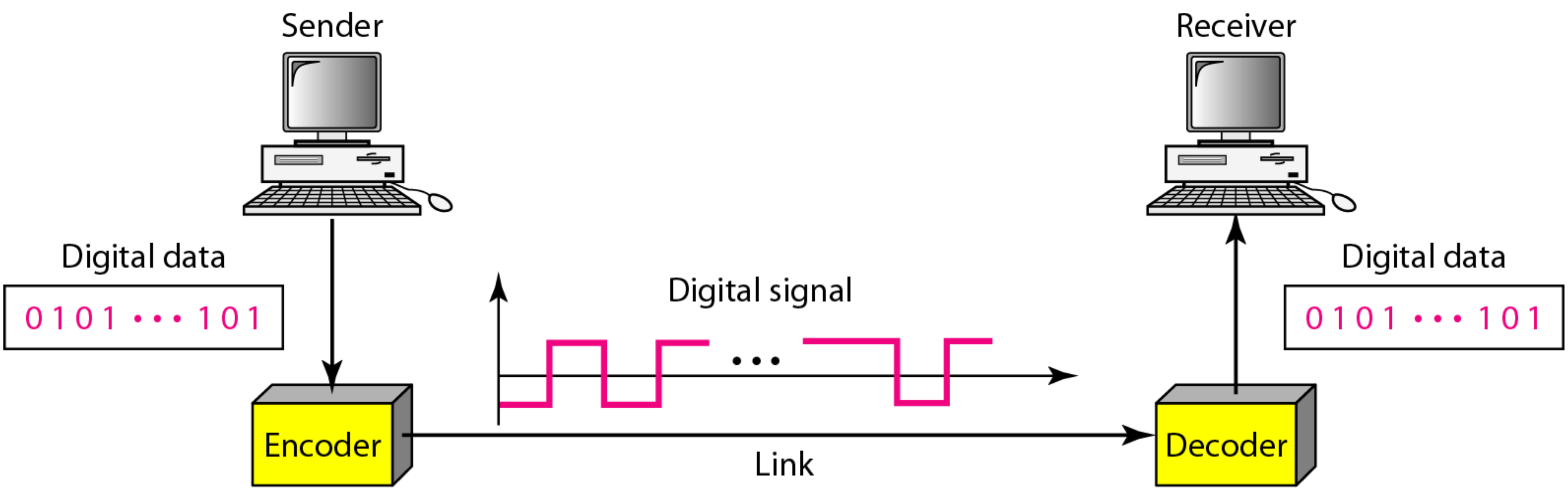
CSE 365: Communication Engineering

Chapter 4: Digital Transmission

Digital-to-Digital Conversion

- Line Coding - Process of converting *digital data* to *digital signal*

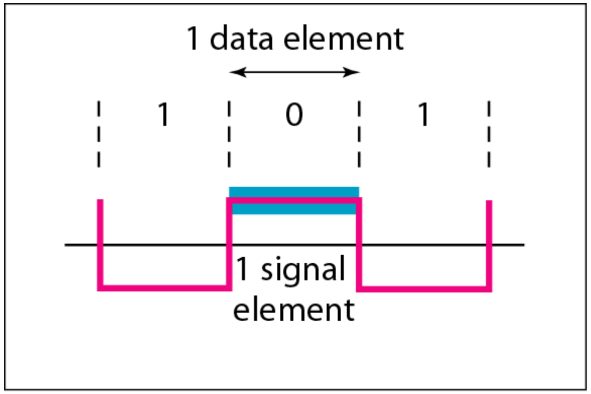


Line coding and decoding

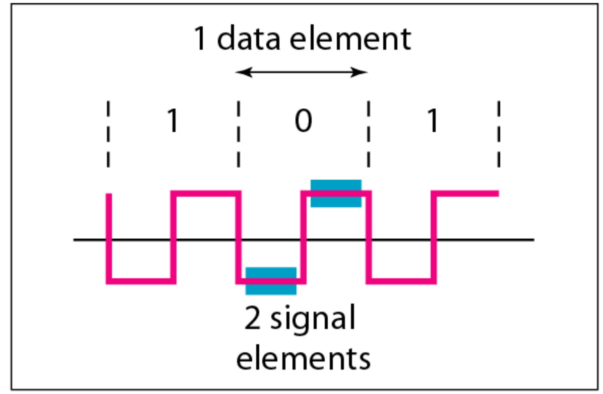
Signal Element vs. Data Element

- A *data element* is the smallest entity that can represent a piece of information, i.e. the bit.
- A *signal element* is the shortest unit (timewise) of a digital signal.
- In data communication, a signal element carries data elements.
- Data elements are being carried; signal elements are the carriers.

