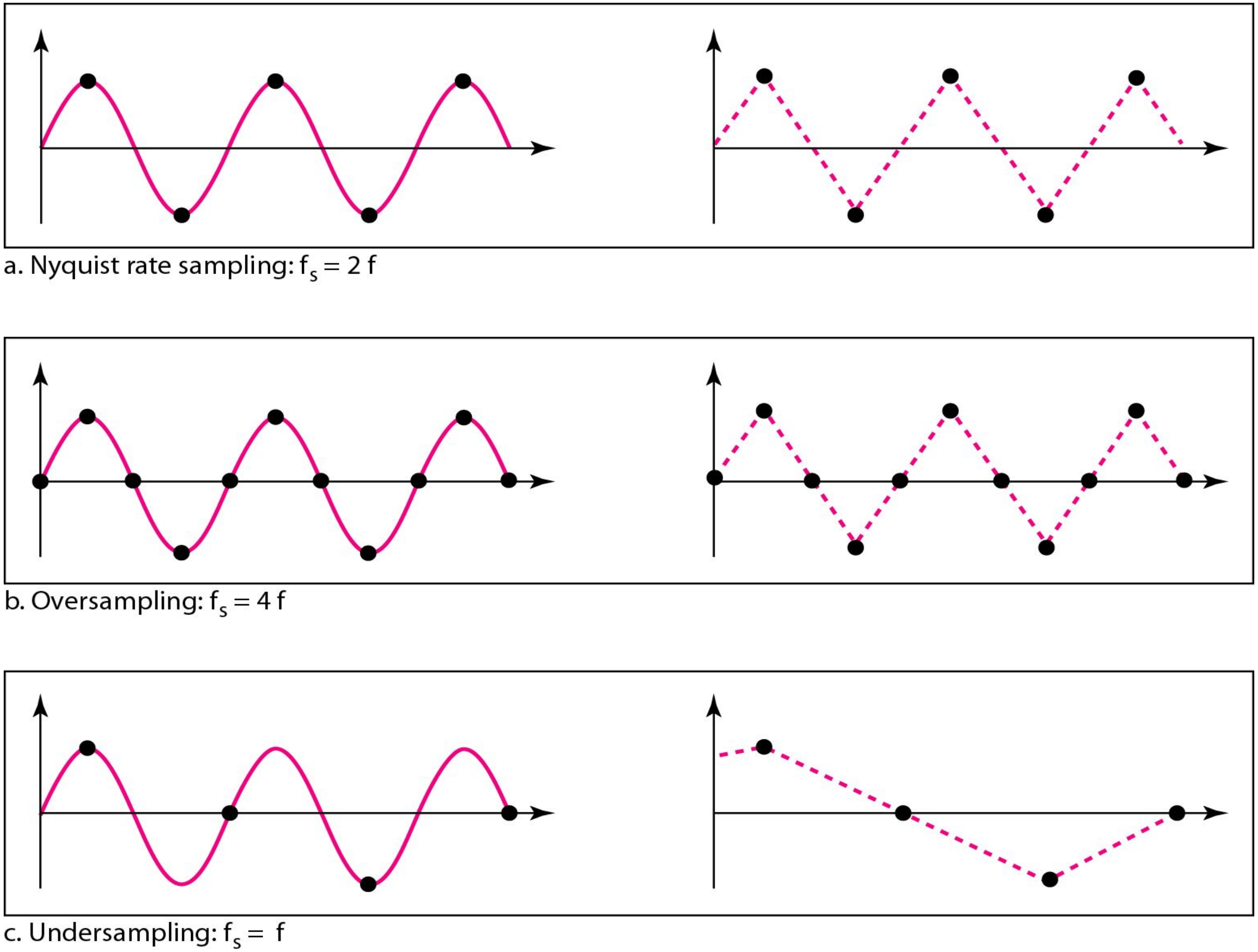
Example 4.6

For an intuitive example of the Nyquist theorem, let us sample a simple sine wave at three sampling rates: $f_s = 4f$ (2 times the Nyquist rate), $f_s = 2f$ (Nyquist rate), and $f_s = f$ (one-half the Nyquist rate). Figure 4.24 shows the sampling and the subsequent recovery of the signal.

It can be seen that sampling at the Nyquist rate can create a good approximation of the original sine wave (part a). Oversampling in part b can also create the same approximation, but it is redundant and unnecessary. Sampling below the Nyquist rate (part c) does not produce a signal that looks like the original sine wave.

Sampling (cont'd)

Figure 4.24 ***Recovery of a sampled sine wave for different sampling rates***



Sampling (cont'd)

Example 4.9

Telephone companies digitize voice by assuming a maximum frequency of 4000 Hz. The sampling rate therefore is 8000 samples per second.

