Chapter 4

Digital Transmission

Introduction

- A computer network is designed to send information from one point to another.
- Information needs to be converted to either a digital signal or an analog signal for transmission.
- Digital-to-Digital Conversion
- Analog-to-Digital Conversion
- Transmission Modes

Digital-to-Digital Conversion

- Data – Digital or Analog
- Signal – Digital or Analog
- Representation of digital data 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.

Line Coding

- is a process of converting a string of bits in form of 1's and 0's (digital data) into digital signals.
- At sender, digital data are encoded into a digital signal; at receiver, the digital signal is decoded to recreate the digital data.
- For example a high voltage level (+V) could represent a "1" and a low voltage level (0 or -V) could represent a "0".

Line Coding (Conti...)

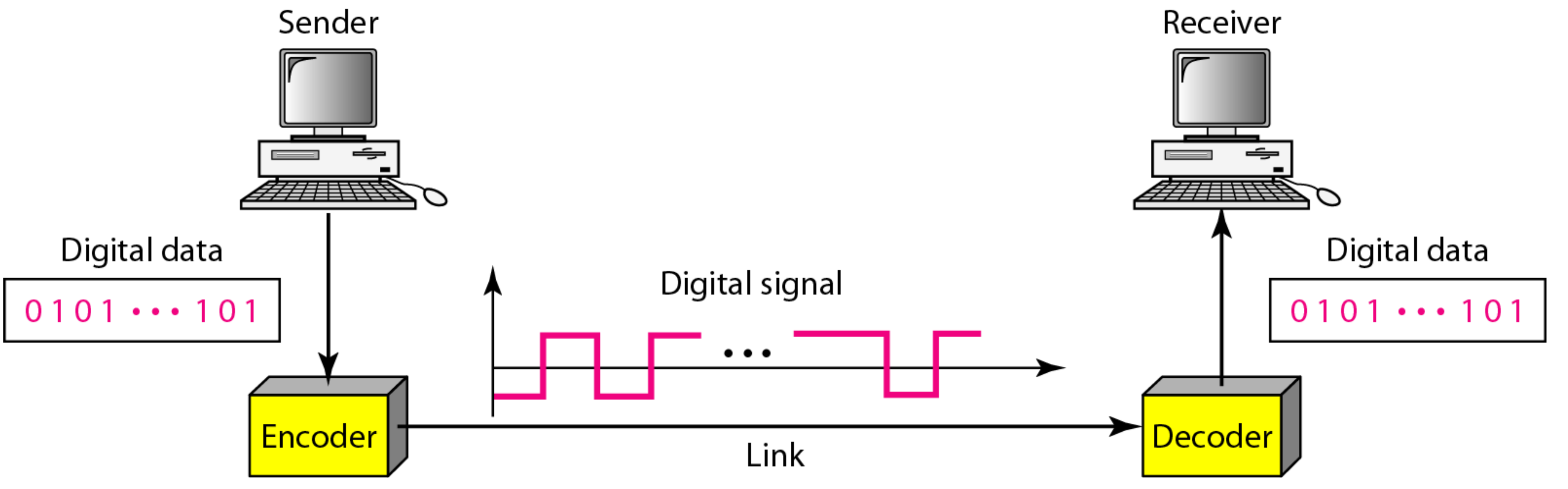


Figure 4.1 *Line coding and decoding*

Line Coding (Conti...)

- In data communication, the goal is to send data element.
- A data element is the smallest entity representing a piece of information (bit) while a signal element is the shortest unit (time-wise) of signal that carries the data elements.
- Data elements need to send while signal elements are what can send.
- Data elements are being carried while signal elements are the carriers.

Line Coding - Mapping Data symbols onto Signal levels

- A data symbol (or element) can consist of a number of data bits:
  - 1 , 0 or
  - 11, 10, 01, ……
- A data symbol can be coded into a single signal element or multiple signal elements
  - 1 -> +V, 0 -> -V
  - 1 -> +V and -V, 0 -> -V and +V
- The ratio ‘r’ is the number of data elements carried by a signal element.

Line Coding - Mapping Data symbols onto Signal levels (Conti...)

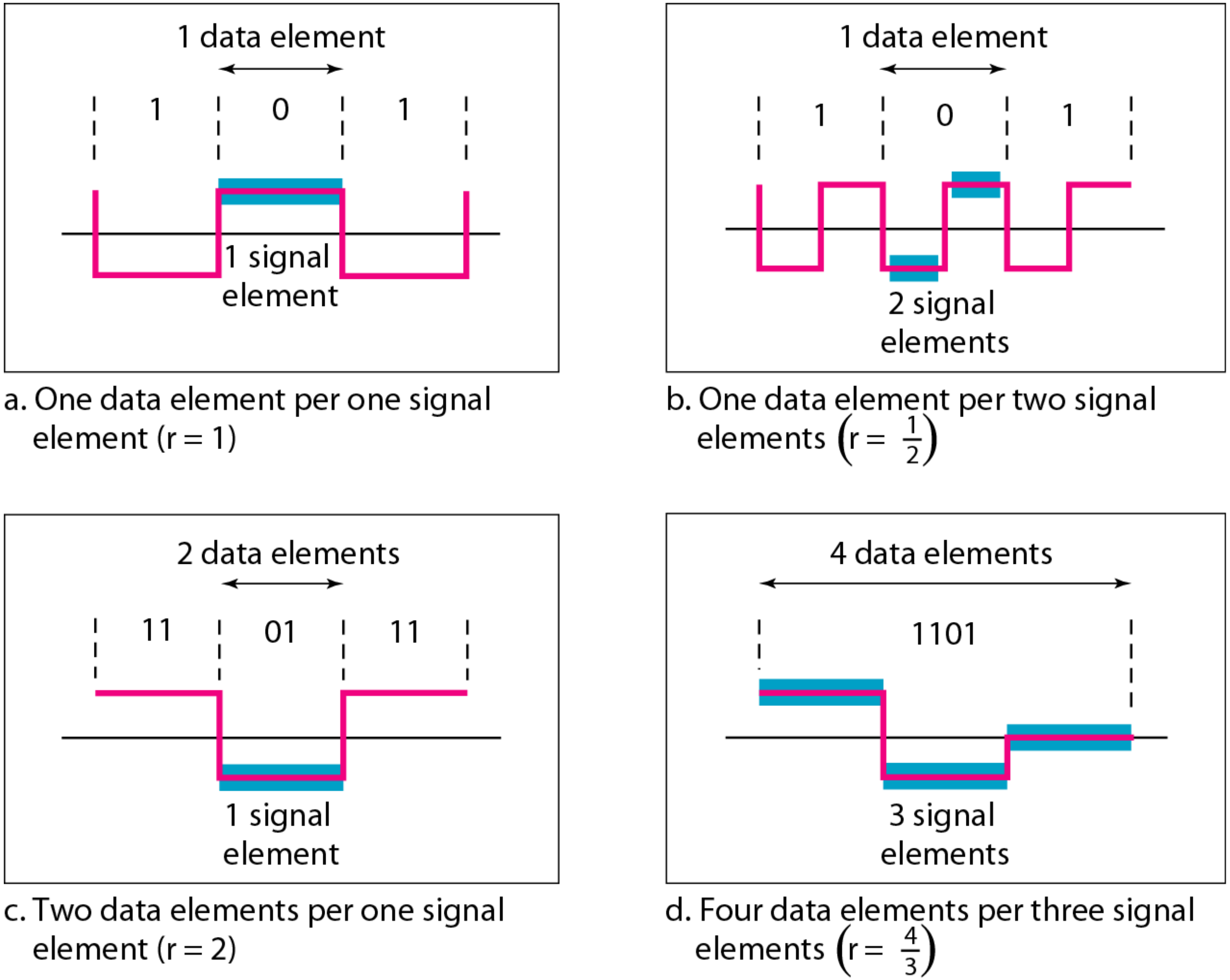


Figure 4.2 *Signal element versus data element*

Line Coding – Data Rate and Signal Rate

- The data rate defines the number of bits sent per sec - bps. It is often referred to the bit rate.
- The signal rate is the number of signal elements sent in a second and is measured in bauds. It is also referred to as pulse rate, modulation rate or baud rate.
- Goal is to increase the data rate whilst reducing the baud rate.
- Increasing the data rate increases the speed of transmission and decreasing the signal rate decreases the bandwidth requirement.

Line Coding – Data Rate and Signal Rate (Conti...)

- The baud or signal rate can be expressed as:

$S = c \times N \times 1/r$ bauds

where N is data rate

c is the case factor (worst, best & avg.)

r is the ratio between data element & signal element

Line Coding – Data Rate and Signal Rate (Conti...)

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

Line Coding – Bandwidth

- The digital signal that carries information is non-periodic.
- The bandwidth of a non-periodic signal is continuous with infinite range.
- Most of real life digital signals have bandwidth with finite values.
- Theoretically the bandwidth of non-periodic signals is infinite but many of the components with small amplitude can be ignored.
- The effective bandwidth is finite.

Line Coding – Baseline Wandering

- In decoding a digital signal, the receiver calculates a running average of the received signal power known as baseline.
- The incoming signal power is evaluated against the baseline to determine the value of data element.
- A long string of 0s and 1s will cause drift in the baseline (baseline wandering) and causes errors while decoding the incoming signal.
- A good line encoding scheme will prevent long runs of fixed amplitude.

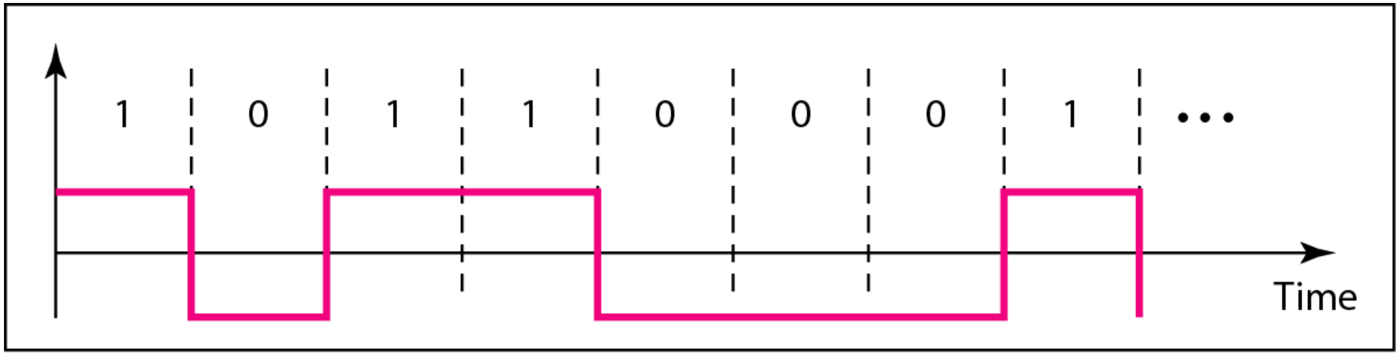
Line Coding – DC Components

- When the voltage level remains constant for long periods of time, there is an increase in the low frequencies of the signal (results of Fourier analysis).
- Most channels are band-pass and may not support the low frequencies.
- For example, telephone line cannot pass frequencies below 200Hz.
- A good line encoding scheme will remove the DC components.

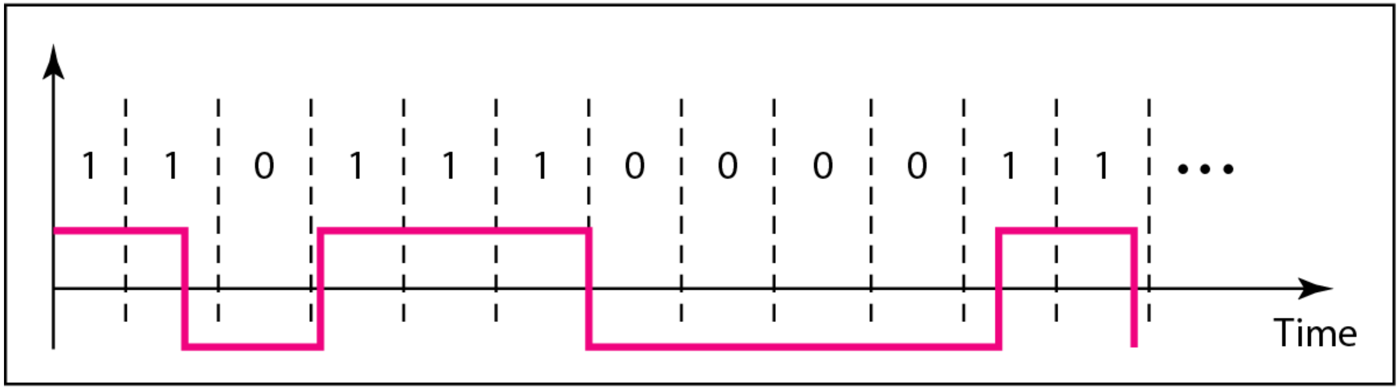
Line Coding – Self Synchronization

- The clocks at the sender and the receiver must have the same bit interval.
- If the receiver clock is faster or slower it will misinterpret the incoming bit stream.
- A self-synchronizing digital signal including the timing information is being transmitted to synchronize the clocks for both the sender and the receiver.

Line Coding – Self Synchronization (Conti...)



a. Sent



b. Received

Figure 4.3 *Effect of lack of synchronization*

Line Coding – Self Synchronization (Conti...)

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 – Built-in Error Detection

- Errors occur during transmission due to line impairments.
- Some codes are constructed with built-in error detection capabilities i.e. when an error occurs it can be detected.
- For example, a particular signal transition is not part of the code. When it occurs, the receiver will know that a symbol error has occurred.

Line Coding – Immunity to Noise and Interference

- Noise and interference - there are line encoding techniques that make the transmitted signal "immune" to noise and interference.
- This means that the signal cannot be corrupted, it is stronger than error detection.

Line Coding – Complexity

- The more robust and resilient the code, the more complex it is to implement.
- The price is often paid in baud rate or required bandwidth.
- For example, a scheme that uses four signal levels is more difficult to interpret than one that uses only two levels.

Line Coding Schemes

- The line coding schemes are roughly divided into five broad categories:
  - Unipolar
  - Polar
  - Bipolar
  - Multilevel
  - Multi-transition
- Each category has several schemes.

Line Coding Schemes (Conti...)