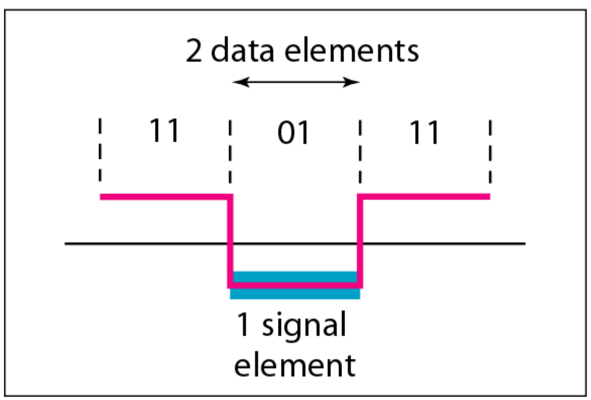
Signal Element vs. Data Element



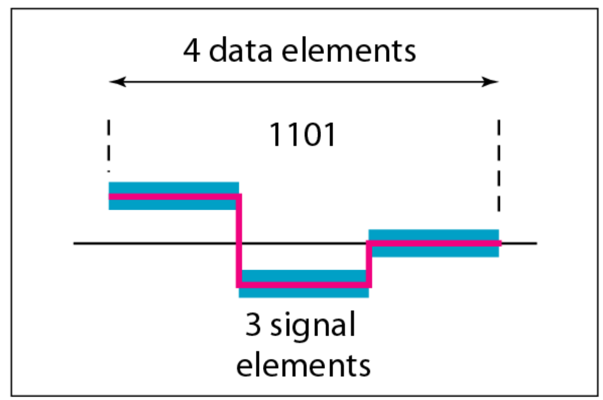
a. One data element per one signal element ($r = 1$)



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

- The *data rate* defines the number of data elements (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 the *modulation rate* or *pulse rate* or *baud rate*.
- Goal is to increase the data rate whilst reducing the baud rate.
- The relationship between data rate (N) and signal rate (S) is:

$$S = N/r \text{ baud}$$

$$S_{ave} = c \times N \times 1/r \text{ baud;}$$

where N is data rate, c is the case factor (worst, best & avg.) and r is the ratio between data element & 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

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

Bandwidth

- A digital signal is non-periodic with an infinite signal (From previous chapter)

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

- Bandwidth is proportional to the signal rate or baud rate
  - The minimum bandwidth

    $$B_{min} = c \times N \times (1 / r)$$

  - Maximum Data rate

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

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

- Baseline wandering – While decoding a digital signal, the receiver calculates a running average of the received signal power, which is called the baseline and this is used to determine the value of the incoming data elements.
- If the incoming signal does not vary over a long period of time (i.e. a long string of 0s or 1s), it causes a drift in the baseline (baseline wandering) and makes it difficult for the receiver to decode correctly.
- A good line encoding scheme needs to prevent baseline wandering.

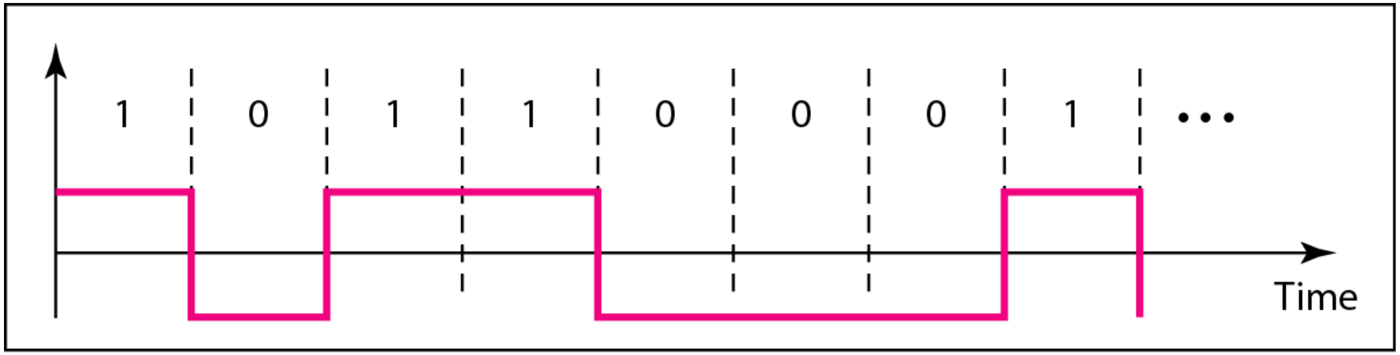
DC Components

- When the voltage level in a digital signal is constant for a while, the spectrum creates very low frequencies. These frequencies around zero, called DC (Direct Current) components.
- Creates problem for a system that cannot pass low frequencies.
- Leaves extra (useless) energy on the line.
- DC component means 0/1 parity that causes baseline wandering.
- DC components in signals are not desirable and we need a scheme with no DC component.