Quantization

- The result of sampling is a series of pulses with amplitude values between the max. and min. amplitudes of the signal.
- These values cannot be used in the encoding process.
- The following are the steps in quantization:
  - Assume the original analog signal has instantaneous amplitudes between V_{min} and V_{max}.
  - Divide the range into L zones, each of height Δ (delta)

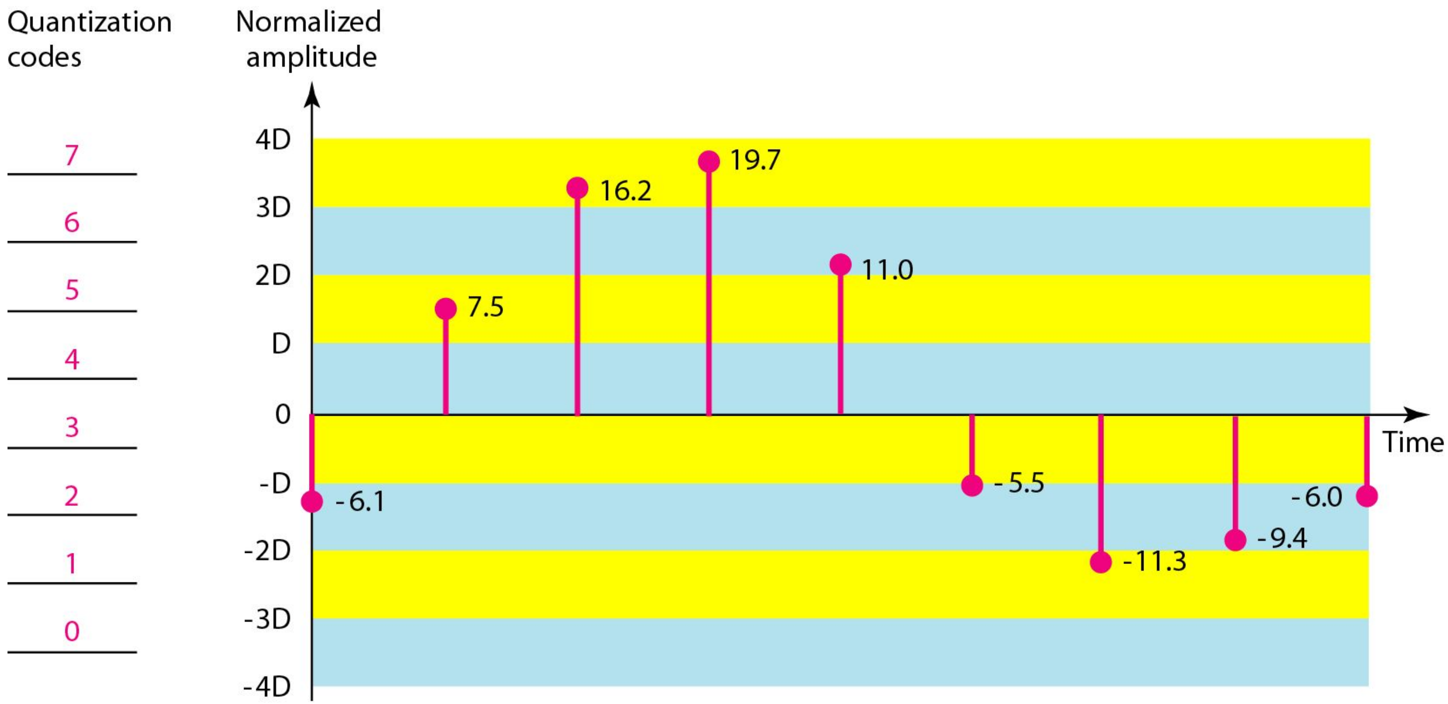
    $\Delta = (V_{max} - V_{min}) / L$
  - Assign quantized values of 0 to L-1 to the midpoint of each zone
  - Approximate the value of the sample amplitude to the quantized values.
- Quantization Error

$$SNR_{dB} = 6.02n_b + 1.76 \text{ dB}$$

N_b : bits per sample

Quantization (cont'd)

Figure 4.26 ***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

Quantization (cont'd)

Example 4.13

A telephone subscriber line must have an SNR_{dB} above 40. What is the minimum number of bits per sample?

Solution

We can calculate the number of bits as

$$\boxed{SNR_{dB} = 6.02n_b + 1.76 = 40 \;\Rightarrow\; n = 6.35}$$

Telephone companies usually assign 7 or 8 bits per sample.

Encoding

- The last step in PCM is encoding.
- After each sample is quantized and the number of bits per sample is decided, each sample can be changed to an n_b-bit code word.
- Bit Rate Formula
  - Bit rate = sampling rate x number of bits per sample = f_s x n_b
    - Where No. of quantization level : L , No. of bits (n_b)= $\log_2$ L

Example 4.14

We want to digitize the human voice. What is the bit rate, assuming 8 bits per sample?