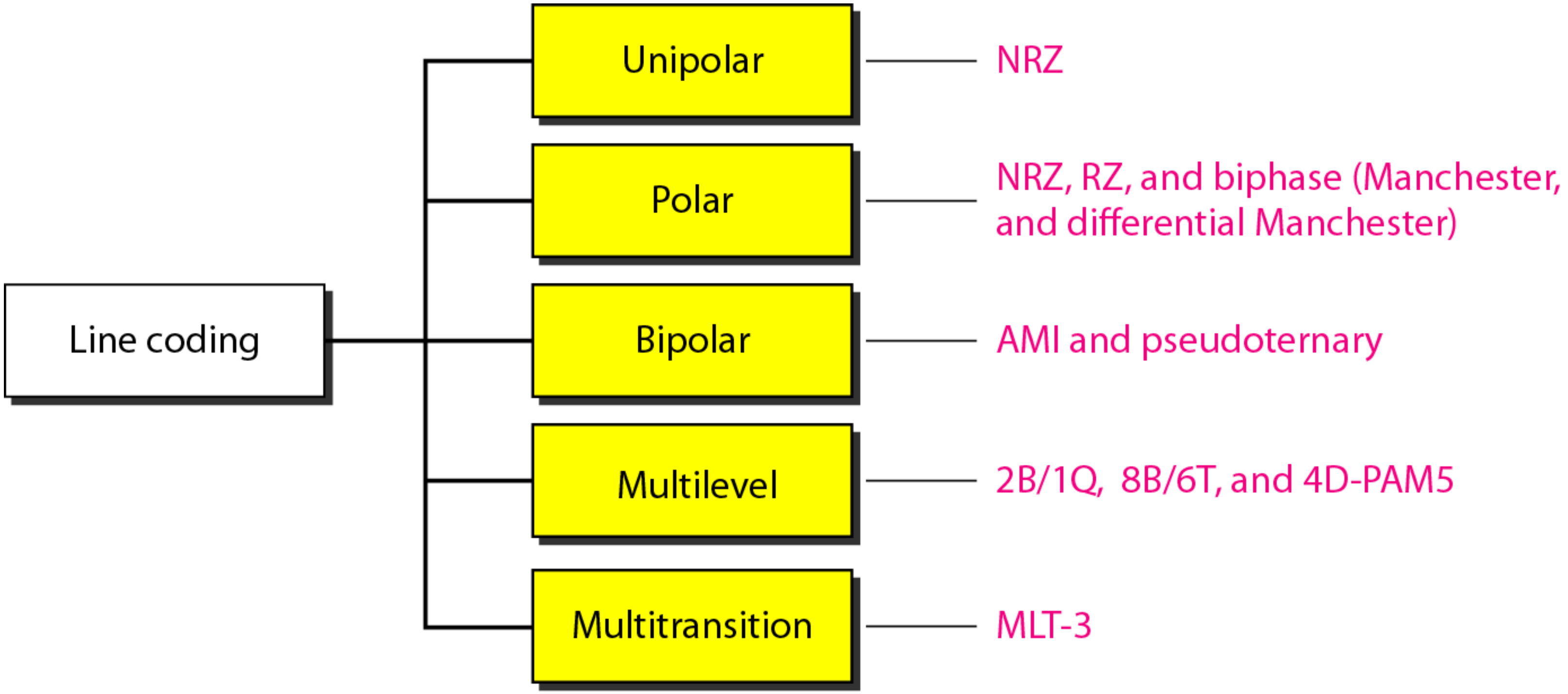
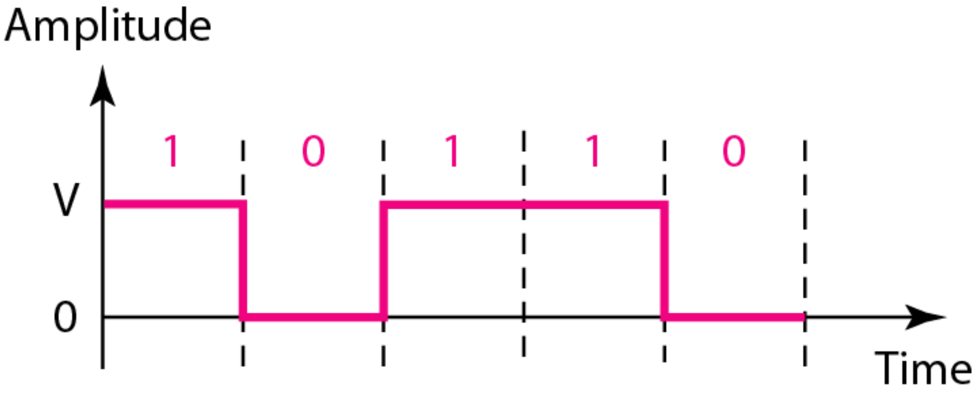


Figure 4.4 *Line coding schemes*

Unipolar – NRZ (Non Return to Zero)

- In NRZ the positive voltage defines bit 1 while zero voltage define bit 0.
- Known as NRZ because the signal does not return to zero during the middle of the bit.
- NRZ is prone to baseline wandering and DC components.
- It has no synchronization or any error detection.
- It is simple but costly in power consumption.

Unipolar – NRZ (Conti...)



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

Figure 4.5 *Unipolar NRZ scheme*

Polar – NRZ (Non Return to Zero)

- In Polar NRZ two voltage levels are used.
- Two version of polar NRZ: NRZ-L and NRZ-I.
- NRZ-L (NRZ-Level): voltage level determines the value of the bit.
- NRZ-I (NRZ-Inverted): the change or lack of change in voltage level determines the value of next bit.
    - If there is no change, the next bit is 0; if there is a change, the next bit is 1.

Polar – NRZ (Conti...)

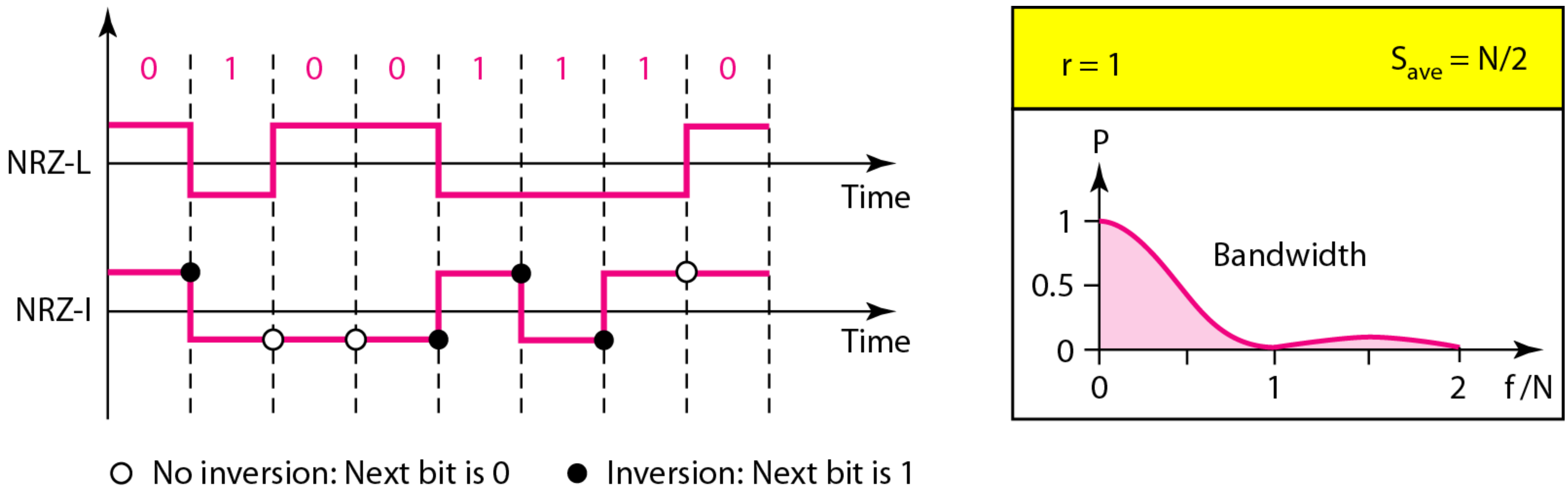


Figure 4.6 *Polar NRZ-L and NRZ-I schemes*

Polar – NRZ (Conti...)

- NRZ-L and NRZ-I both have an average signal rate of N/2 Bd.
- NRZ-L and NRZ-I both have a DC component problem and baseline wandering, it is worse for NRZ-L.
- Both have no self synchronization and no error detection.
- Both are relatively simple to implement.

Polar – NRZ (Conti...)

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= c x N x R = 1/2 x N x 1 = 500 kbaud. The minimum bandwidth for this average baud rate is Bmin = S = 500 kHz.

Note c = 1/2 for the avg. case as worst case is 1 and best case is 0.

Polar – RZ (Return to Zero)

- The RZ scheme uses three voltage values: positive (+), zero (0), and negative (-).
- Each symbol has a transition in the middle. Either from high to zero or from low to zero.
- This scheme has more signal transitions (two per symbol) and therefore requires a wider bandwidth.
- No DC components or baseline wandering.
- Self synchronization - transition indicates symbol value.
- More complex as it uses three voltage level. It has no error detection capability.

Polar – RZ (Conti...)

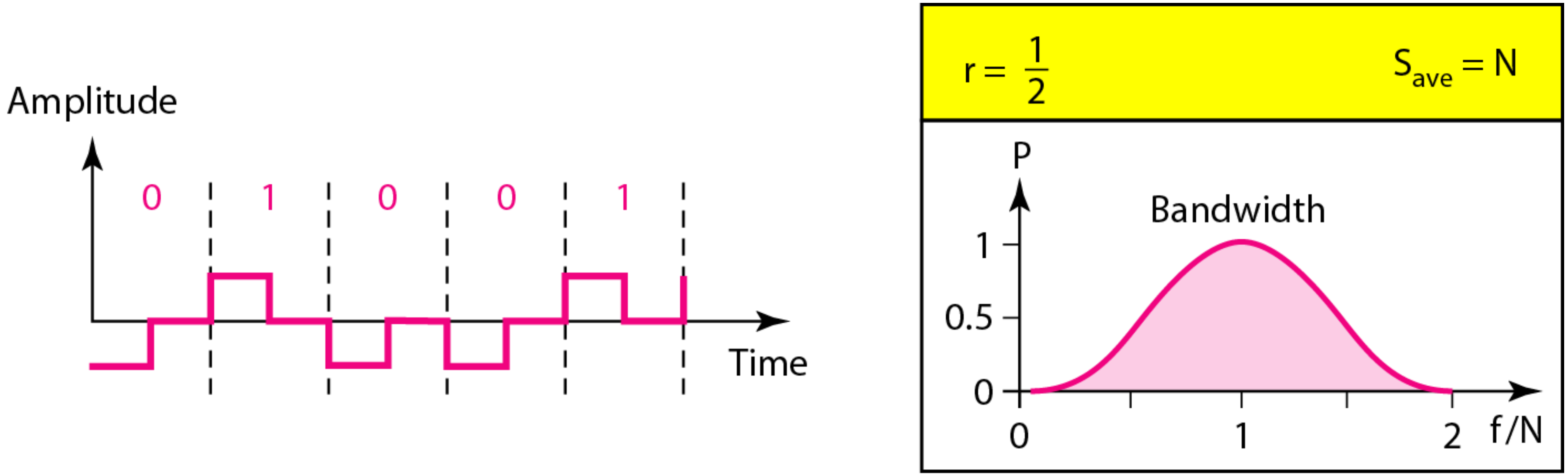


Figure 4.7 *Polar RZ scheme*

Polar - Biphase: Manchester and Differential Manchester

- Manchester coding consists of combining the NRZ-L and RZ schemes.
  - Every symbol has a level transition in the middle: from high to low or low to high. Uses only two voltage levels.
- Differential Manchester coding consists of combining the NRZ-I and RZ schemes.
  - Every symbol has a level transition in the middle. But the level at the beginning of the symbol is determined by the symbol value.
  - One symbol causes a level change the other does not.

Polar - Biphase: Manchester and Differential Manchester (Conti...)

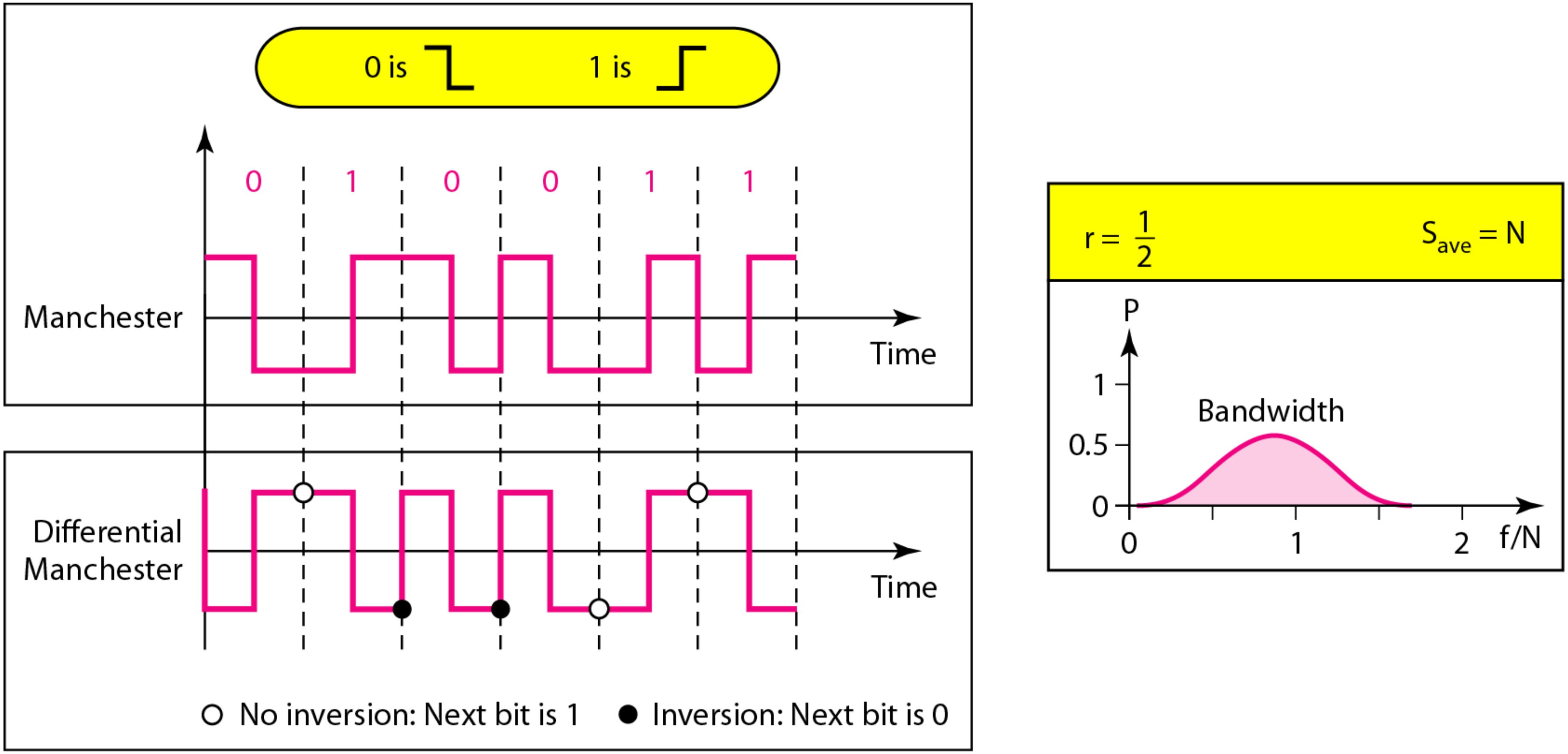


Figure 4.8 *Polar biphase: Manchester and differential Manchester schemes*

Polar - Biphase: Manchester and Differential Manchester (Conti...)

- 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.
- The is no DC component and no baseline wandering.
- None of these codes has error detection.

Bipolar - AMI and Pseudoternary

- uses three voltage levels: positive, zero, and negative to represent the symbols (note: no transitions to zero as in RZ).
- Voltage level for one symbol is at “0” and the other alternates between positive and negative.
- Bipolar Alternate Mark Inversion (AMI) - the “0” symbol is represented by zero voltage and the “1” symbol alternates between +V and -V.
- Pseudoternary is the reverse of AMI.

Bipolar - AMI and Pseudoternary (Conti...)