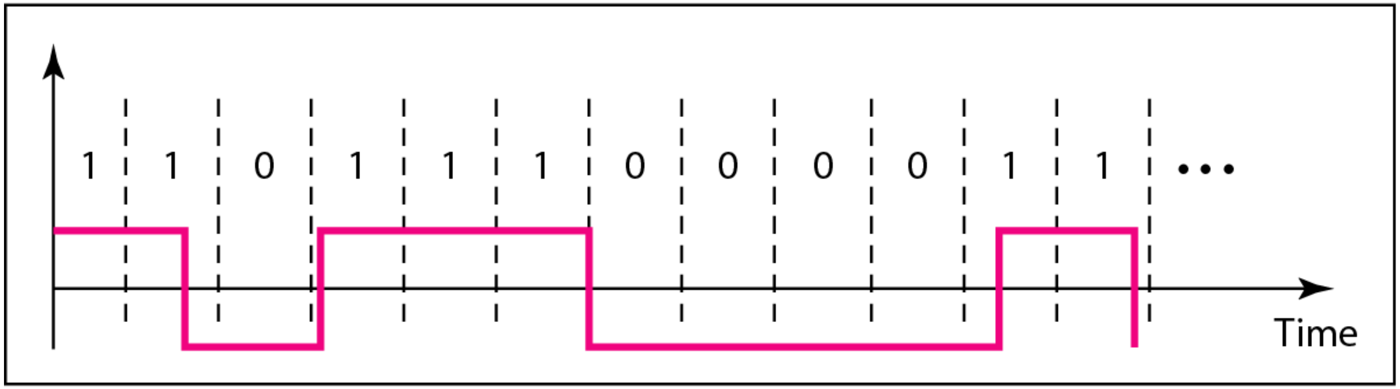
Self Synchronization

- Self synchronization – to correctly interpret the signals received from the sender, the receiver’s bit intervals must correspond exactly to the sender’s bit intervals.
- If the receiver clock is faster or slower it will misinterpret the incoming bit stream.
- A self-synchronizing digital signal includes timing information in the data being transmitted. This can be achieved if there are transitions in the signal that alert the receiver to the beginning, middle or end of the pulse.

Effect of lack of Synchronization



a. Sent

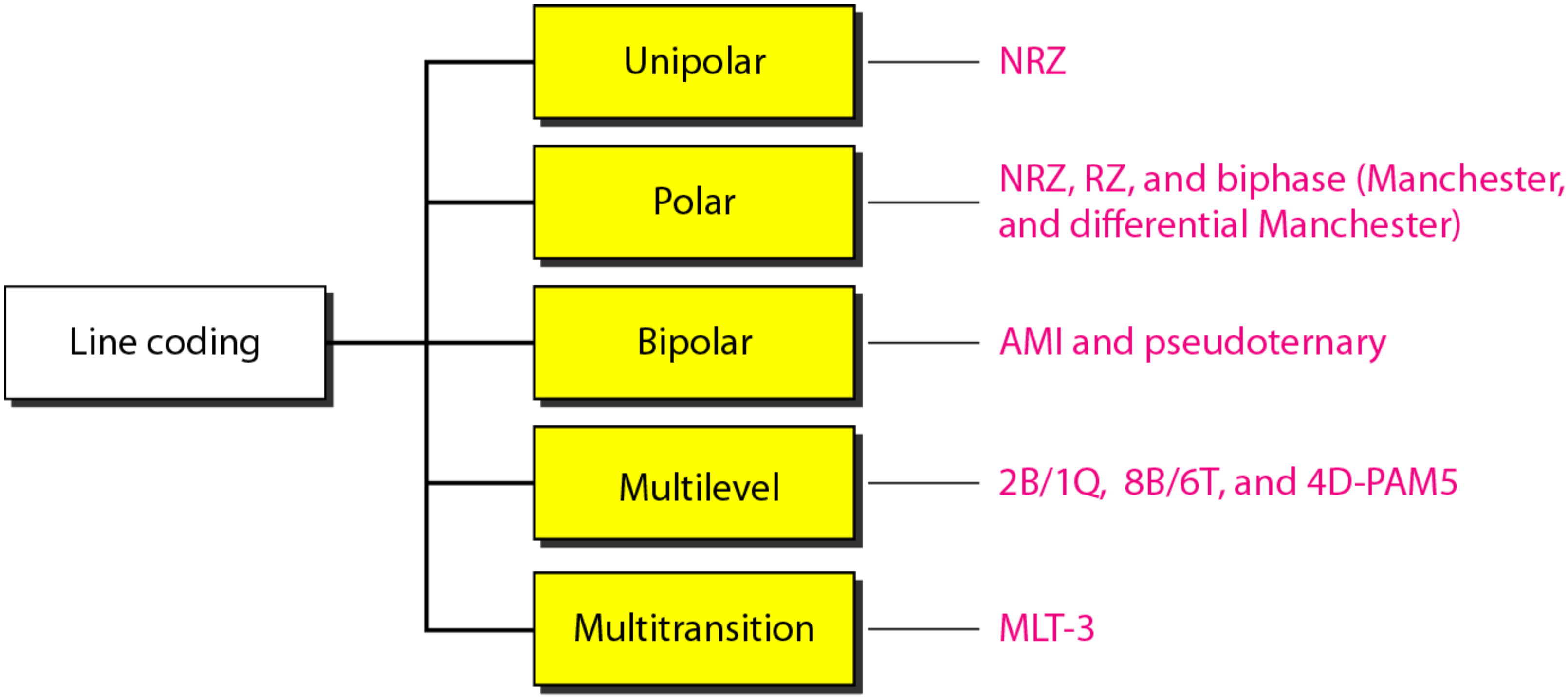


b. Received

Other Encoding Considerations

- *Built-in Error Detection* - errors occur during transmission due to line impairments.
- *Immunity to Noise and Interference* - there are line encoding techniques that make the transmitted signal "immune" to noise and interference.
- *Complexity*