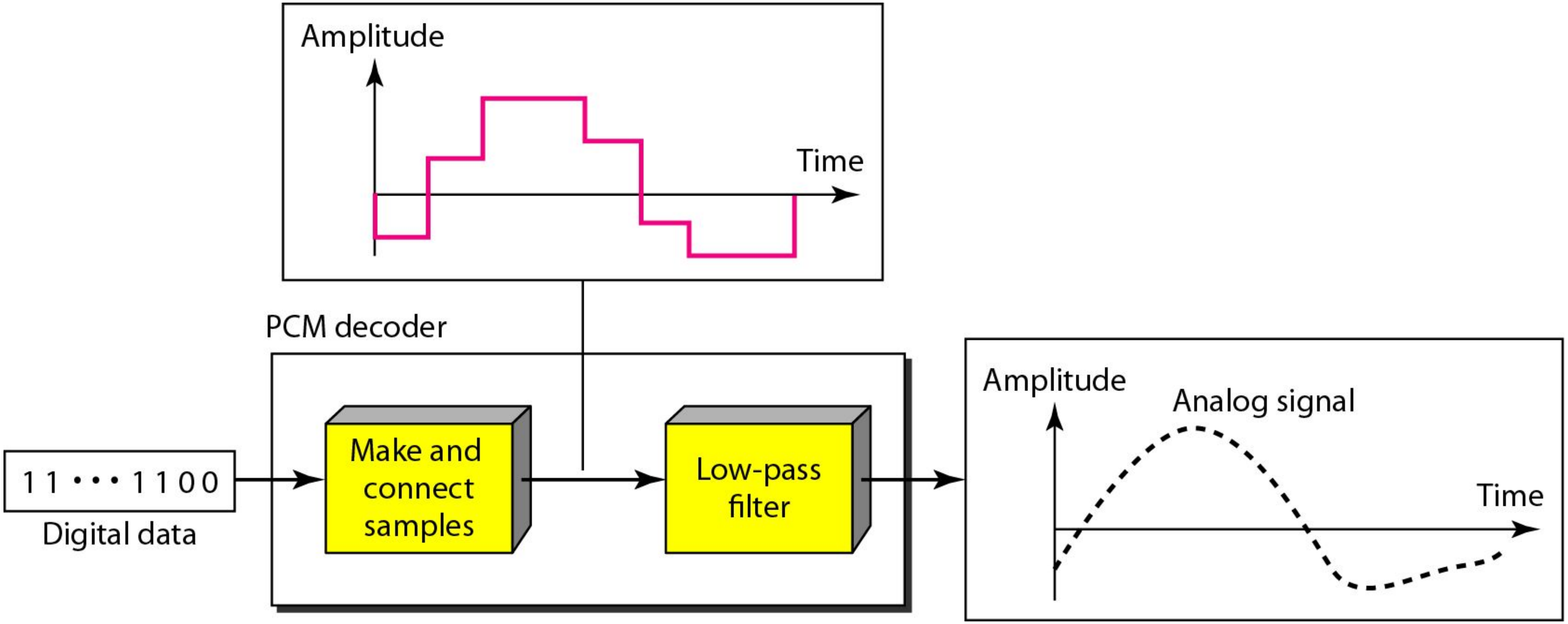
Solution

The human voice normally contains frequencies from 0 to 4000 Hz. So the sampling rate and bit rate are calculated as follows:

$$\text{Sampling rate} = 4000 \times 2 = 8000 \text{ samples/s}$$
$$\text{Bit rate} = 8000 \times 8 = 64{,}000 \text{ bps} = 64 \text{ kbps}$$

Original Signal Recovery

Figure 4.27 ***Components of a PCM decoder***



PCM Bandwidth

- If we digitized the signal, what is the new bandwidth of the channel ?
  - $B_{min} = c \times N \times 1/r = c \times n_b \times f_s \times 1/r = c \times n_b \times 2\ B_{analog} \times 1/r$
- The minimum bandwidth (1/r = 1 for NRZ or bipolar, c= 1/2)
  - $B_{min} = n_b \times B_{analog}$
- The maximum data rate of a Channel
  - $N_{max} = 2 \times B \times \log_2 L$ (bps)
- The minimum bandwidth
  - $B_{min} = N / (2 \times \log_2 L)$ (Hz)