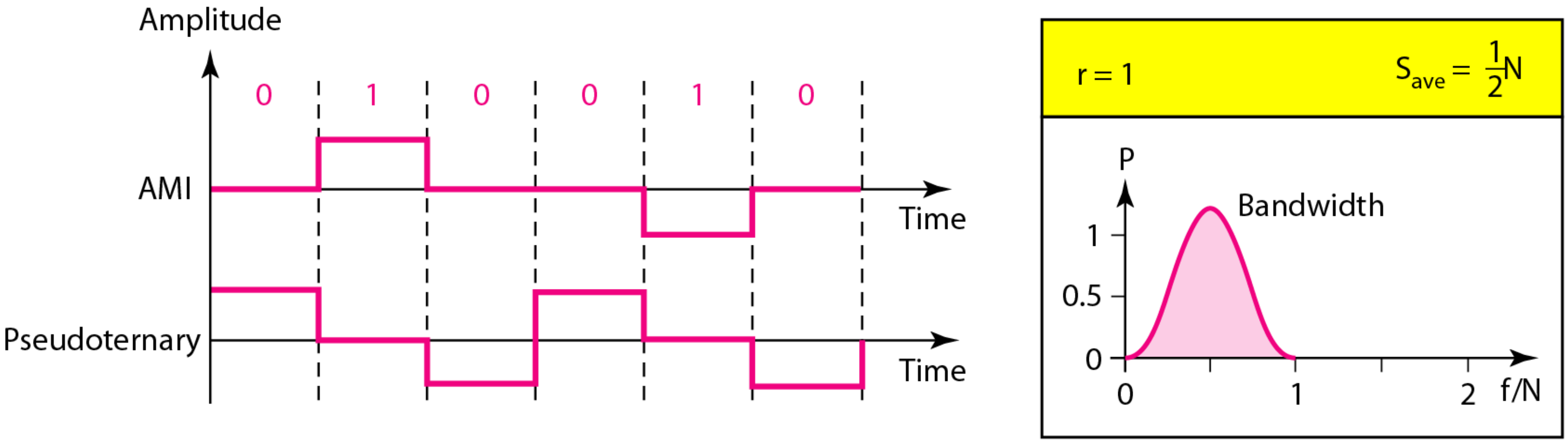


Figure 4.9 *Bipolar schemes: AMI and pseudoternary*

Bipolar - AMI and Pseudoternary (Conti...)

- better alternative to NRZ.
- no DC component or baseline wandering.
- no self synchronization because long runs of "0"s results in no signal transitions.
- No error detection.

Multilevel Schemes

- In these schemes the goal is to increase the data speed while decreasing the bandwidth.
  - increasing the number of data elements per signal element
  - encoding a pattern of m data elements into a pattern of n signal elements
- Two types of data elements (0 and 1) can produce 2^m data patterns for m data elements.
- L different levels can produce only L^n combinations of signal patterns.

Multilevel Schemes (Conti...)

- Now we have 2^m symbols and L^n signals.
- For $2^m > L^n$, data encoding is not possible due to insufficient signal patterns.
- For $2^m = L^n$, each data pattern is encoded into one signal pattern.
- For $2^m < L^n$, only a subset of signal patterns are occupied by data patterns, while the remaining signal patterns can be used:
  - to prevent baseline wandering
  - to provide synchronization
  - to detect errors

Multilevel Schemes (Conti...)

- In *mBnL* schemes, a pattern of *m* data elements is encoded as a pattern of *n* signal elements in which $2^m \leq L^n$.
  - m is the length of the binary pattern
  - B represents binary data
  - n represents the length of the signal pattern
  - L represents the number of levels
- L = B binary (2) , L = T for 3 ternary, L = Q for 4 quaternary.

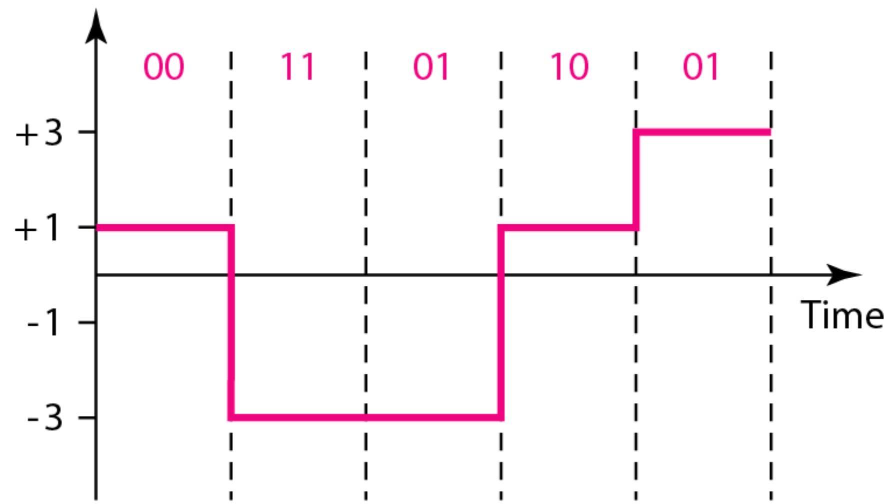
Multilevel Schemes – 2B1Q

- 2B1Q (two binary, one quaternary) uses data patterns of size 2 and encode it as 1 signal belonging to a four-level signal.
- In 2B1Q m = 2, n = 1, and L = 4.
- Average signal rate S = N/4
- There are no redundant signal patterns ($2^2 - 4^1 = 0$) therefore having DC component, no synchronization, no error detection.
- Use of four different signal levels means that the receiver has to discern four different thresholds.

Multilevel Schemes – 2B1Q (Conti…)

	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



Assuming positive original level

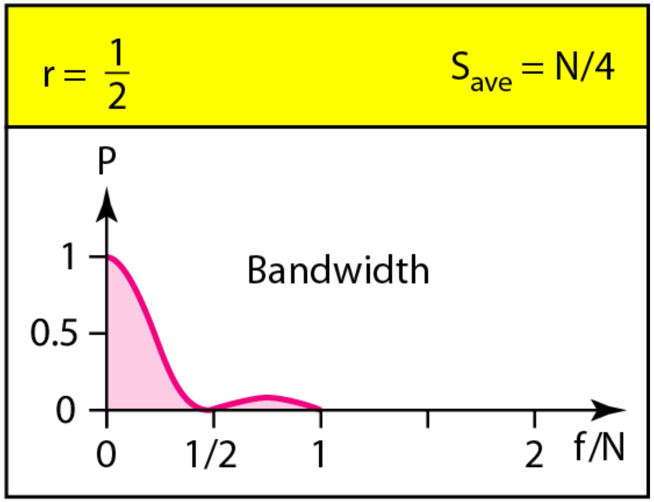


Figure 4.10 *Multilevel: 2B1Q scheme*

Multilevel Schemes – 8B6T

- 8B6T (eight binary, six ternary) uses data patterns of size 8 and encode it as a pattern of 6 signal elements where the signal has 3 levels.
- In 8B6T m = 8, n = 6, and L = 3.
- Average signal rate $S = 3N/8$
- There are redundant signal patterns (($2^8=256$) - ($3^6=478$) = 222) therefore:
  - having no DC Component
  - provide synchronization and error detection

Multilevel Schemes – 8B6T (Conti...)

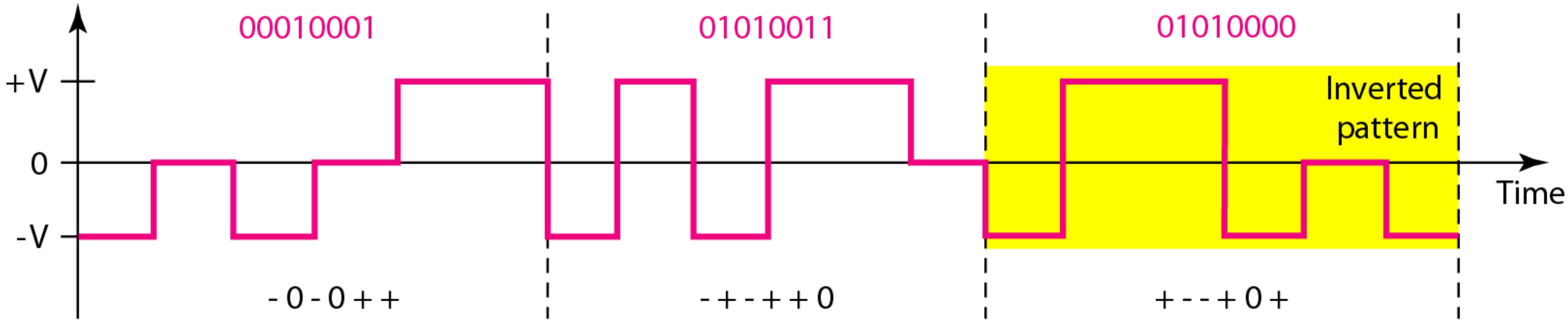


Figure 4.11 *Multilevel: 8B6T scheme*

Multilevel Schemes – 4D-PAM5

- 4D-PAM5 (Four-dimensional Five-levels Pulse Amplitude Modulation) send data over four channel (wires) using five voltage levels.
- It splits the signal transmission and send over four links.
- Average signal rate S = N/8
- The separate segments are transmitted simultaneously, thus reduces the signal rate per link results in lower bandwidth.
- It requires that all bits for a code to be stored.

Multilevel Schemes – 4D-PAM5 (Conti...)

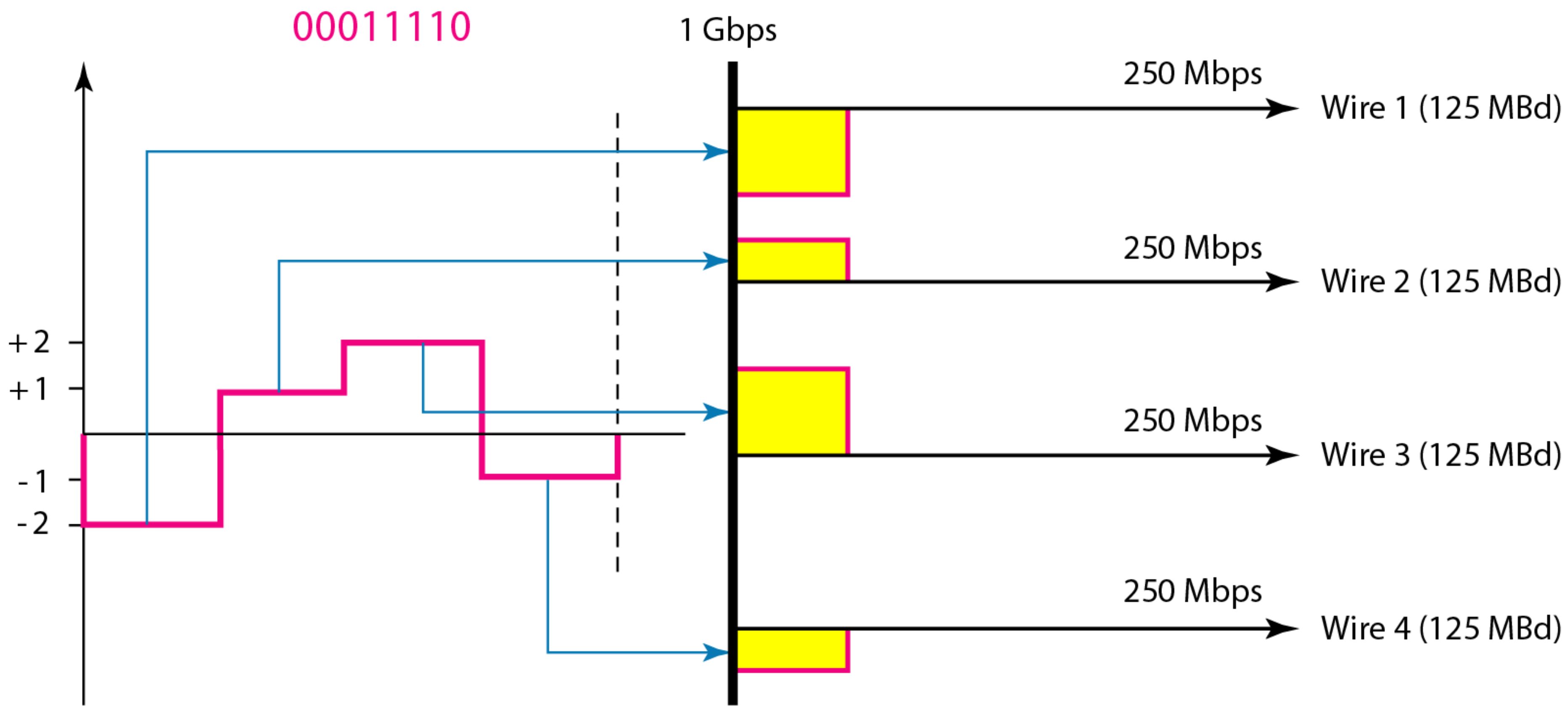


Figure 4.12 *Multilevel: 4D-PAM5 scheme*

Multi-transition – MLT-3

- Due to synchronization requirements transitions are forced (NRZ-I and Differential Manchester), resulting in very high bandwidth.
- Codes can be created that are differential at the bit level forcing transitions at bit boundaries.
- MLT-3 (Multi-Line Transmission, Three levels) scheme uses three levels (+V, 0, and –V) and three transition rules to move between levels.
  - If next bit is 0, there is no transition
  - If next bit is 1, and current level is not 0, the next level is 0.
  - If next bit is 1, and current level is 0, the next level is the opposite of the last non-zero level.

Multi-transition – MLT-3 (Conti…)

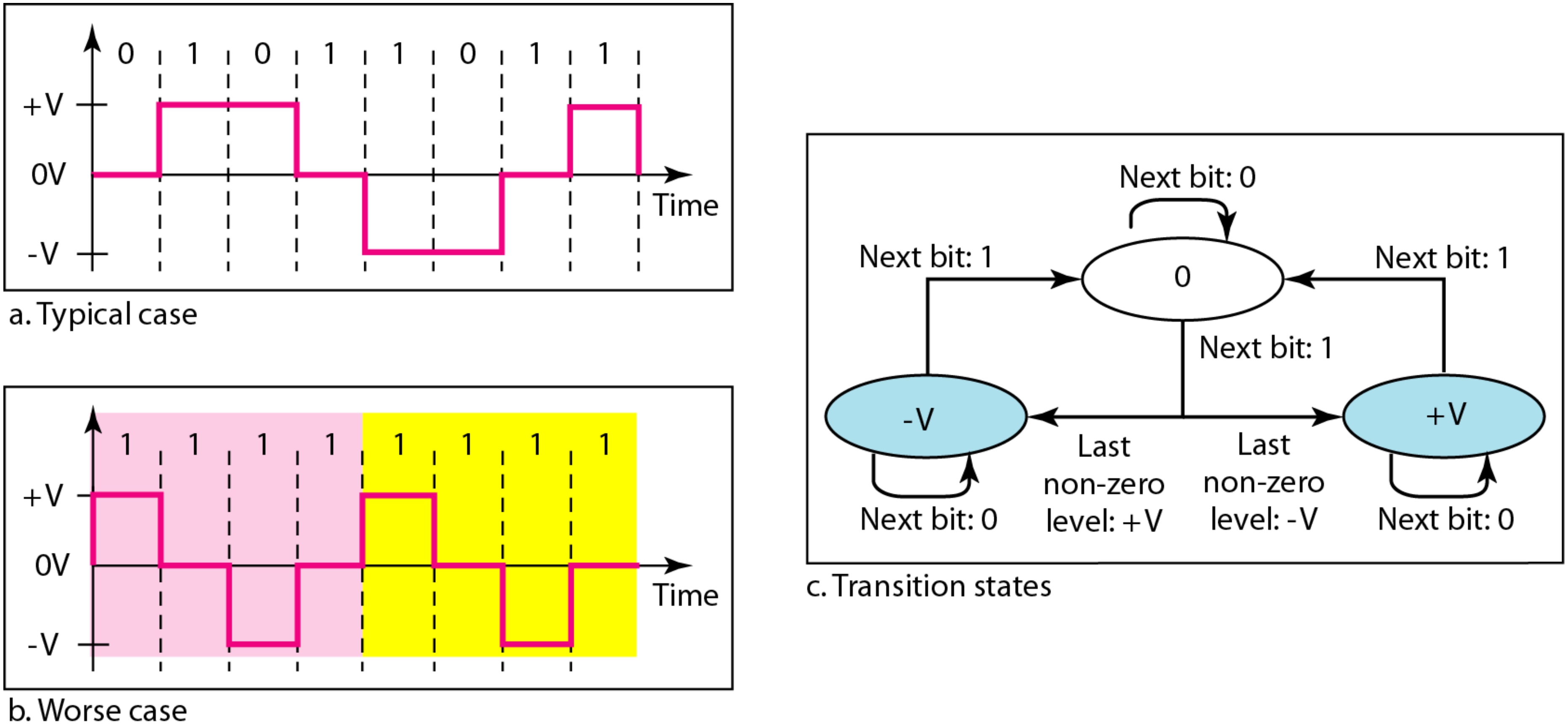


Figure 4.13 ***Multitransition: MLT-3 scheme***

Summary of line coding schemes

Table 4.1 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

- Redundancy (adding extra bits to the data bits) is required to ensure synchronization and provide error detection.
- Block Coding provide this redundancy to improve the performance of line coding.
- It changes a block of m bits into a block of n bits, where $n > m$.
- Block coding is referred to as an *mB/nB* encoding technique.
- Block coding is done in three steps: division, substitution and combination.