Line Coding Schemes

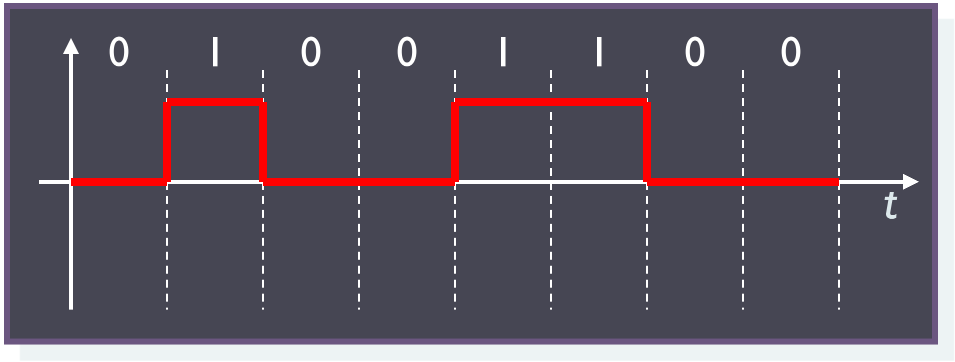


Line Coding Methods

- Unipolar
  - Uses only one voltage level (one side of time axis)
- Polar
  - Uses two voltage levels (negative and positive)
  - e.g., NRZ, RZ, Manchester, Differential Manchester
- Bipolar
  - Uses three voltage levels (+, 0, and –) for data bits

Unipolar

- Simplest form of digital encoding
  - ⇨Rarely used
- Only one polarity of voltage is used
- E.g., polarity assigned to 1

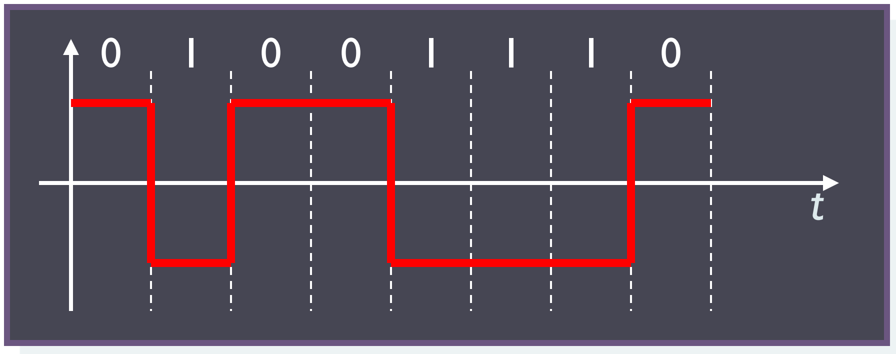


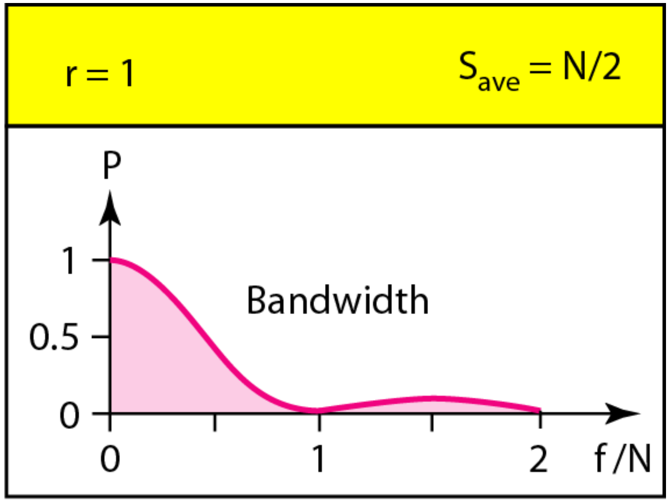
Polar

- Two voltage levels (+,-) represent data bits
- Most popular four
  - Nonreturn-to-Zero (NRZ)
  - Return-to-Zero (RZ)
  - Manchester
  - Differential Manchester