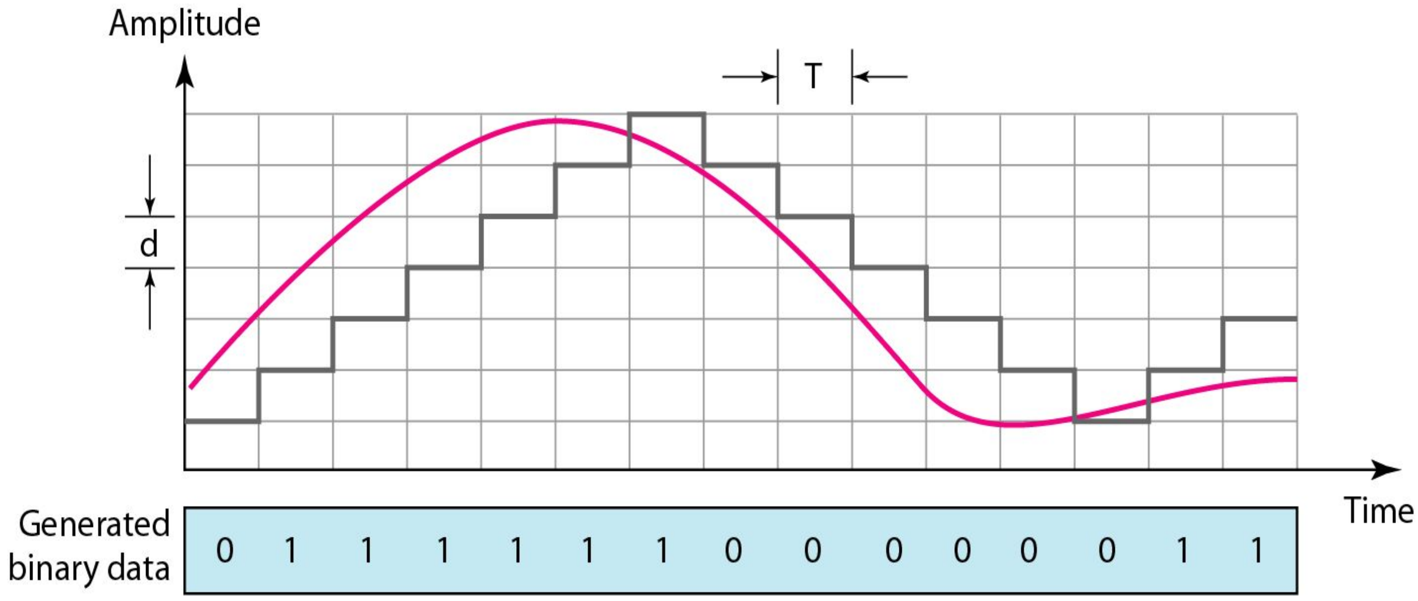
Example 4.15

We have a low-pass analog signal of 4 kHz. If we send the analog signal, we need a channel with a minimum bandwidth of 4 kHz. If we digitize the signal and send 8 bits per sample, we need a channel with a minimum bandwidth of 8 × 4 kHz = 32 kHz.

Delta Modulation

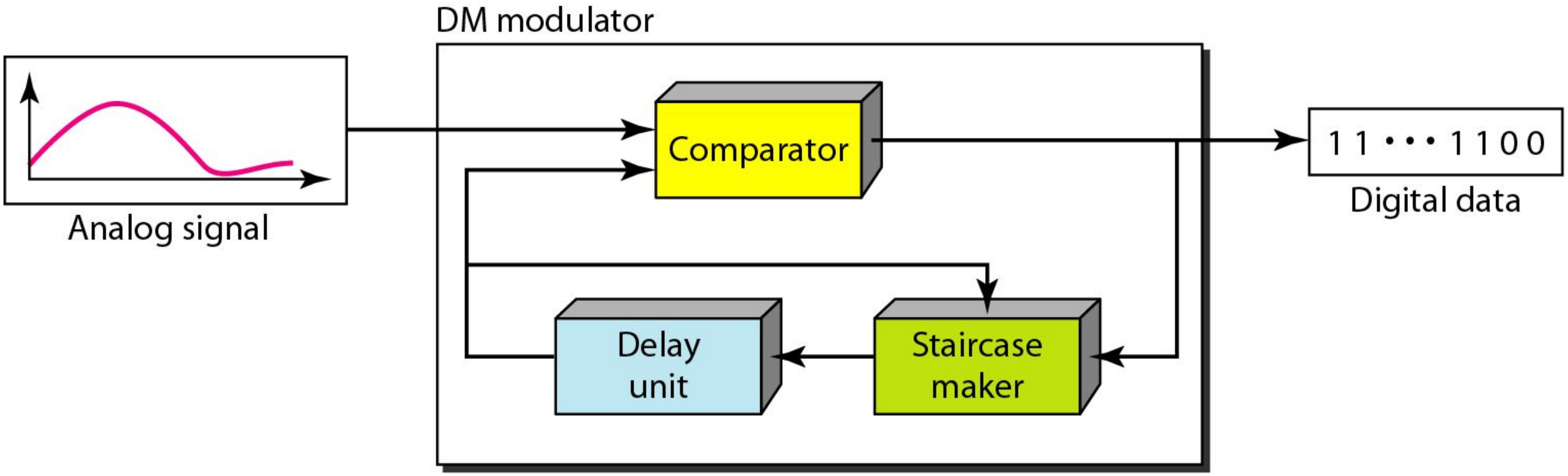
- Delta Modulation (DM) techniques have been developed to reduce the complexity of PCM.
- PCM finds the value of the signal amplitude for each sample; DM finds the change from the previous sample.