Block Coding (Conti...)

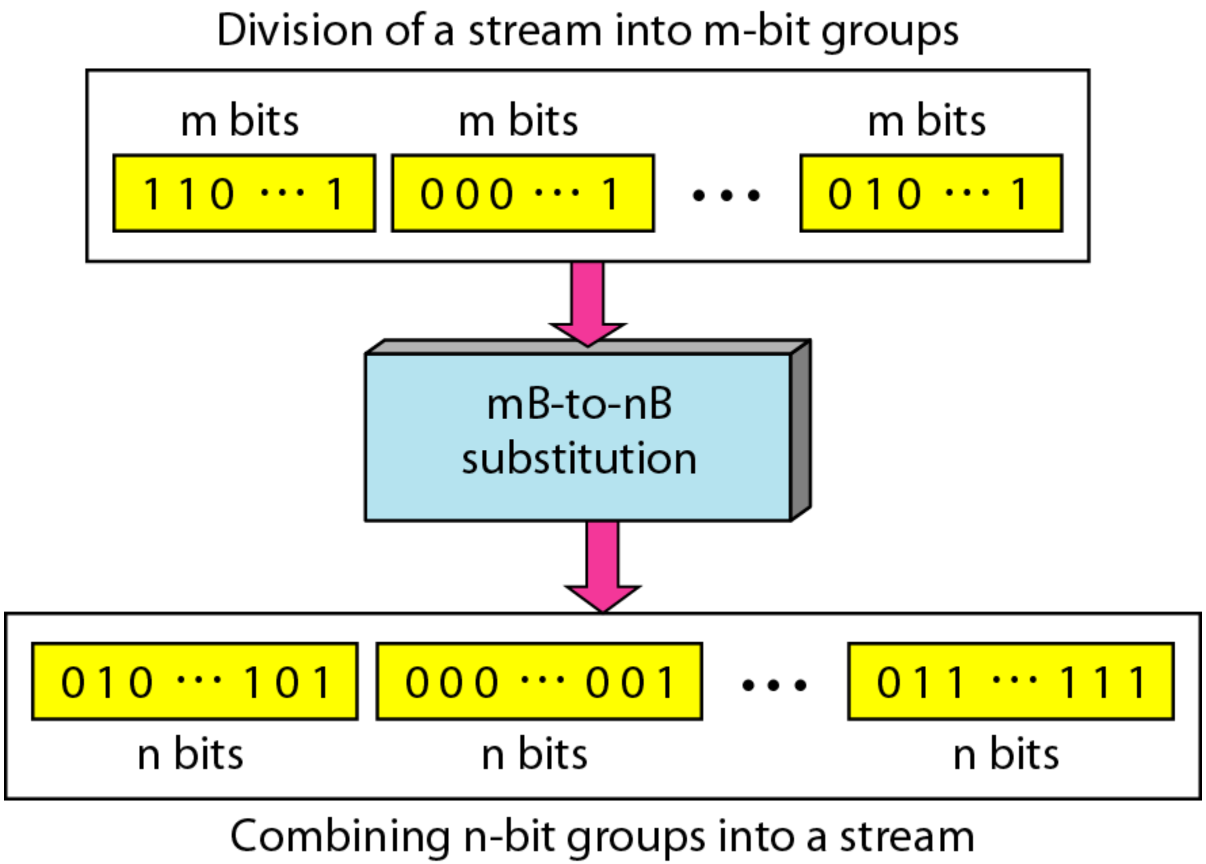


Figure 4.14 *Block coding concept*

Block Coding – 4B/5B

- Designed to be used with NRZ-I having good signal rate but it has synchronization problem.
- At sender the data is first encoded with 4B/5B then with NRZ-I, while at receiver the signal is first decoded into stream of bits then decoded to remove redundancy.
- A group of 4-bits can have only 16 patterns while 5-bits can have 32 different patterns.
- Some of the extra 16 patterns are used for control purposes while others are not used at all.

Block Coding – 4B/5B (Conti...)

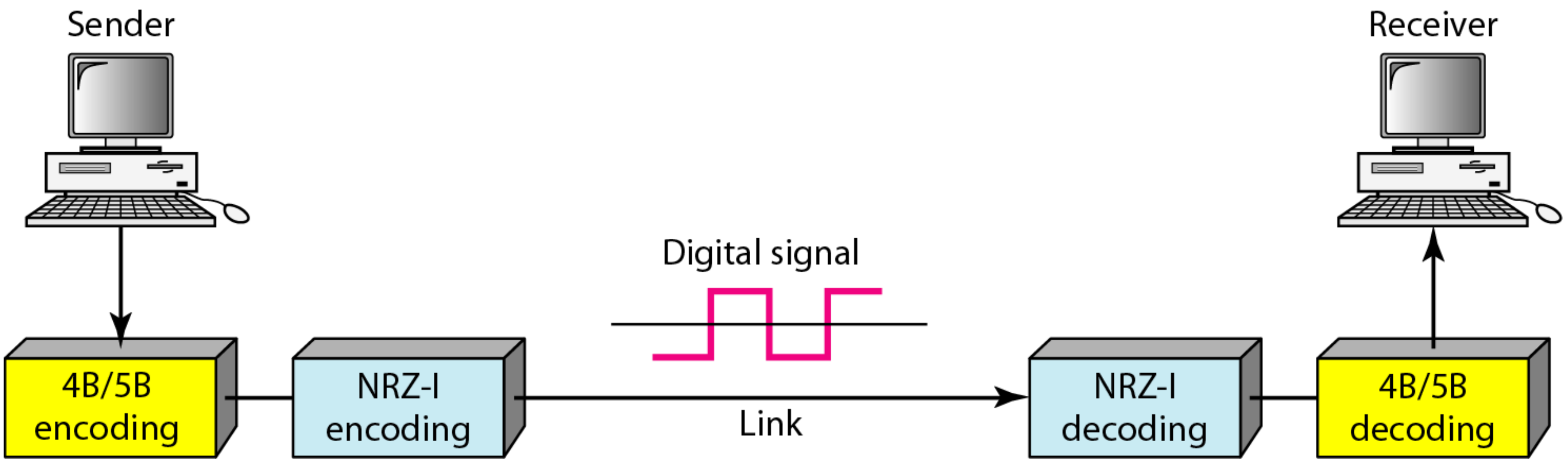


Figure 4.15 *Using block coding 4B/5B with NRZ-I line coding scheme*

Block Coding – 4B/5B (Conti...)

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		

Block Coding – 4B/5B (Conti…)

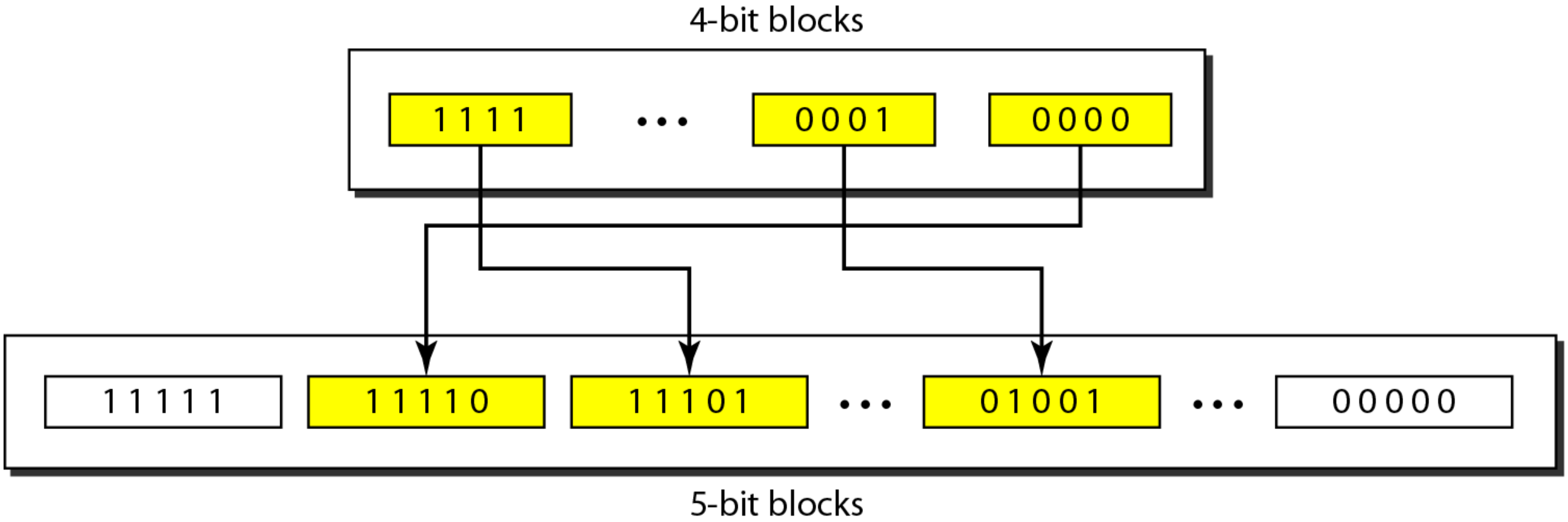


Figure 4.16 *Substitution in 4B/5B block coding*

Block Coding – 8B/10B

- 8B/10B encoding is similar to 4B/5B except that a group of 8-bits of data is substituted by a 10-bits code.
- Provides greater error detection than 4B/5B.
- Combination of 5B/6B and 3B/4B encoding.
- The significant 5-bits of 8-bits data block is fed into the 5B/6B encoder while the least significant 3-bits into 3B/4B encoder.
- To prevent a stream of 0s and 1s it uses a disparity controller.
- Having $2^{10} - 2^{8} = 768$ redundant groups used for disparity checking and error detection.

Block Coding – 8B/10B (Conti...)

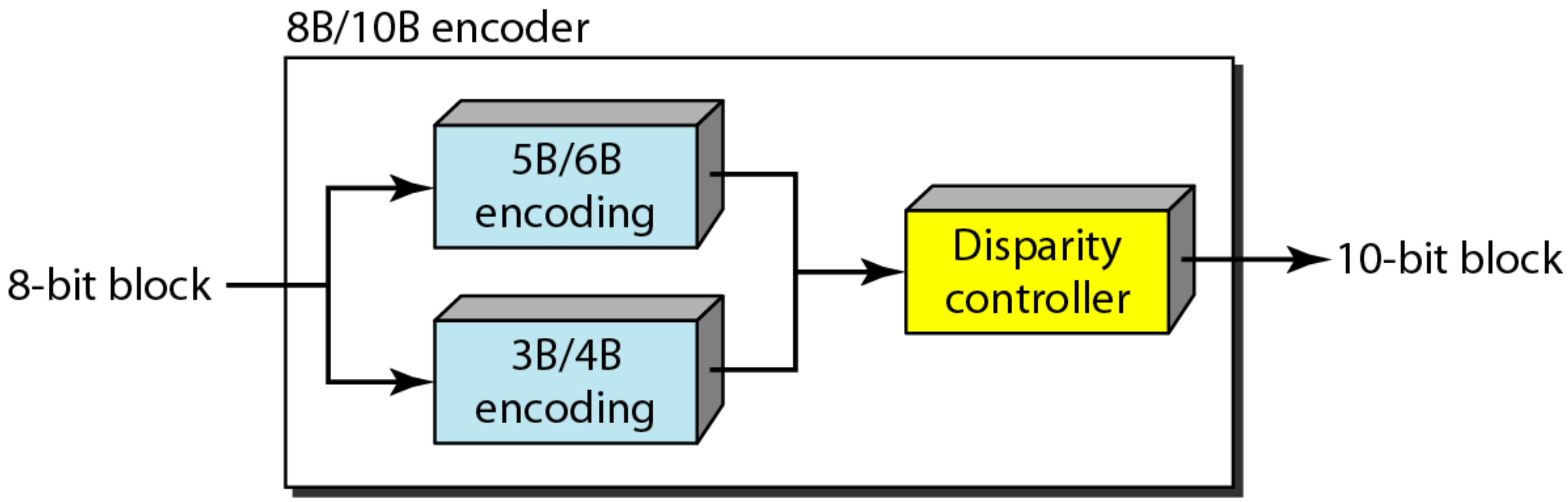


Figure 4.17 *8B/10B block encoding*

Scrambling

- Biphase schemes are suitable for LANs but not for long-distance communication due to wide bandwidth requirements.
- Combination of block coding and NRZ line coding is not suitable for long-distance communication due to DC component.
- Bipolar AMI encoding has narrow bandwidth and does not create DC component but long sequence of 0s upsets the synchronization.
- Scrambling is a technique used to create a sequence of bits that has self clocking, no low frequencies, no wide bandwidth and no DC components.

Scrambling (Conti...)