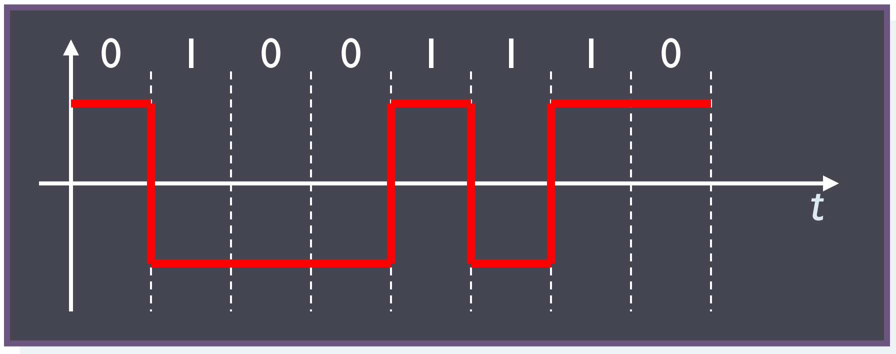
NRZ Encoding

- Nonreturn to Zero
  - **NRZ-L (NRZ-Level):** Signal level depends on bit value





  - **NRZ-I (NRZ-Invert):** Signal is inverted if 1 is encountered



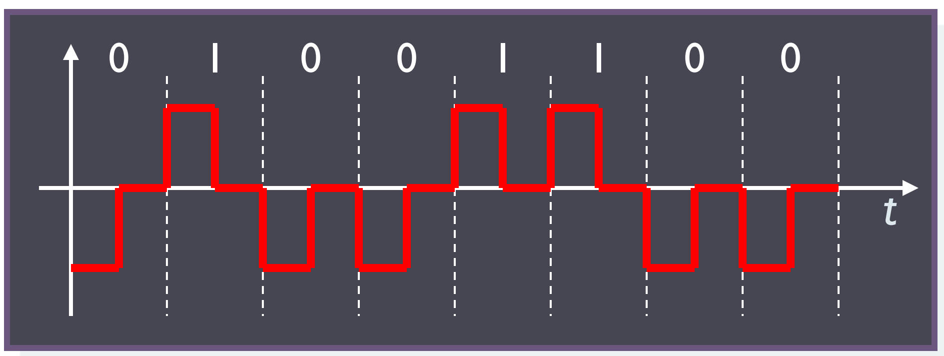
N = Bit rate
S_{ave} = Average signal rate

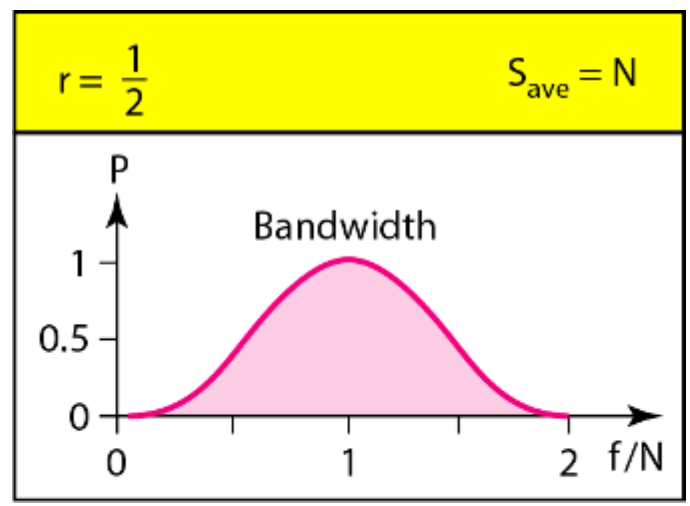
Comparison of NRZ-L and NRZ-I

- Baseline wandering is a problem for both.
  - In NRZ-L, it is two times severe than NRZ-I.
  - In NRZ-I, this problem occurs only for a long sequence of 0s.
- Synchronization problem: While a long sequence of 0s can cause a problem in both schemes, a long sequence of 1s affects only NRZ-L
- Polarity problem in NRZ-L: When there is a sudden change of polarity in the system. For example, if twisted-pair cable is the medium, a change in the polarity of the wire results in all 0s interpreted as 1s and all 1s interpreted as 0s. NRZ-I does not have this problem

RZ Encoding

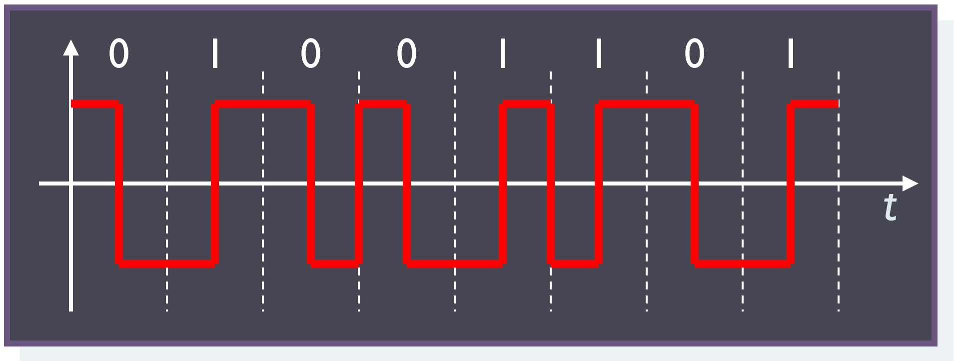
- Return to Zero
  - Uses three voltage levels: +, - and 0, but only + and - represent data bits
  - Half way thru each bit, signal returns to zero