Figure 4.28 *The process of delta modulation*



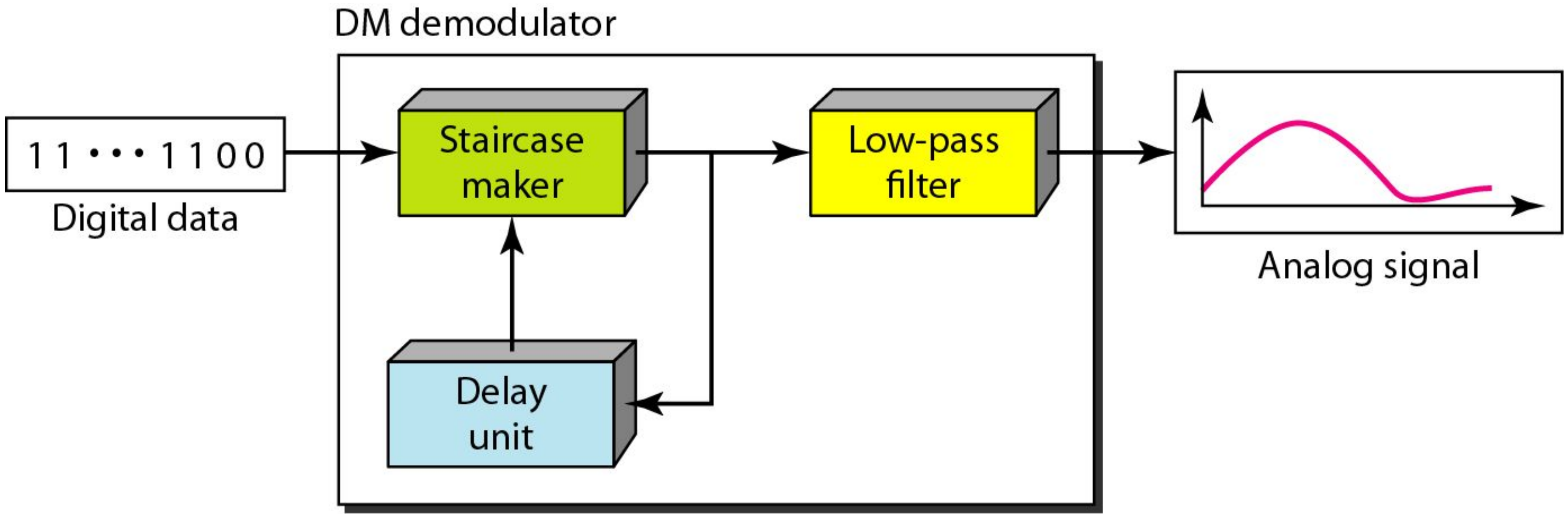
Delta Modulation (cont'd)

Figure 4.29 ***Delta modulation components***



Delta Modulation (cont'd)

Figure 4.30 ***Delta demodulation components***



4.3 TRANSMISSION MODES

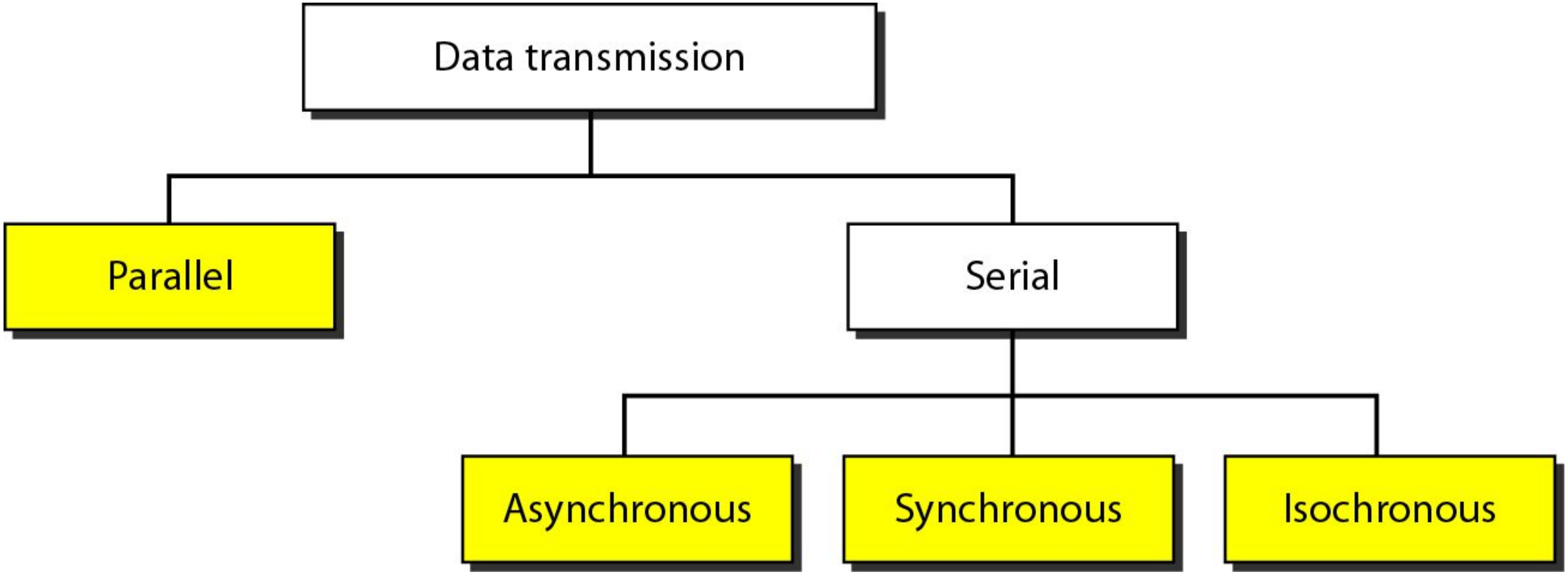
The transmission of binary data across a link can be accomplished in either parallel or serial mode. In parallel mode, multiple bits are sent with each clock tick. In serial mode, 1 bit is sent with each clock tick. While there is only one way to send parallel data, there are three subclasses of serial transmission: asynchronous, synchronous, and isochronous.