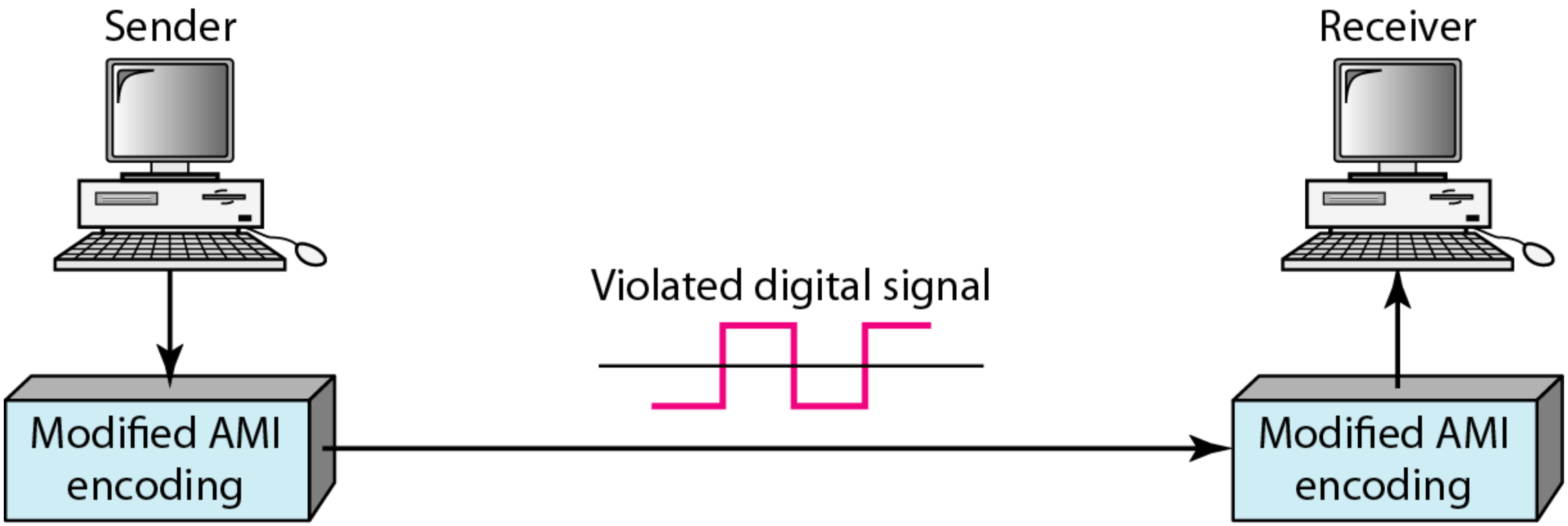
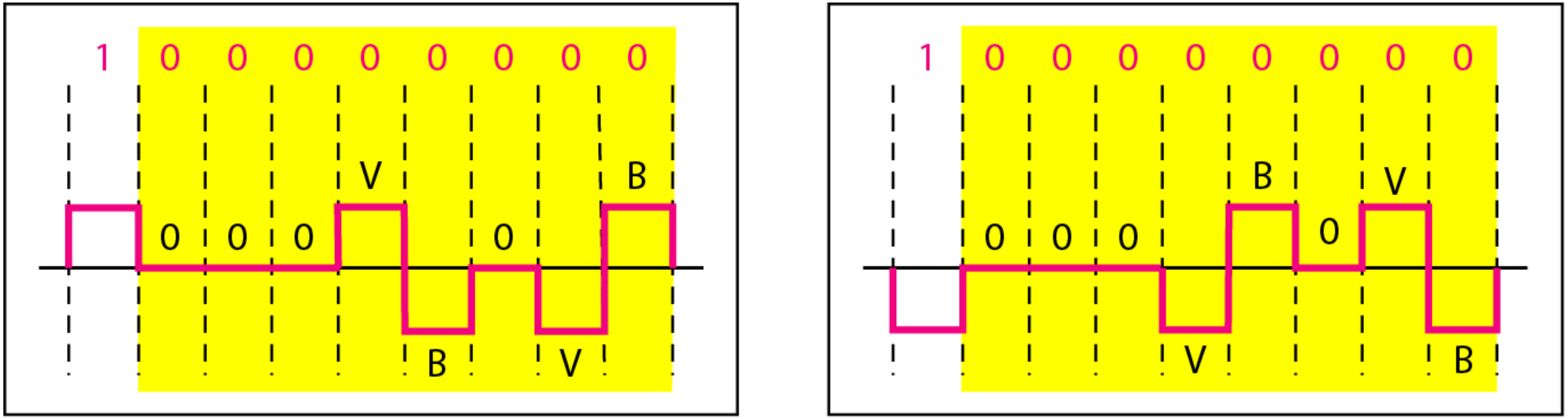


Figure 4.18 *AMI used with scrambling*

Scrambling – Bipolar with 8-Zero Substitution (B8ZS)

- Commonly used in North America.
- Replaces eight consecutive zero-level voltages by sequence 000VB0VB.
  - 0 (zero): zero-level voltage
  - V (violation): non-zero voltage with same polarity as the polarity of the previous non-zero pulse
  - B (bipolar): non-zero voltage with polarity opposite to the polarity of the previous non-zero pulse
- It does not change the bit rate but balances the positive and negative voltage levels

Scrambling – B8ZS (Conti…)



a. Previous level is positive.

b. Previous level is negative.

Figure 4.19 *Two cases of B8ZS scrambling technique*

Scrambling – High-Density Bipolar 3-zero (HDB3)

- Commonly used outside of North America.
- Replaces four consecutive zero-level voltages by sequence 000V or B00V.
- The reason for two different substitutions is to maintain the even number of non-zero pulses after each substitution.
- The two rules can be stated as follows:
  - If the number of non-zero pulses after the last substitution is odd, the substitution pattern will be 000V.
  - If the number of non-zero pulses after the last substitution is even, the substitution pattern will be BOOV.

Scrambling – HDB3 (Conti...)

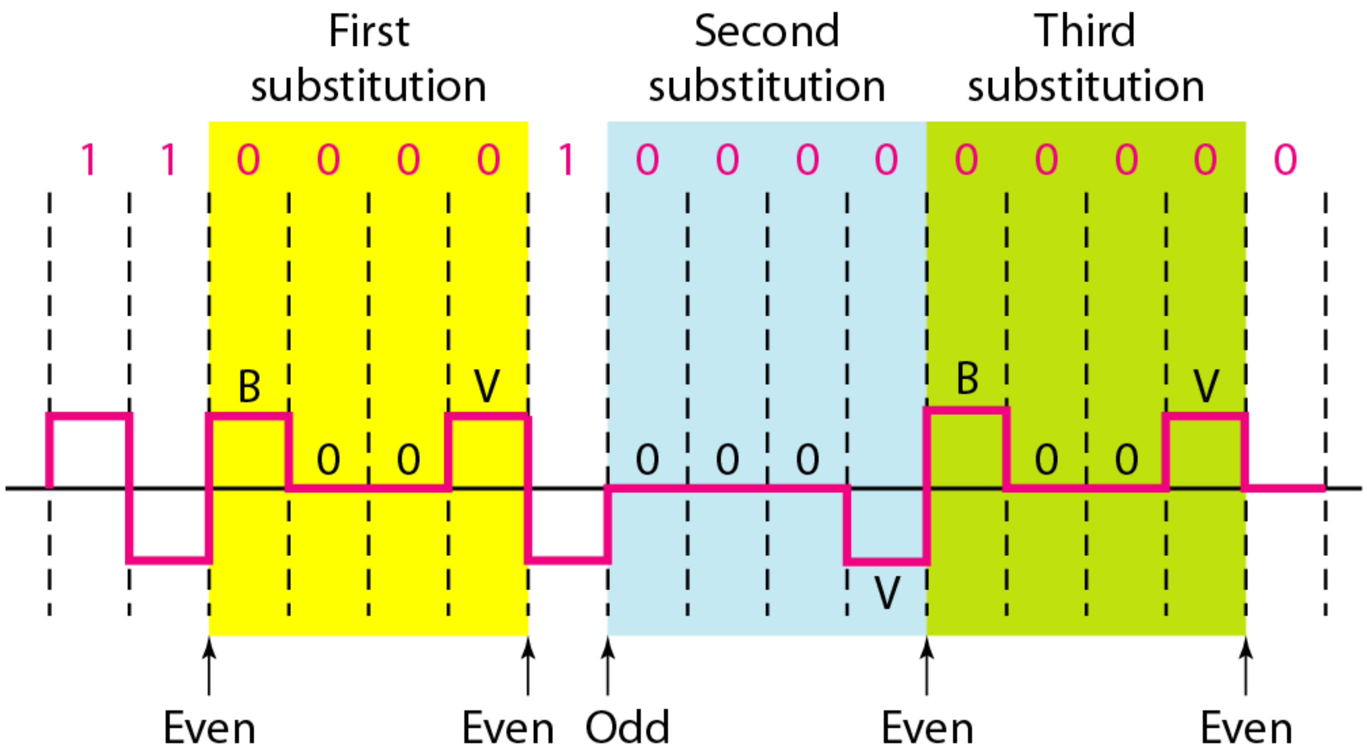


Figure 4.20 *Different situations in HDB3 scrambling technique*

Analog-To-Digital Conversion

- A digital signal is superior to an analog signal because it is more robust to noise and can easily be recovered, corrected and amplified.
- For this reason, the tendency today is to change an analog signal to digital data.
- In this section we describe two techniques.
  - Pulse Code Modulation (PCM)
  - Delta Modulation (DM)

Pulse Code Modulation (PCM)

- The most common technique to change analog signal to digital data (digitization).
- PCM consists of three steps to digitize an analog signal:
  - Sampling: The analog signal is sampled.
  - Quantization: The sampled signal is quantized.
  - Binary encoding: The quantized values are encoded as stream of bits.
- Before sampling the signal is filtered to limit the maximum frequency as it affects the sampling rate.
- Filtering should ensure not to distort the signal.

PCM (Conti...)

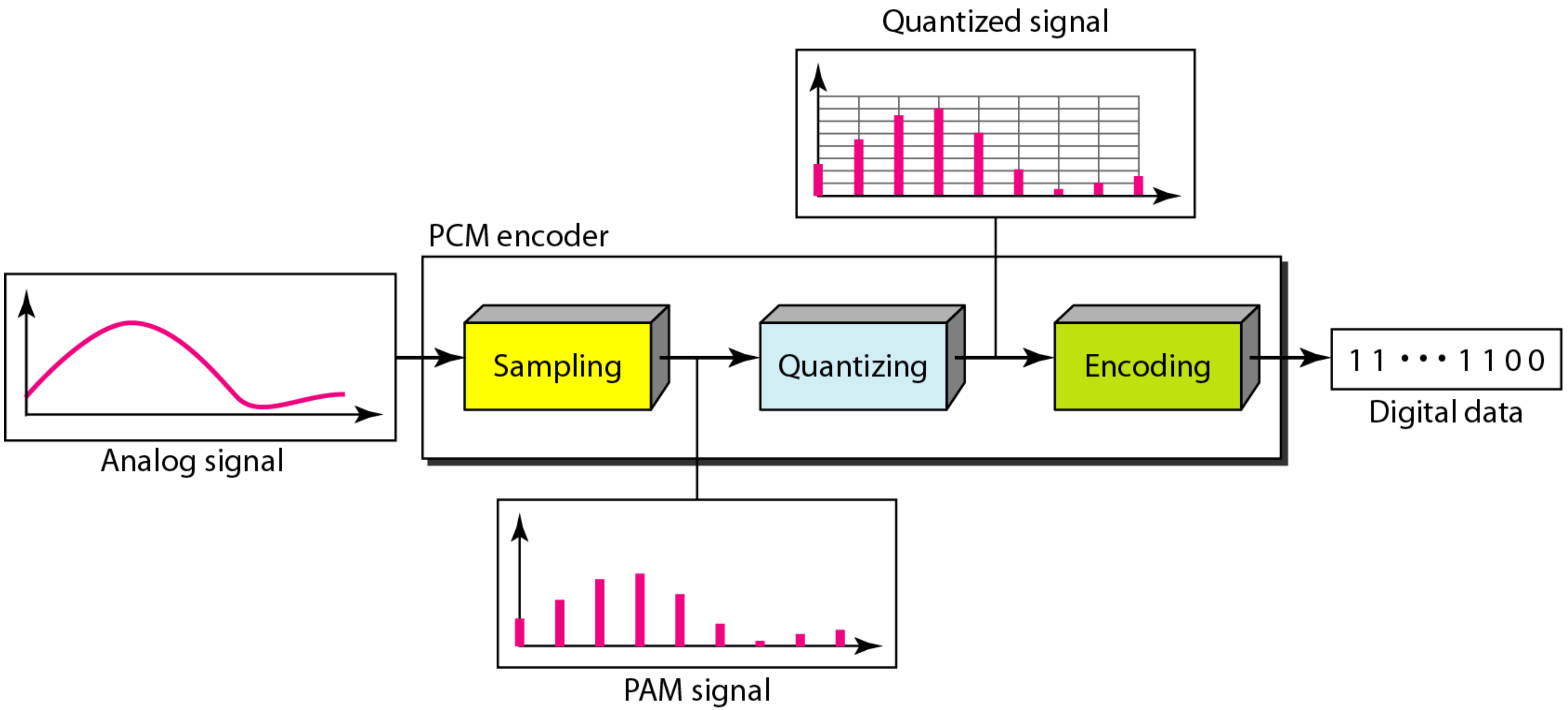


Figure 4.21 *Components of PCM encoder*

Sampling

- The first step of PCM is sampling also referred as Pulse Amplitude Modulation (PAM) .
- Analog signal is sampled every T_S seconds.
- T_s is referred to as the sampling interval.
- $f_s = 1/T_s$ is called the sampling rate or sampling frequency.
- There are 3 sampling methods:
  - Ideal: An impulse at each sampling instant.
  - Natural: A pulse of short width with varying amplitude.
  - Flat-top: Sample and hold, like natural but with single amplitude value

Sampling (Conti...)

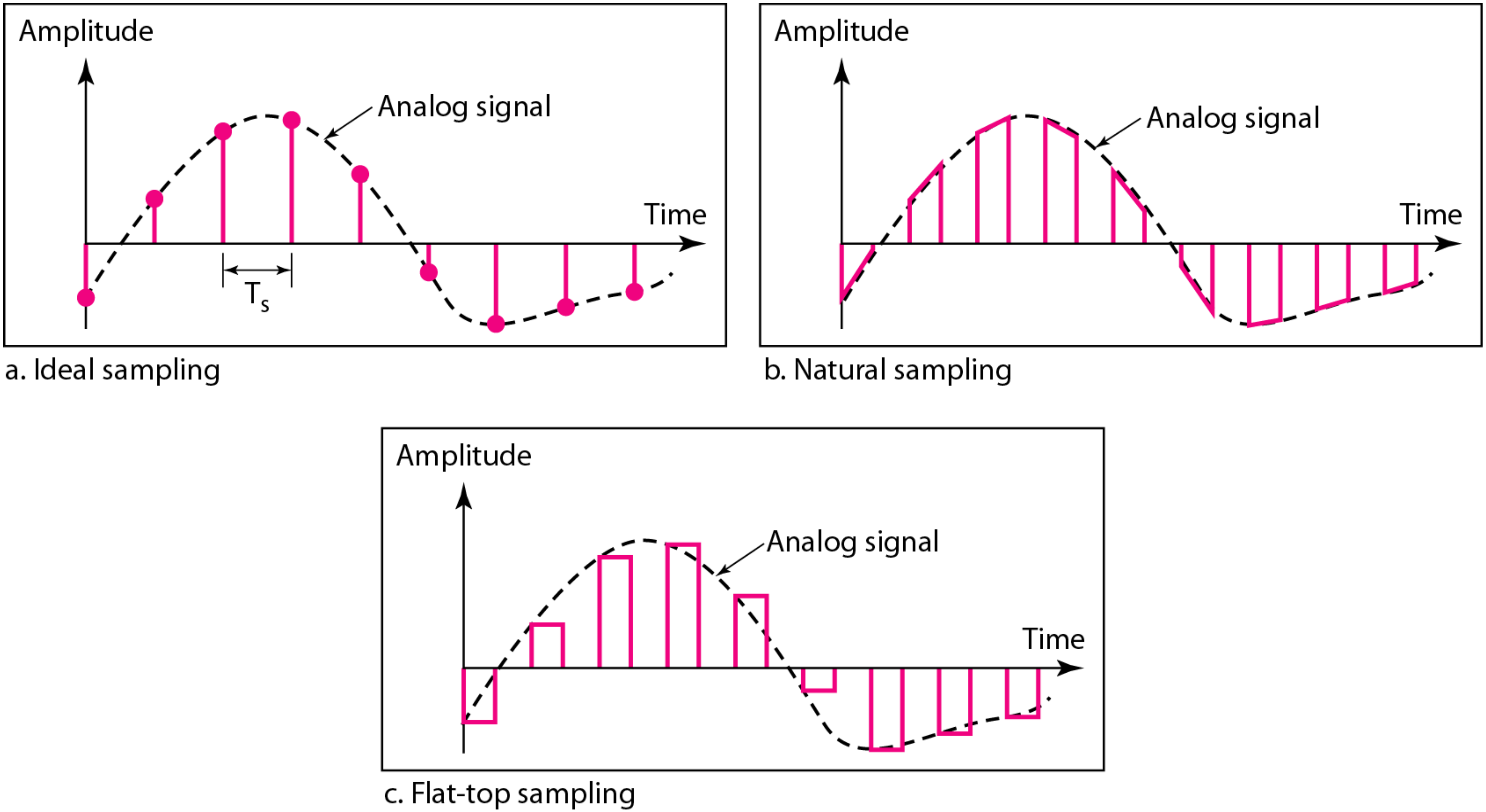


Figure 4.22 *Three different sampling methods for PCM*

Sampling (Conti...)

Note

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

Sampling (Conti...)