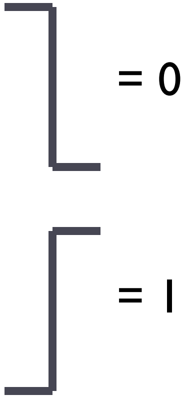




Polar Biphase: Manchester Encoding

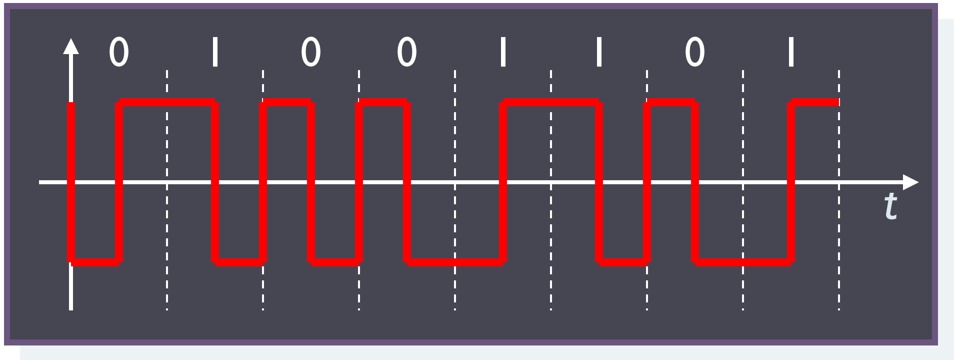
- RZ and NRZ-L are combined.
- Uses an inversion at the middle of each bit
  - For bit representation
  - For synchronization





Polar Biphase: Differential Manchester Encoding

- RZ and NRZ-I are combined.
- The inversion on the middle of each bit is only for synchronization
- Transition at the beginning of each bit tells the value



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

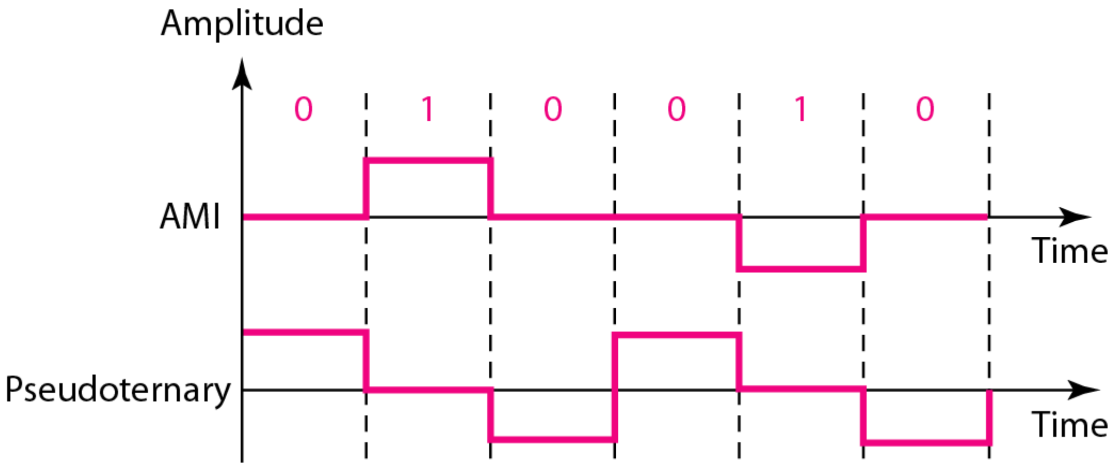
Manchester and Differential Manchester Encoding

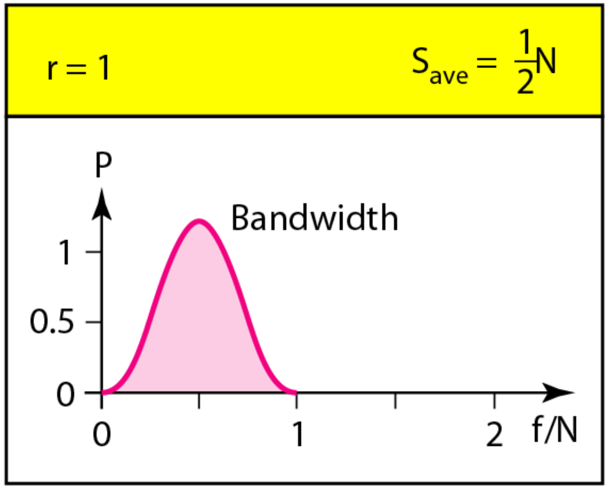
- In Manchester and differential Manchester encoding, the transition at the middle of the bit is used for synchronization.
- The minimum bandwidth of Manchester and differential Manchester is 2 times that of NRZ.
- There is no DC component and no baseline wandering.
- None of these codes has error detection.