Topics discussed in this section:

Parallel Transmission
Serial Transmission

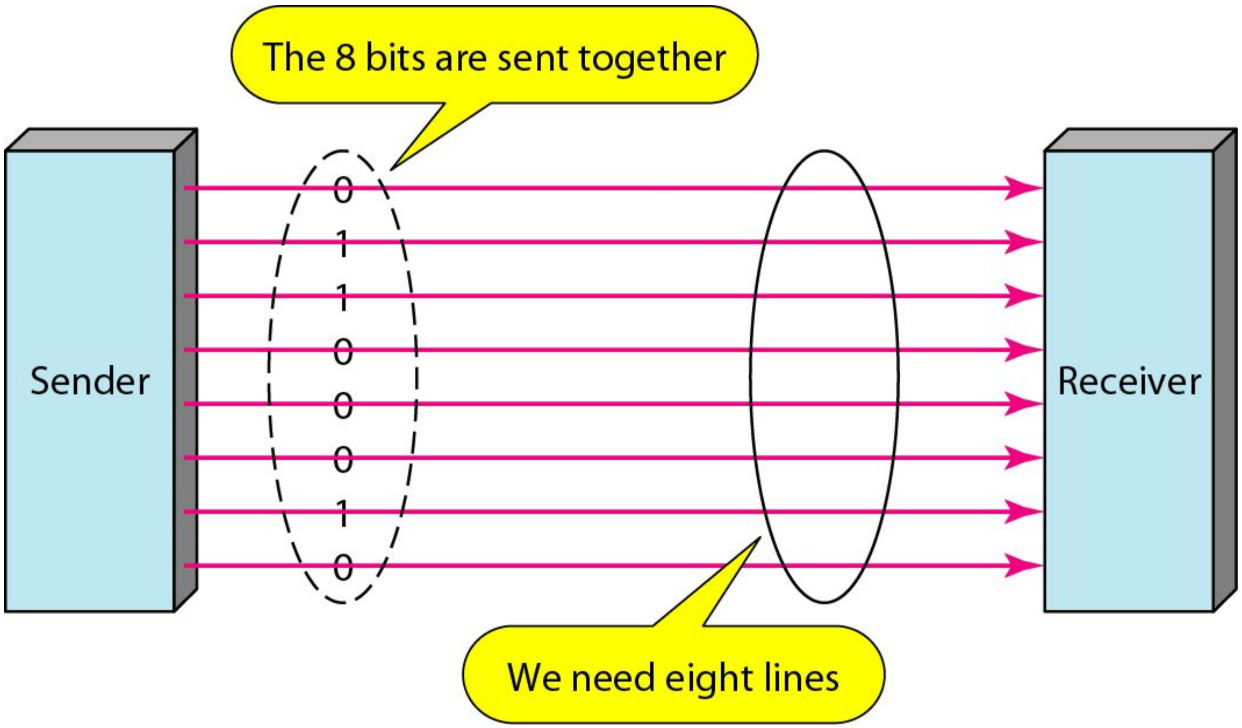
Transmission Modes

Figure 4.31 ***Data transmission and modes***



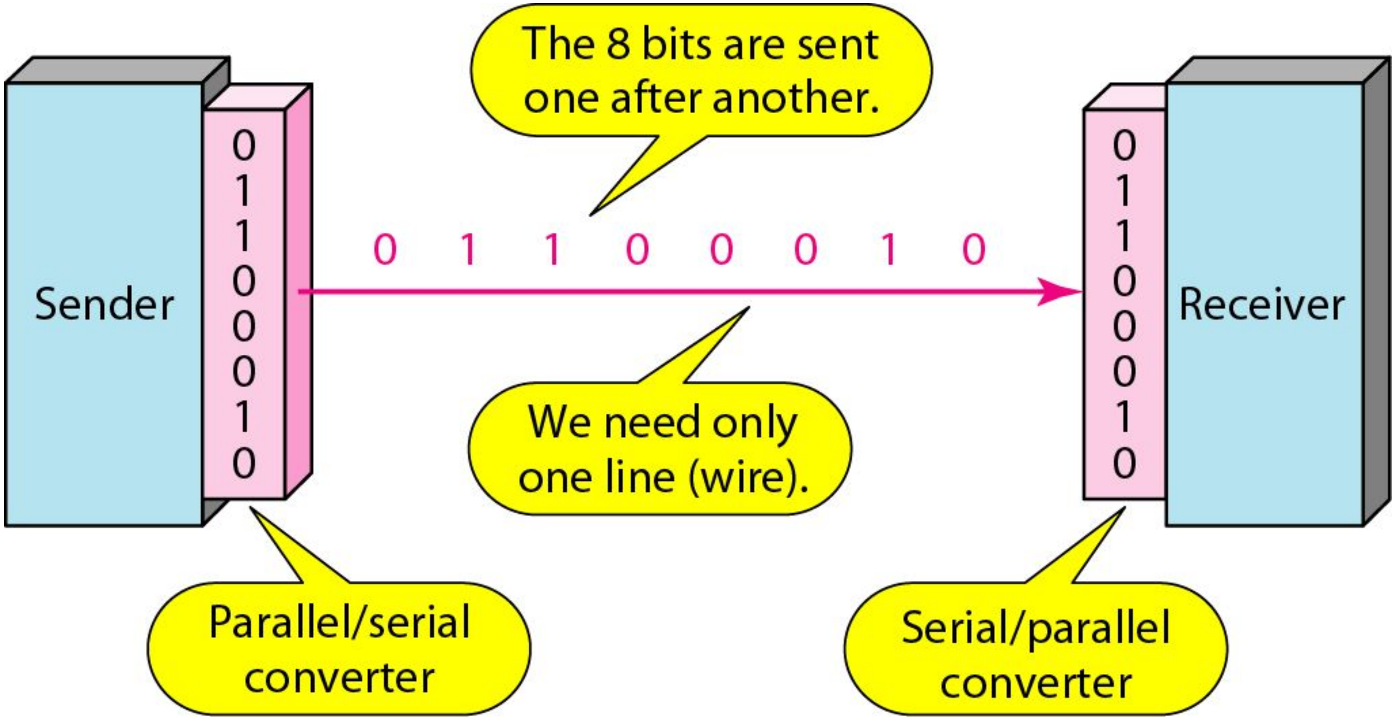