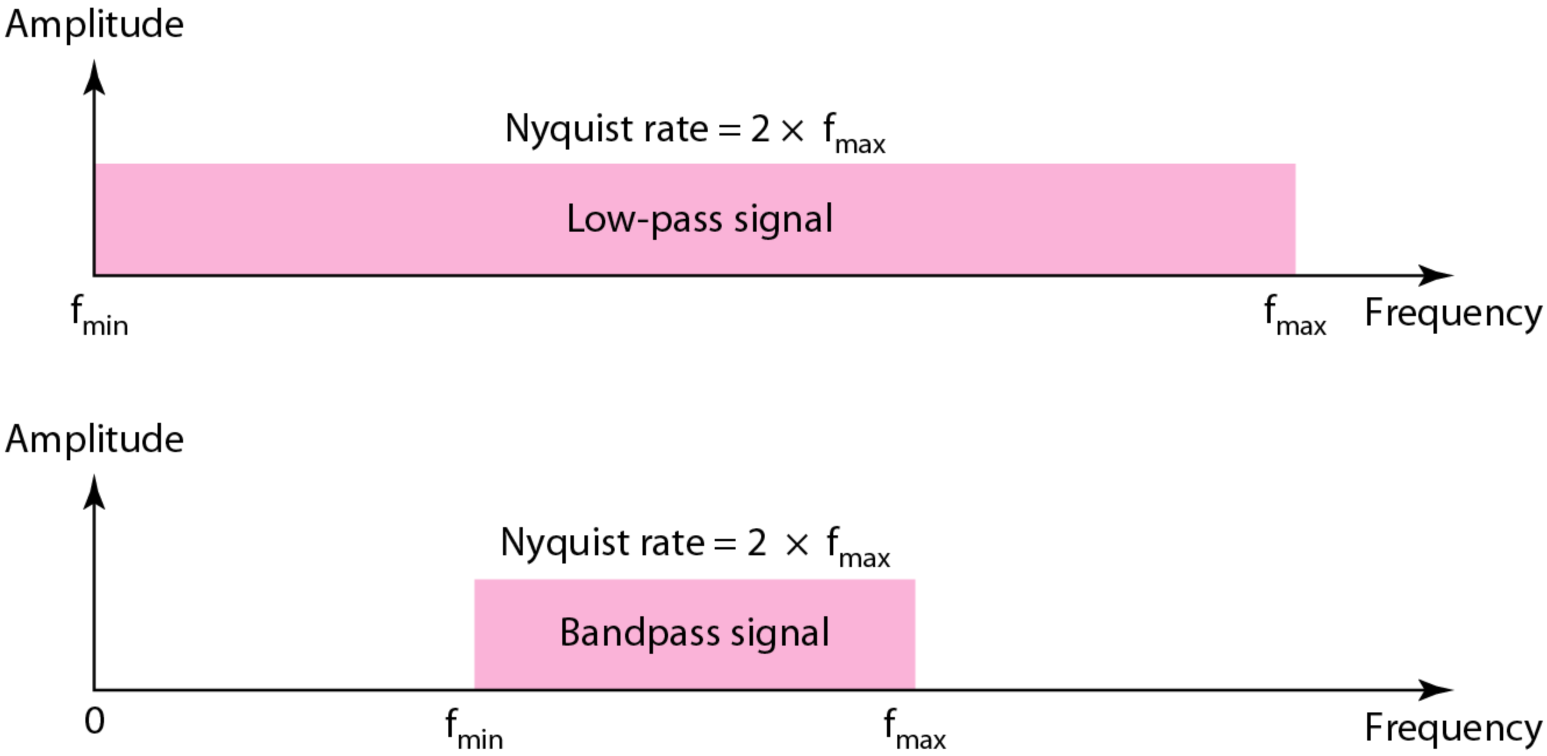


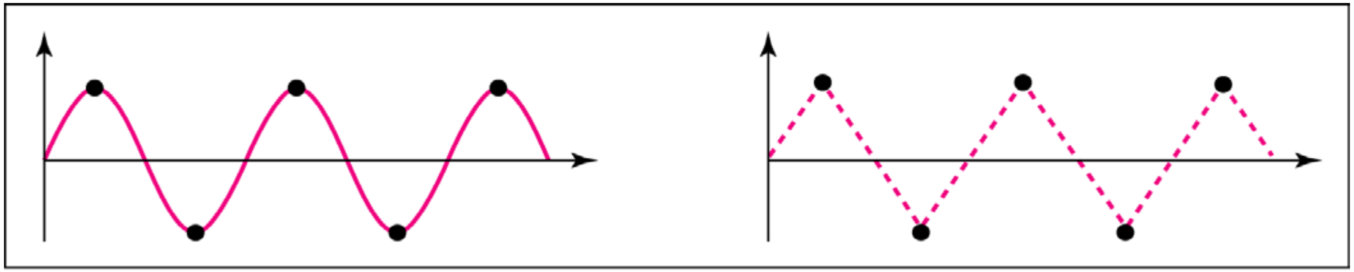
Figure 4.23 *Nyquist sampling rate for low-pass and bandpass signals*

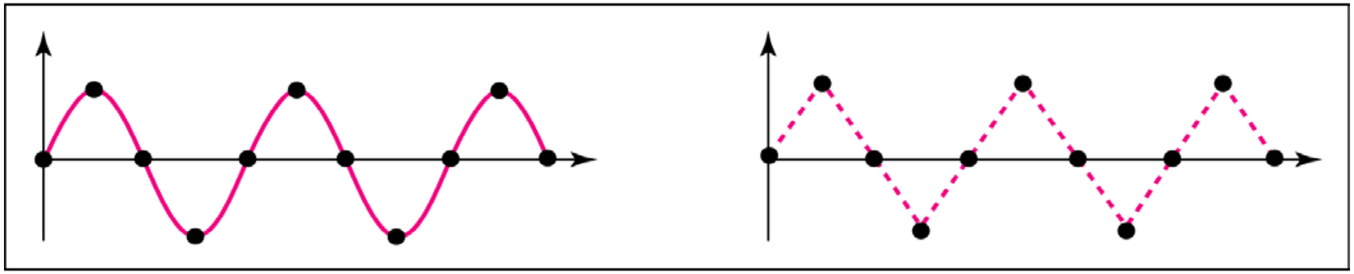
Sampling (Conti...)

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 (Conti...)





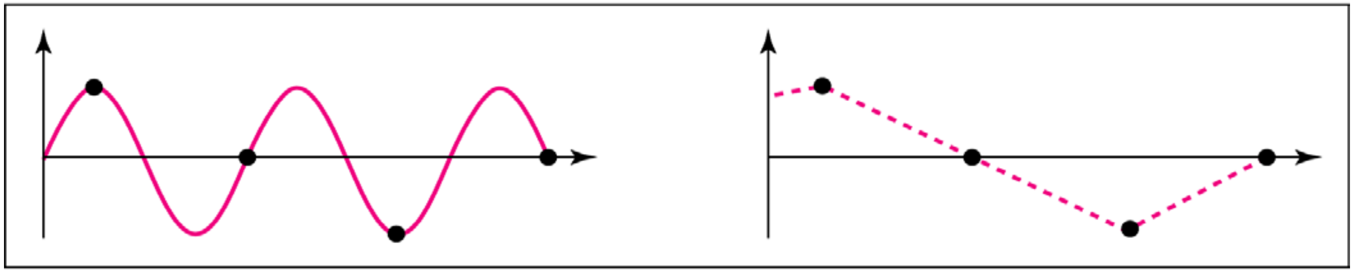


Figure 4.24 *Recovery of a sampled sine wave for different sampling rates*

Sampling (Conti...)

Example 4.7: Consider the revolution of a hand of a clock. The second hand of a clock has a period of 60 s. According to the Nyquist theorem, we need to sample the hand every 30 s (T_s = T/2 or f_s = 2f). In Figure 4.25a, the sample points, in order, are 12, 6, 12, 6, 12, and 6. The receiver of the samples cannot tell if the clock is moving forward or backward. In part b, we sample at double the Nyquist rate i.e. every 15 s(T_s = T/4 or f_s = 4f). The sample points are 12, 3, 6, 9, and 12. The clock is moving forward. In part c, we sample below the Nyquist rate (T_s = 3T/4 or f_s = 4f/3). The sample points are 12, 9, 6, 3, and 12. Although the clock is moving forward, the receiver thinks that the clock is moving backward.

Sampling (Conti...)

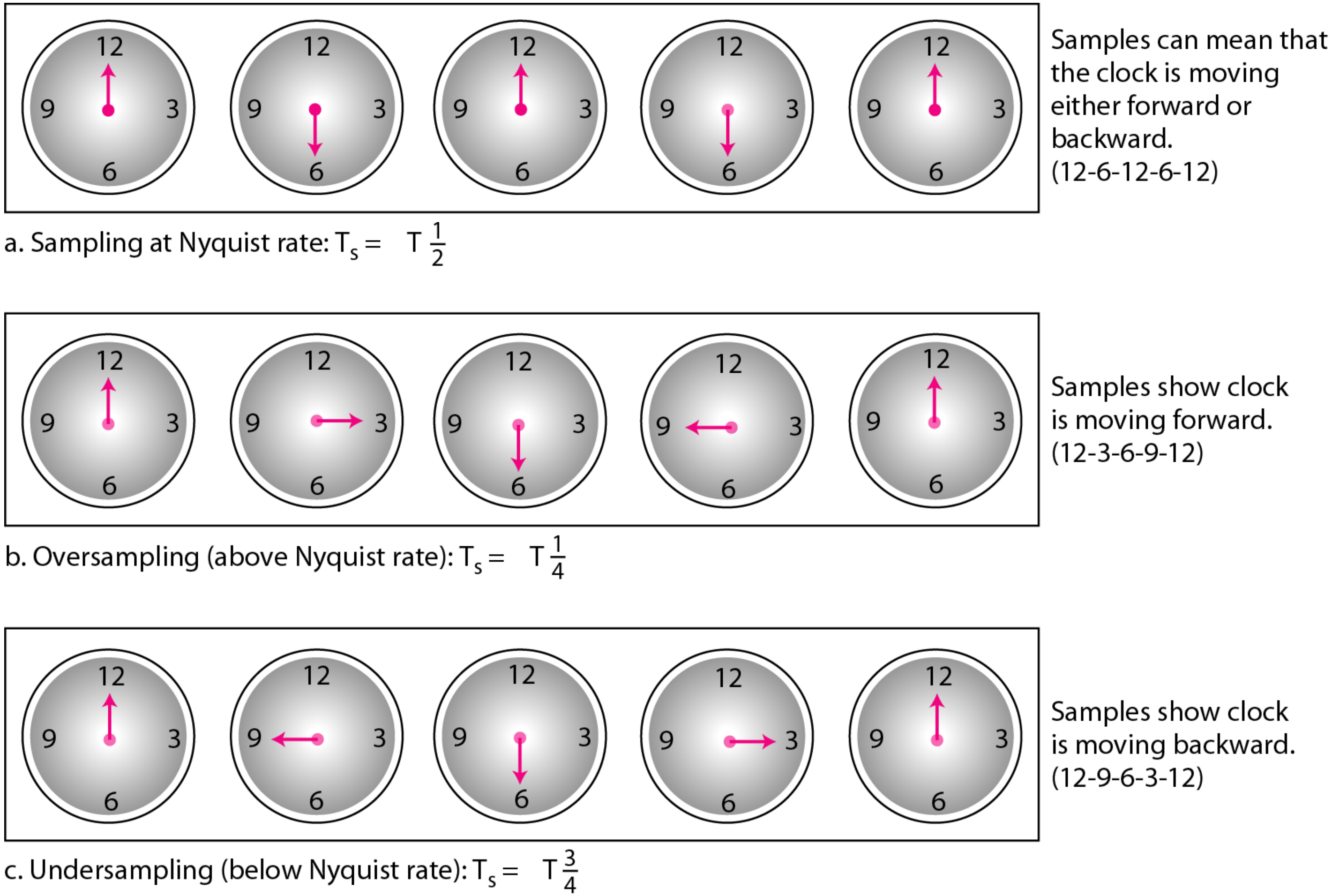


Figure 4.25 *Sampling of a clock with only one hand*

Sampling (Conti...)

Example 4.8: An example related to Example 4.7 is the seemingly backward rotation of the wheels of a forward-moving car in a movie. This can be explained by under-sampling. A movie is filmed at 24 frames per second. If a wheel is rotating more than 12 times per second, the under-sampling creates the impression of a backward rotation.

Sampling (Conti...)

Example 4.9: Telephone companies digitize voice by assuming a maximum frequency of 4000 Hz. The sampling rate therefore is 8000 samples per second.

Example 4.10: A complex low-pass signal has a bandwidth of 200 kHz. What is the minimum sampling rate for this signal?

Solution:

The bandwidth of a low-pass signal is between 0 and f, where f is the maximum frequency in the signal. Therefore, we can sample this signal at 2 times the highest frequency (200 kHz). The sampling rate is therefore 400,000 samples per second.

Example 4.11: A complex band-pass signal has a bandwidth of 200 kHz. What is the minimum sampling rate for this signal?

Solution:

We cannot find the minimum sampling rate in this case because we do not know where the bandwidth starts or ends. We do not know the maximum frequency in the signal.

Quantization

- Sampling results in a series of pulses with amplitude between maximum and minimum amplitudes of signal.
- The amplitude values can be infinite with non-integral values (used in encoding process) between the two limits.
- Following steps are involved in quantization:
  - Assume that the original analog signal has instantaneous amplitudes between V_{min} and V_{max}.

Quantization (Conti...)

- Steps (Conti...):
  - Divide the range between V_{min} and V_{max} into L zones, each of height Δ.

$$\Delta = (V_{max} - V_{min})/L$$

  - The midpoint of each zone is assigned a value from 0 to L-1 (resulting in L values).
  - Each sample falling in a zone is then approximated to the value of the midpoint.

Quantization Zones

- Assume we have a voltage signal with amplitudes V_{min}=-20V & V_{max}=+20V while quantization levels (L) = 8.
- Zone width Δ = (20 - (-20))/8 = 5.
- The 8 zones are: -20 to -15, -15 to -10, -10 to -5, -5 to 0, 0 to +5, +5 to +10, +10 to +15, +15 to +20.
- The midpoints are: -17.5, -12.5, -7.5, -2.5, 2.5, 7.5, 12.5, 17.5.