Bipolar Scheme

- Also known as Multilevel binary.
- Bipolar encoding uses three voltage levels: positive, negative and zero
- Each of all three levels represents a bit
- ***Two schemes:***
  - ***AMI*** (Alternate Mark Inversion)
    - 0V always represents binary 0
    - Binary 1s are represented by alternating positive and negative voltages.
  - ***Pseudoternary***
    - The reverse of AMI.

Bipolar Scheme:
AMI and Pseudoternary





Bipolar Scheme

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

Multilevel Schemes

- In these schemes we increase the number of data bits per baud thereby increasing the bit rate.
- Since we are dealing with binary data we only have 2 types of data element a 1 or a 0.
- We can combine the 2 data elements into a pattern of "m" elements to create "2^m" symbols.
- If we have L signal levels, we can use "n" signal elements to create L^n signal elements.
- Now we have 2^m symbols and L^n signals.

Multilevel Schemes

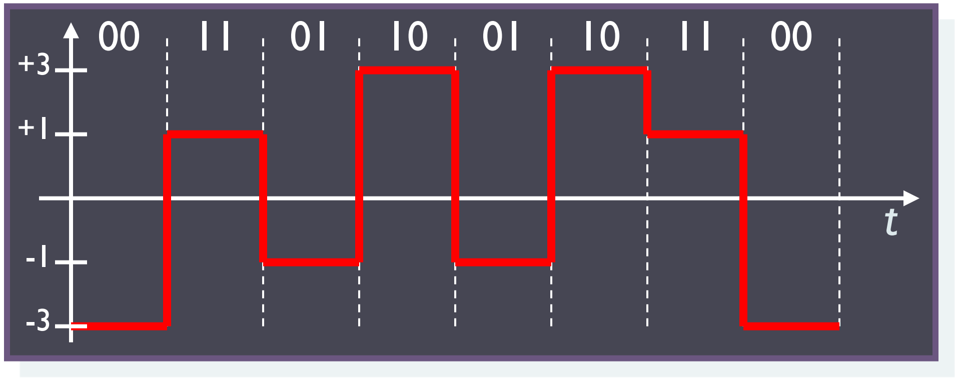
- If $2^m > L^n$, we cannot represent the data elements as we don't have enough signals.
- If $2^m = L^n$, we have an exact mapping of one symbol on one signal.
- If $2^m < L^n$, we have more signals than symbols and we can choose the signals that are more distinct to represent the symbols and therefore have better noise immunity and error detection.

Representing Multilevel Codes

- This type of coding is represented as ***mBnL***, where ***m*** is the length of the binary pattern, ***B*** represents binary data, ***n*** represents the length of the signal pattern and ***L*** is the number of levels.
  - L = B binary,
  - L = T for 3 ternary,
  - L = Q for 4 quaternary.

2B1Q (two binary, 1 quaternary)

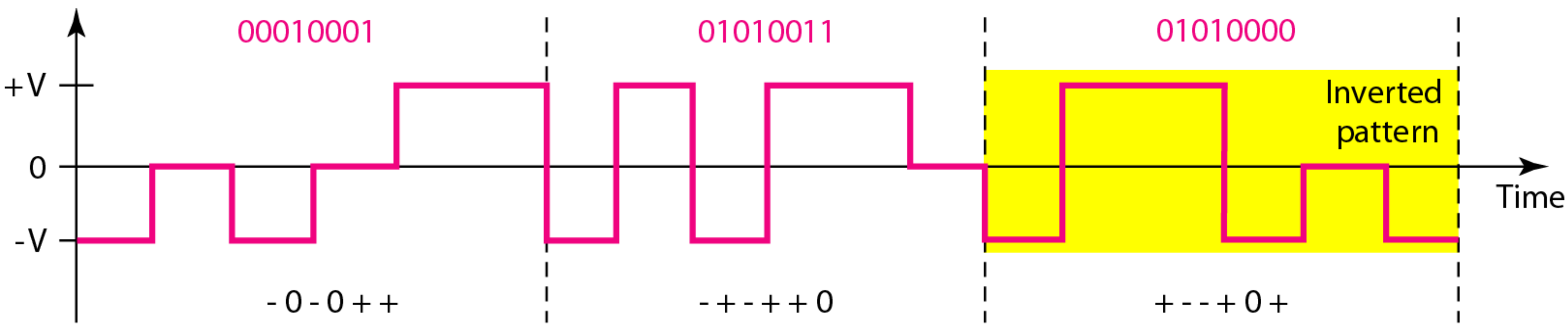
Bit sequence	Voltage level
00	-3
01	-1
10	+3
11	+1



- The average signal rate is S = N/4
- Data rate is two times faster than by using NRZ-L
- No redundancy
- It is used in DSL (Digital Subscriber Line) technology