Transmission Modes (cont'd)

Figure 4.32 ***Parallel transmission***



Transmission Modes (cont'd)

Figure 4.33 ***Serial transmission***



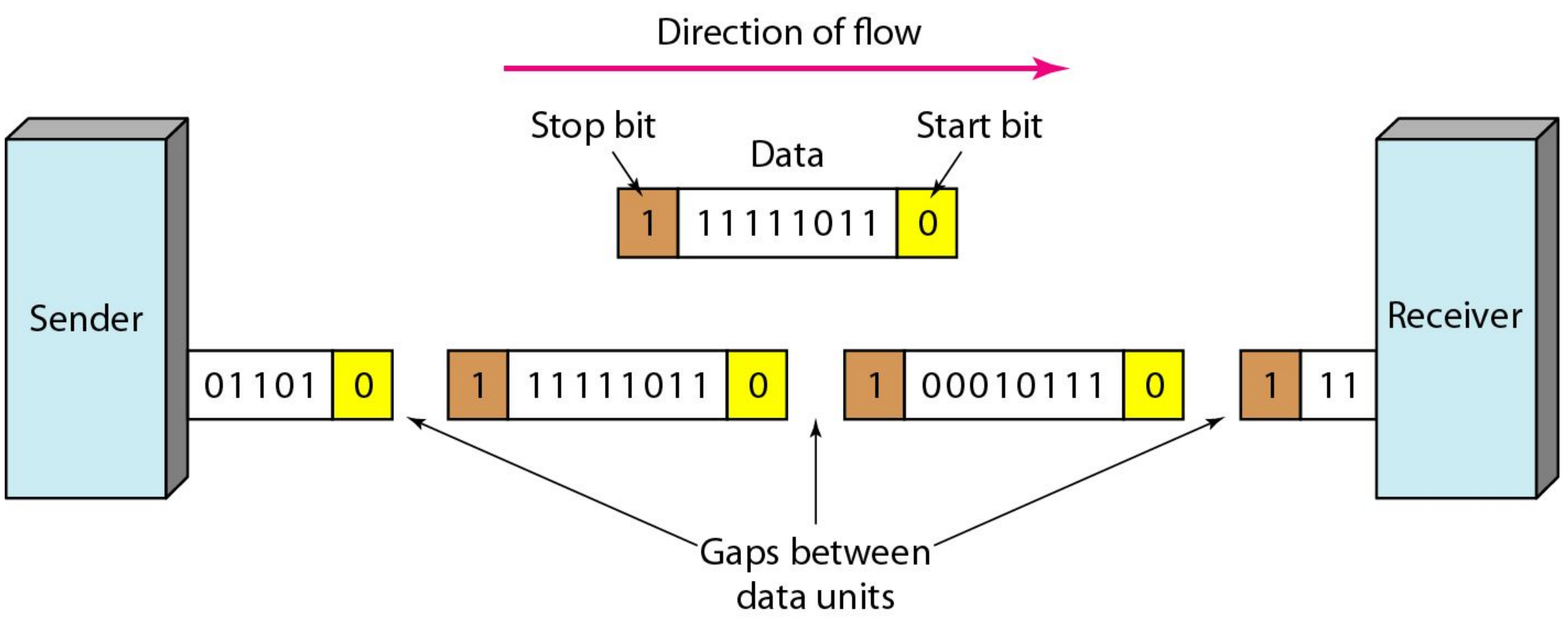
Transmission Modes (cont'd)