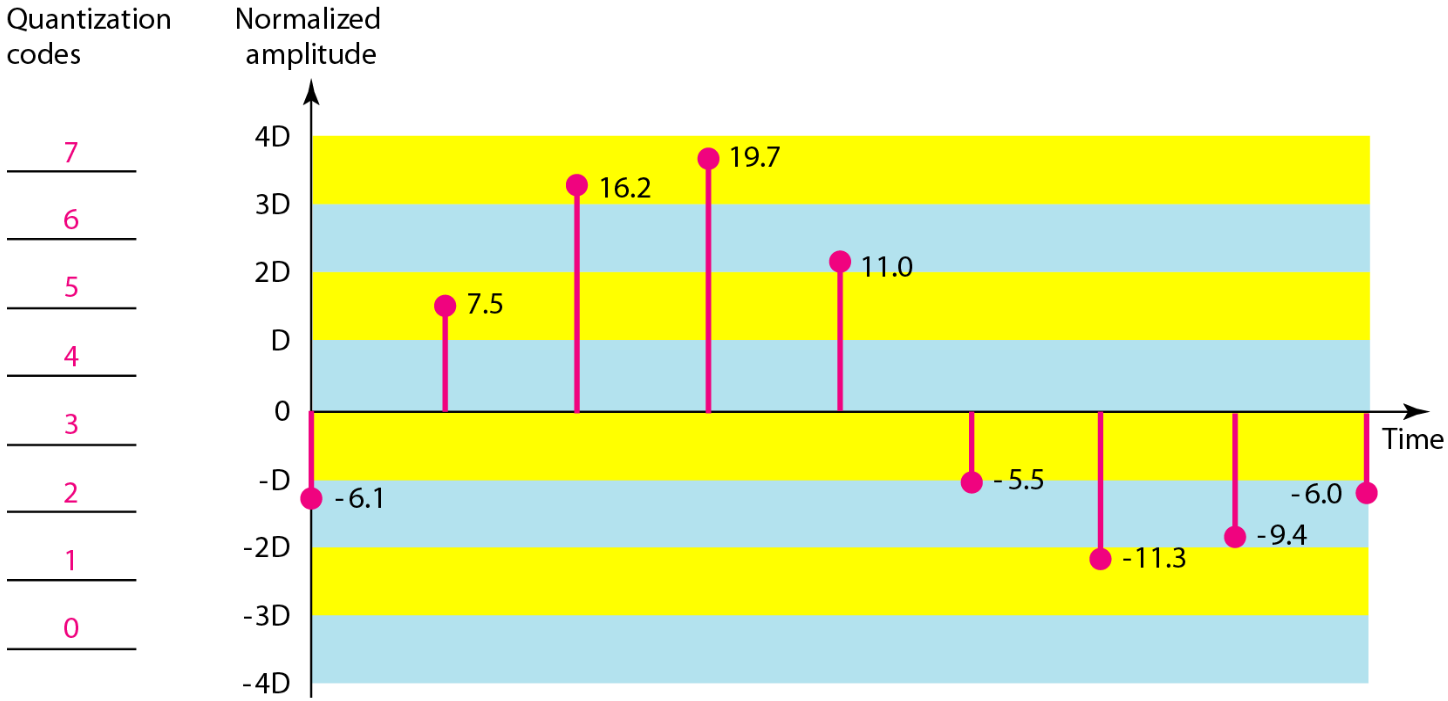
Assigning Codes to Zones

- Each zone is then assigned a binary code.
- The number of bits required to encode the zones, or the number of bits per sample:

$$n_b = \log_2 L$$

- For previous example: $n_b = 3$.
- The 8 zone (or level) codes are therefore: 000, 001, 010, 011, 100, 101, 110, and 111.
- Assigning codes to zones:
  - 000 will refer to zone -20 to -15.
  - 001 to zone -15 to -10, etc.

Quantization (Conti…)



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

Figure 4.26 *Quantization and encoding of a sampled signal*

Bit Rate and Bandwidth Requirements of PCM

- The bit rate of a PCM signal can be calculated:

$$\text{Bit rate} = n_b \times f_s$$

- The bandwidth required to transmit this signal depends on the type of line encoding used.
- A digitized signal will always need more bandwidth than the original analog signal.
- The price to pay for robustness and other features of digital transmission.

Bit Rate and Bandwidth Requirements of PCM (Conti...)

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:

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

Bit Rate and Bandwidth Requirements of PCM (Conti...)

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.

PCM Decoder

- To recover an analog signal from a digitized signal follow the following steps:
  - Use a hold circuit that holds the amplitude value of a pulse till the next pulse arrives.
  - Pass this signal through a low pass filter with a cutoff frequency that is equal to the highest frequency in the pre-sampled signal.
- The higher the value of L, the less distorted a signal is recovered.

PCM Decoder (Conti...)

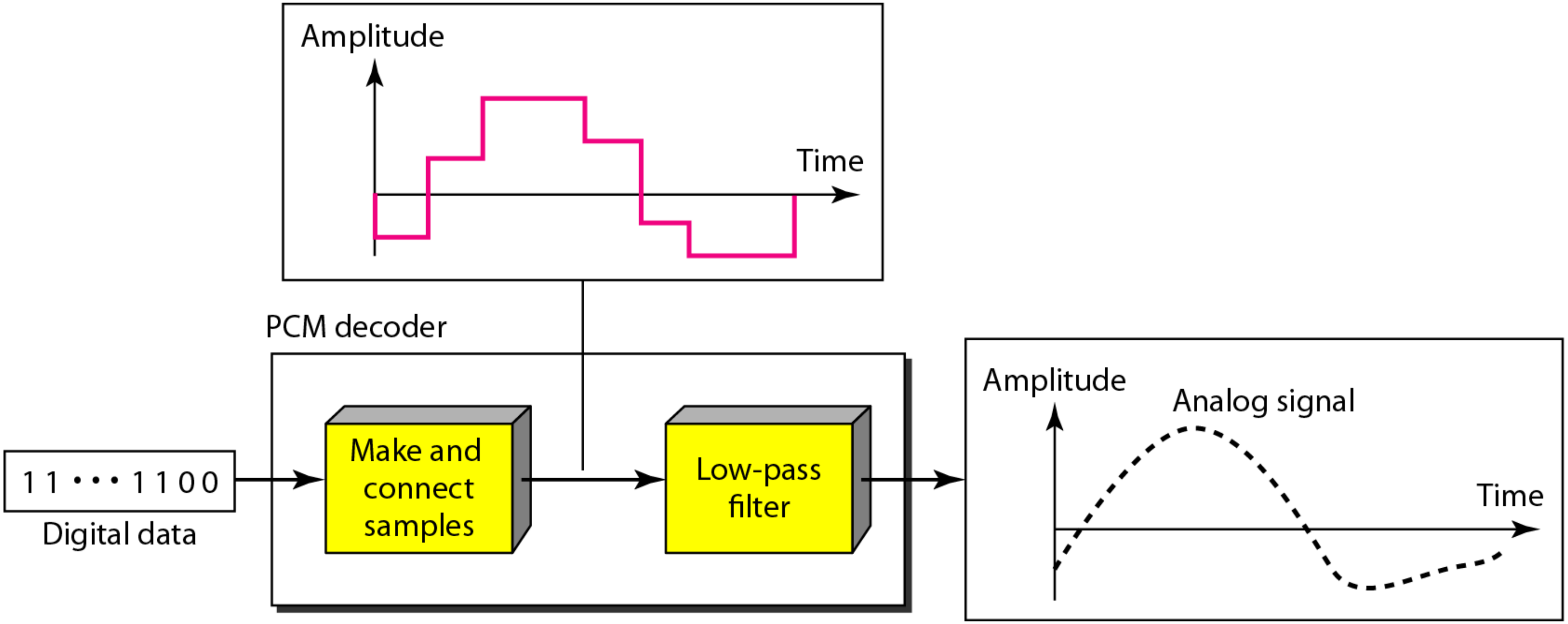


Figure 4.27 *Components of a PCM decoder*

Delta Modulation (DM)

- PCM is very complex technique, however, other techniques have 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 previous sample.
- This scheme sends only the difference between pulses.

DM (Conti...)

- If the pulse at time t_{n+1} is higher in amplitude value than the pulse at time t_n, then a single bit, say a “1”, is used to indicate the positive value.
- If the pulse is lower in value, resulting in a negative value, a “0” is used.
- This scheme works well for small changes in signal values between samples.
- If changes in amplitude are large, this will result in large errors.

DM (Conti...)

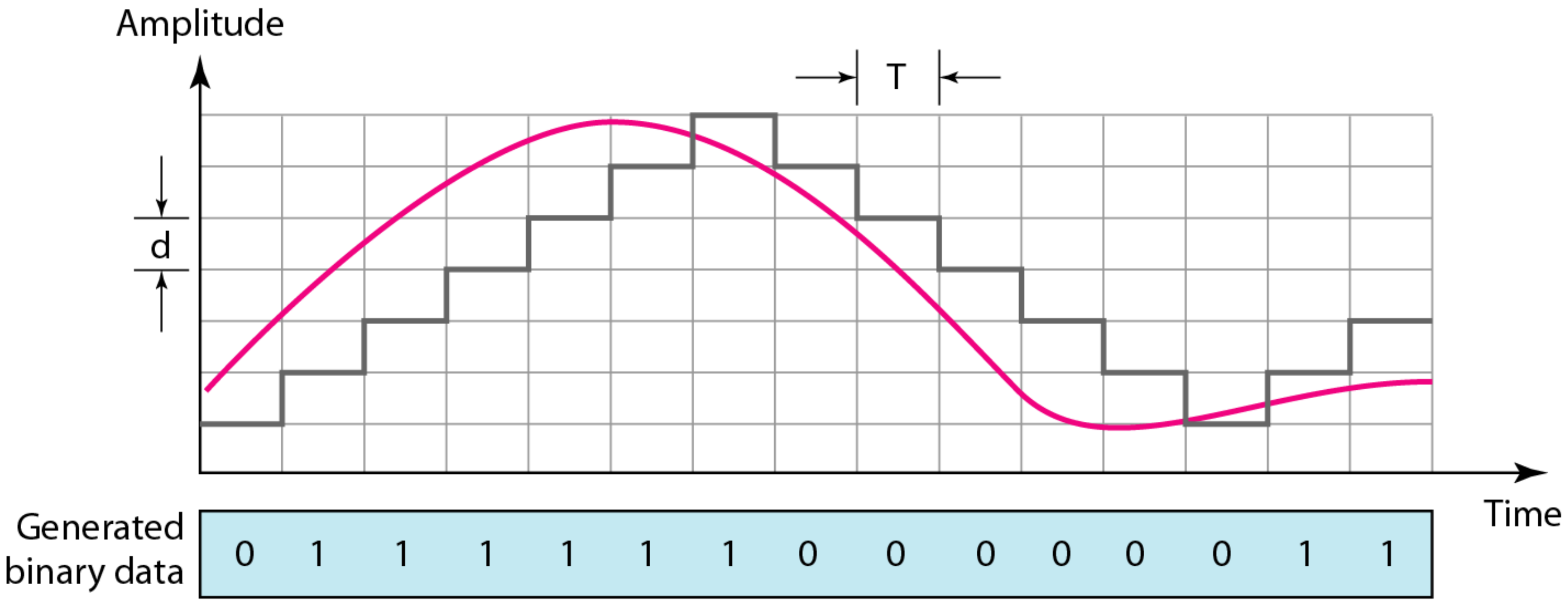


Figure 4.28 *The process of delta modulation*

DM (Conti...)

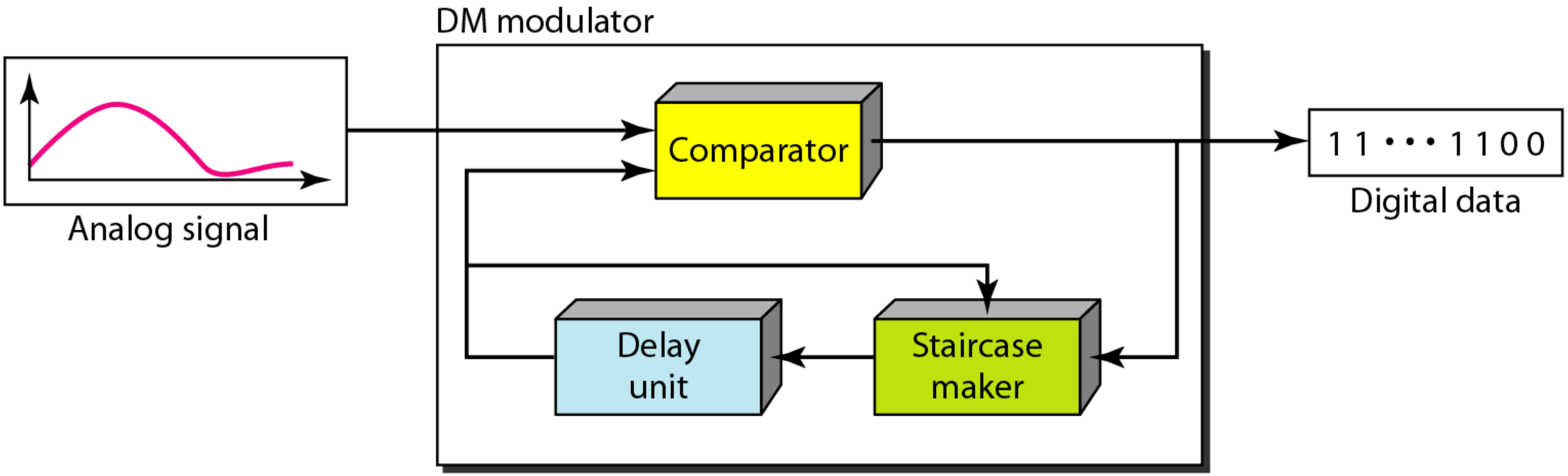


Figure 4.29 *Delta modulation components*

DM (Conti...)

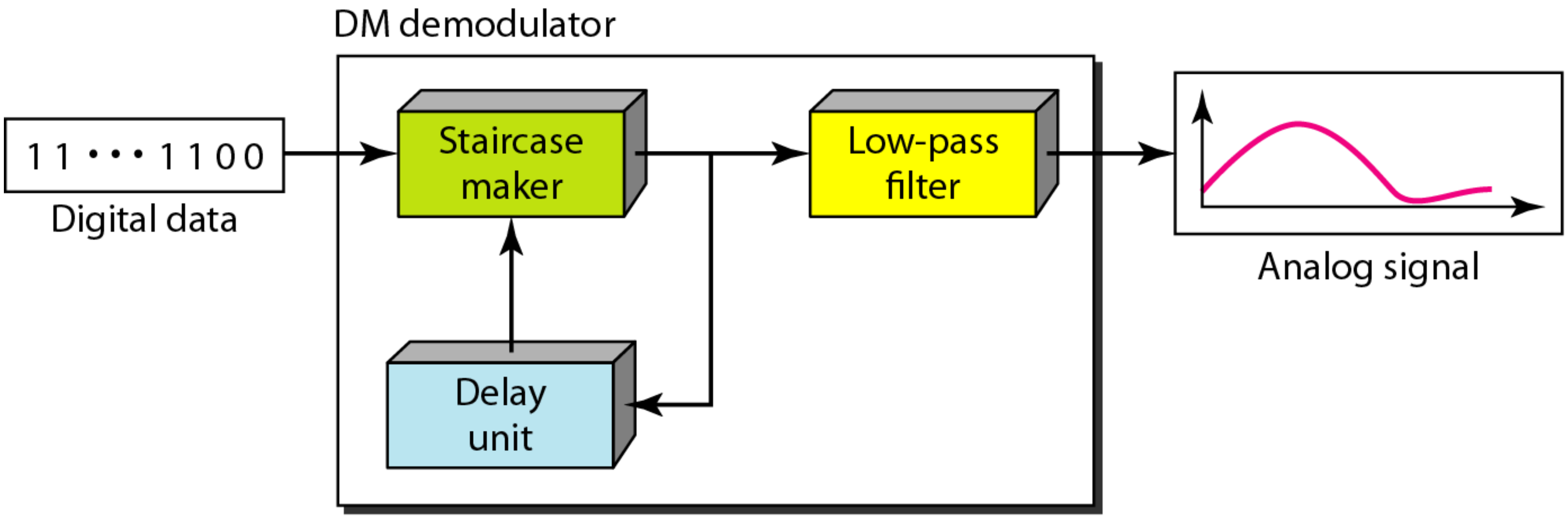


Figure 4.30 *Delta demodulation components*

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.
- There is only one way to send parallel data, while there are three subclasses of serial transmission: asynchronous, synchronous, and isochronous.

Transmission Modes (Conti...)

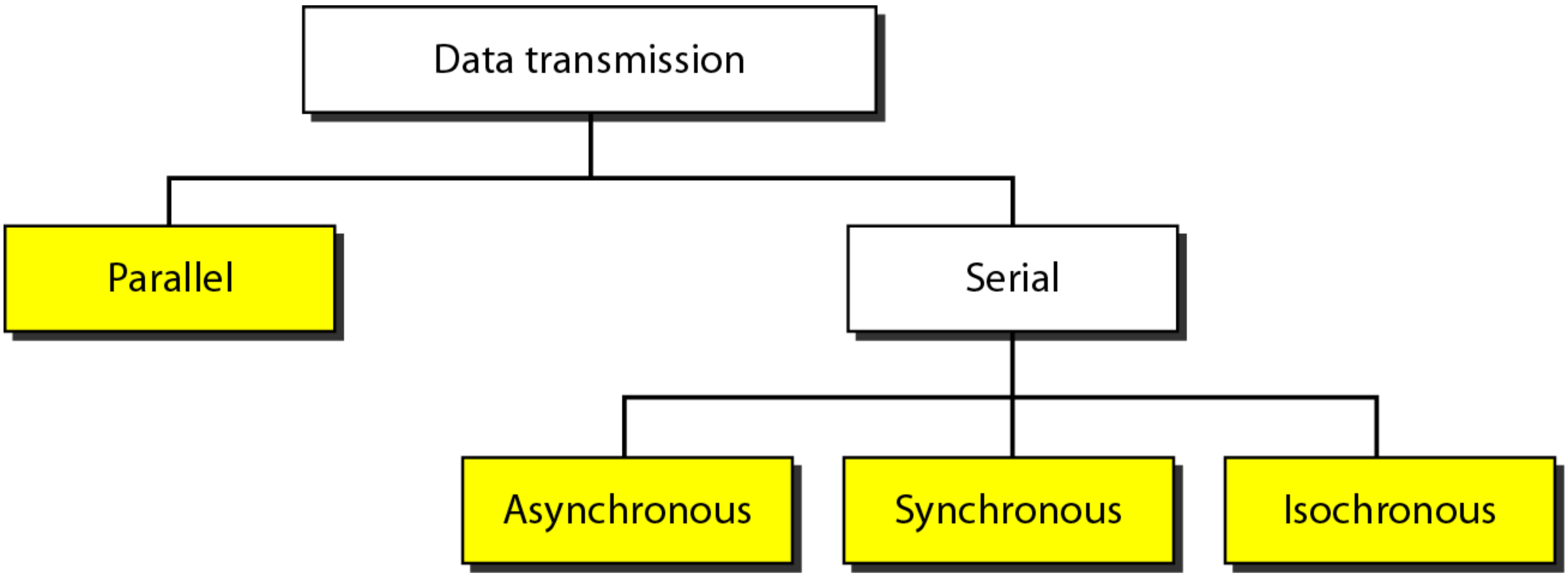


Figure 4.31 *Data transmission and modes*

Parallel Transmission

- Binary data in form of 1s and 0s may be organized into groups of *n* bits each.
- In parallel transmission, the group of *n* bits data can send at a time instead of 1 bit.
- n transmission lines are used to send *n* bits at a time with a single clock tick from one device to another.
  - Advantage: Speed
  - Disadvantage: Cost

Parallel Transmission (Conti...)

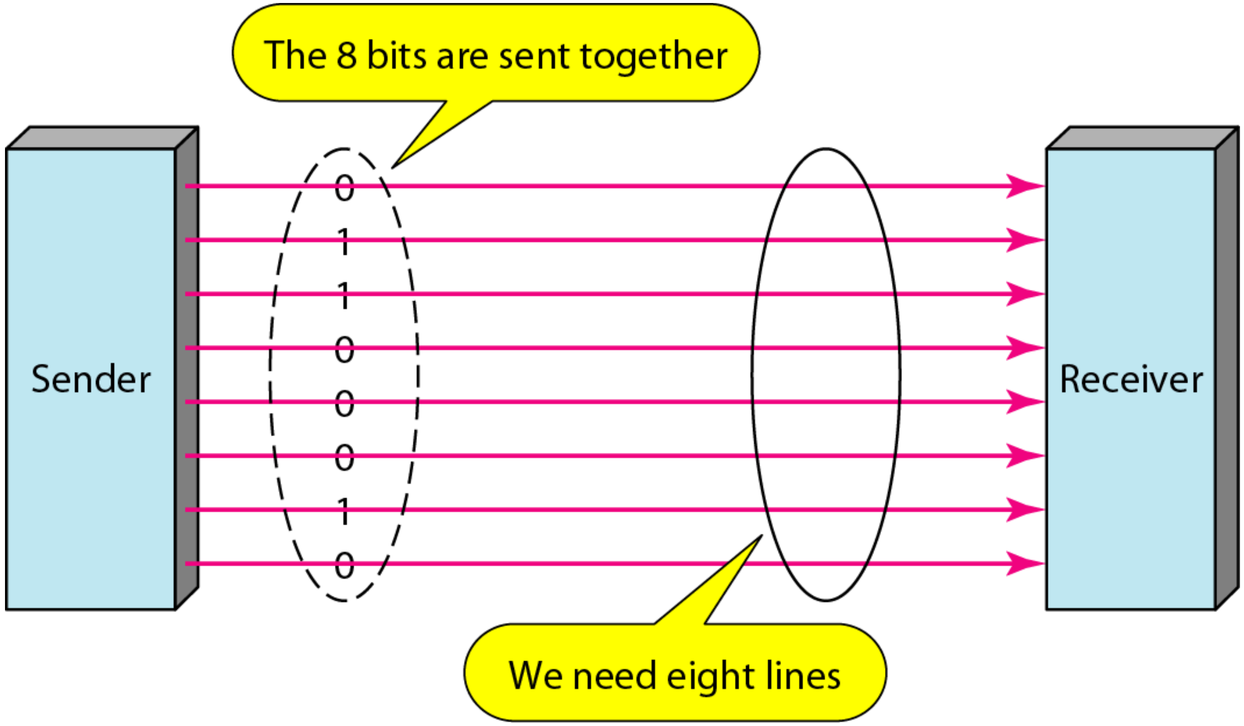


Figure 4.32 *Parallel transmission*

Serial Transmission

- In serial transmission 1 bit follow another, so one communication channel is required to send *n* bits of data from one device to another.
- Communication within devices is parallel, conversion devices are required at interfaces:
  - Between sender and line – Parallel to Serial
  - Between line and receiver – Serial to Parallel
- Serial transmission occurs in one of three ways:
  - Asynchronous
  - Synchronous
  - Isochronous

Serial Transmission (Conti...)

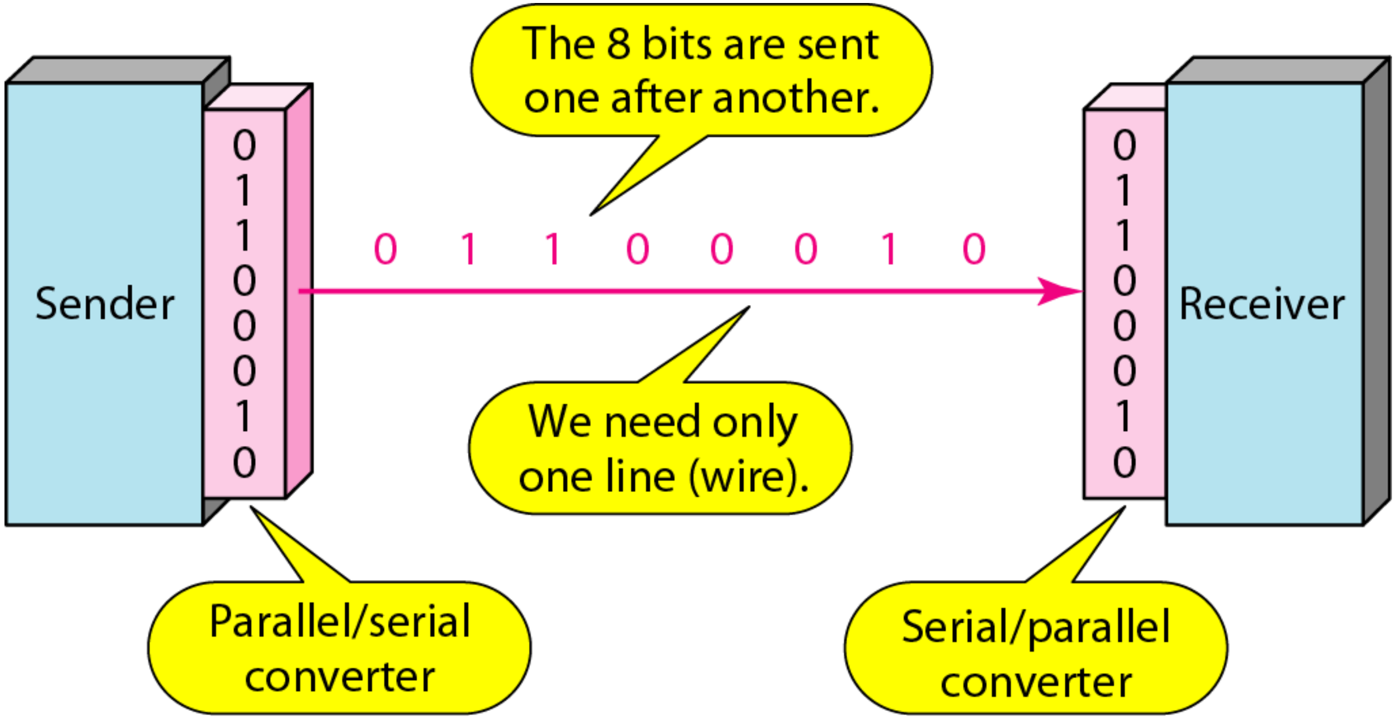


Figure 4.33 *Serial transmission*

Asynchronous Transmission

- In asynchronous transmission timing of signal is not important while information and agreed upon patterns are important.
- Patterns are based on grouping the bit stream into bytes.
- The sender handles each group (byte) independently, relaying to the link whenever ready, without regard to a timer.
- Without synchronization, the receiver is not able to predict the arrival of next group (byte).

Asynchronous Transmission (Conti...)

- Receiver is alerted about the arrival of the new group (byte) by an extra bit usually a 0, known as start bit.
- One or more additional bits, usually 1s (known as stop bits) are appended at the end of each byte to let the receiver know about the end of the byte.
- There may be gaps between each byte.
- Asynchronous means “asynchronous at byte level,” but the bits are still synchronized; their durations are known.

Asynchronous Transmission (Conti...)

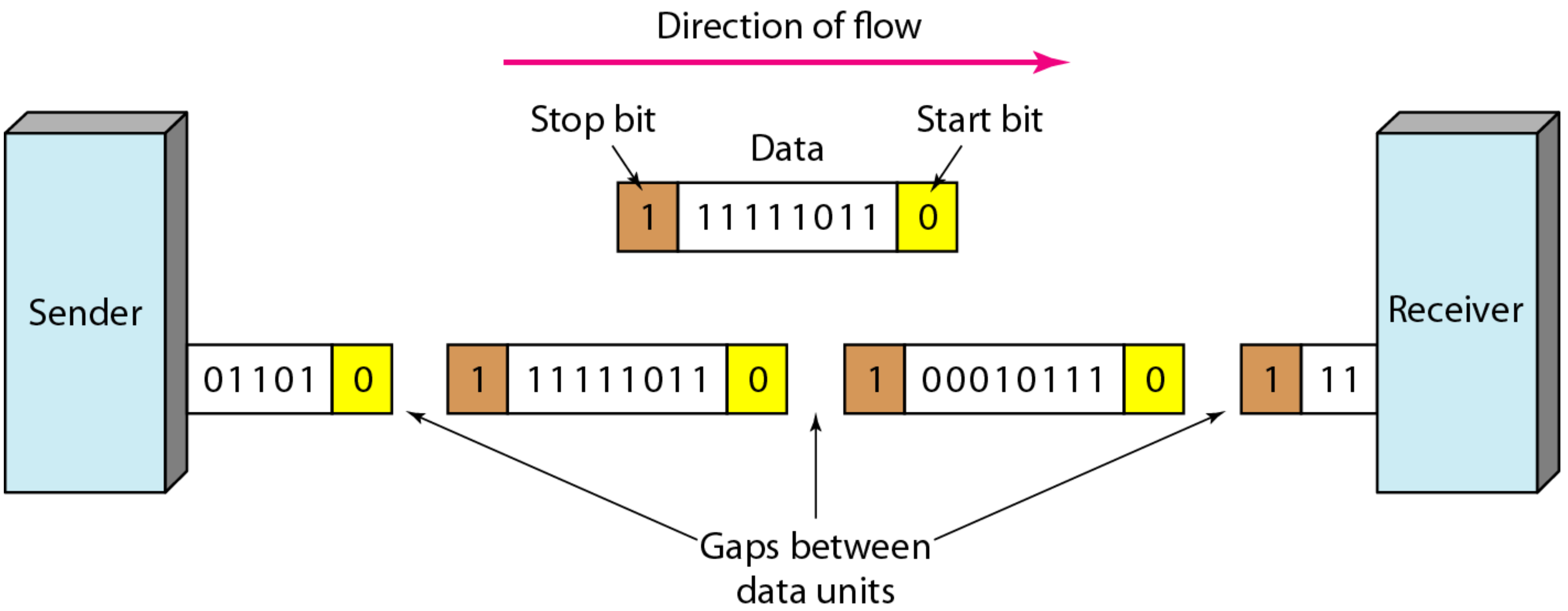


Figure 4.34 *Asynchronous transmission*

Synchronous Transmission

- 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 bits are usually sent as bytes and many bytes are grouped in a frame.
- A frame is identified with a start and an end byte.
- The gaps (if any) between the bit streams are filled with special sequence of 0s and 1s that means idle.

Synchronous Transmission (Conti...)

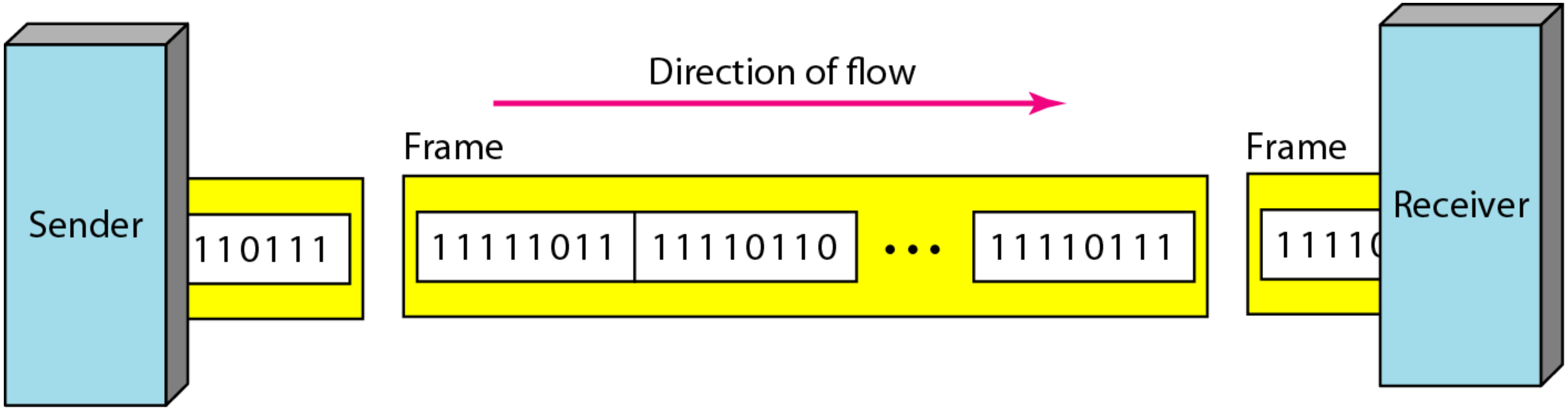


Figure 4.35 *Synchronous transmission*

Isochronous Transmission

- Synchronous transmission fails in real-time audio and video transmission where uneven delays (gaps) between frames are not acceptable.
- For such type of transmissions synchronization between characters is not enough; the entire stream of bits must synchronized.
- Isochronous transmission guarantees that the data arrive at a fixed rate.