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.

Asynchronous here means "asynchronous at the byte level," but the bits are still synchronized; their durations are the same.

Transmission Modes (cont'd)

Figure 4.34 *Asynchronous transmission*

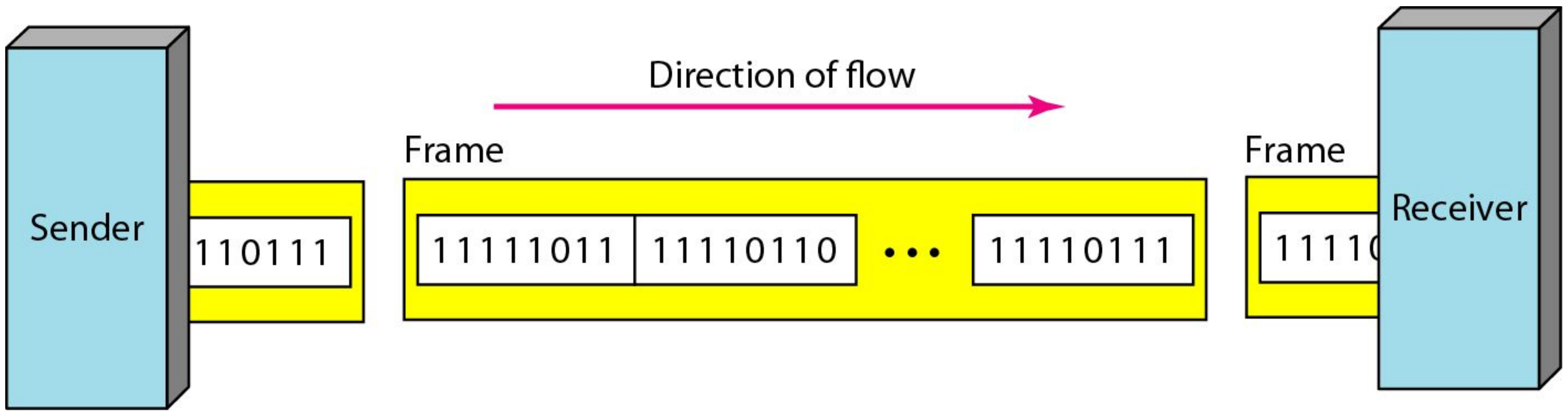


Transmission Modes (cont'd)

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.

Transmission Modes (cont'd)

Figure 4.35 ***Synchronous transmission***



Transmission Modes (cont'd)

- **Isochronous transmission**

  - In the real-time audio and video, in which uneven delays between frames are not acceptable, synchronous transmission fails.
  - TV images are broadcast at the rate of 30 images per second;
    - They must be viewed at the same rate
    - the entire stream of bits must be synchronized
  - The isochronous transmission guarantees that the data arrive at a fixed rate

Summary (1)

- Digital-to-digital conversion involves three techniques: line coding, block coding and scrambling.
- The most common technique to change an analog signal to digital date(digitization) is called pulse code modulation (PCM).
- According to the Nyquist theorem, to reproduce the original analog signal, one necessary condition is that the sampling rate be at least twice the highest frequency in the original signal.
- Other sampling techniques have been developed to reduce the complexity of PCM, The simplest one is delta modulation. PCM finds the value of the signal amplitude for each sample; DM finds the change from the previous sample.

Summary(2)

- There are three subclasses of serial transmission: asynchronous, synchronous, and isochronous

Q & A