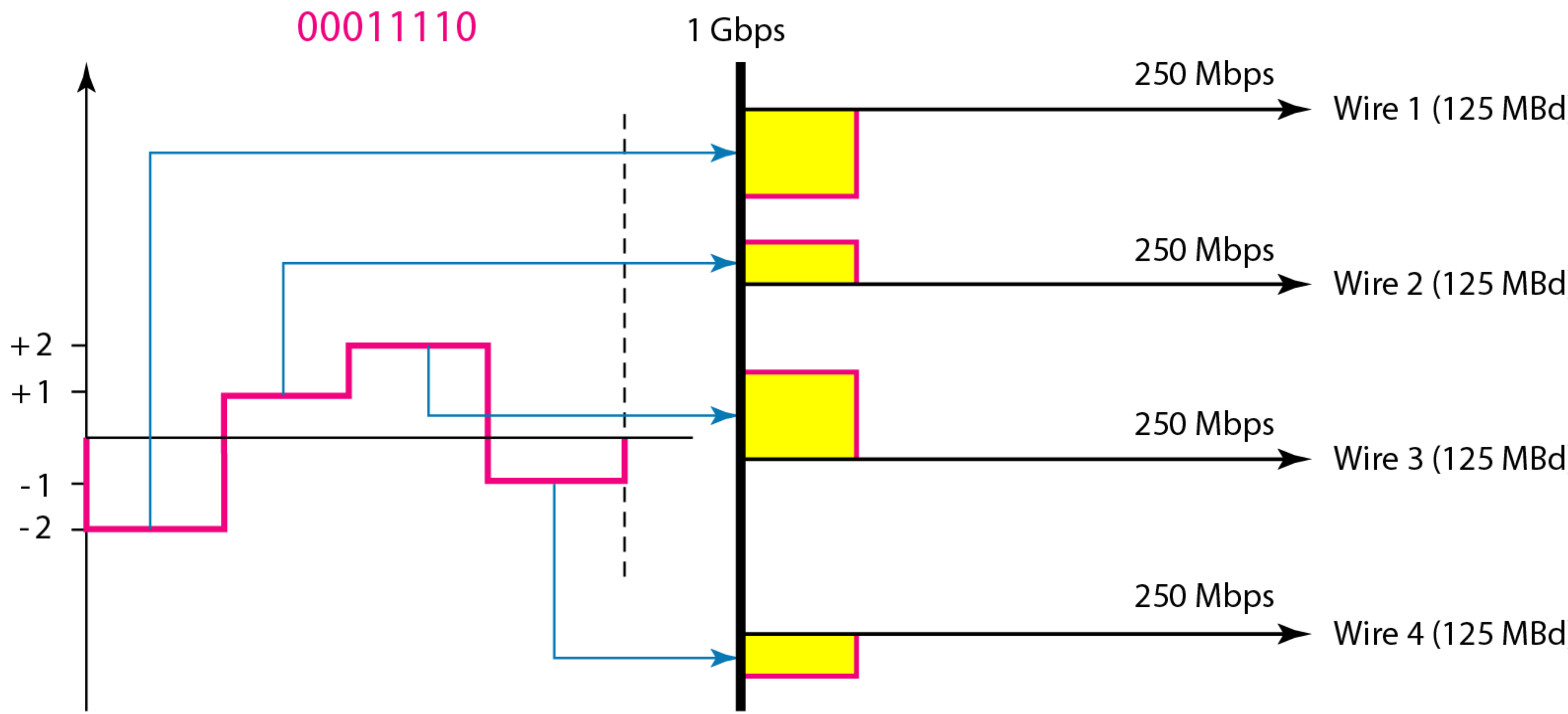
8B6T (Eight binary, six ternary)

- $2^8 = 256$ data patterns and $3^6 = 729$ different signal patterns
- There are 729 – 256 = 473 redundant signal elements to provide synchronization and error detection.
- The sender keeps track of the weight.



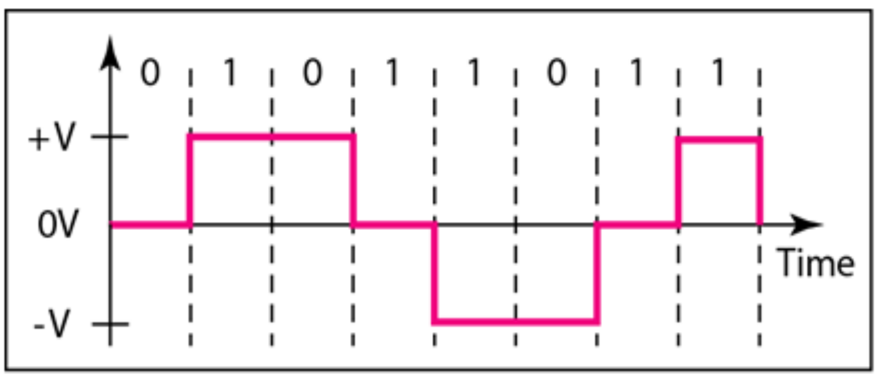
4D-PAM5: Four dimensional five level pulse amplitude modulation

- The 4D means that the data is sent over four wires at the same time.
- It uses five voltage levels: -2, -1, 0, 1, 2.
- 0 is only used for error detection.

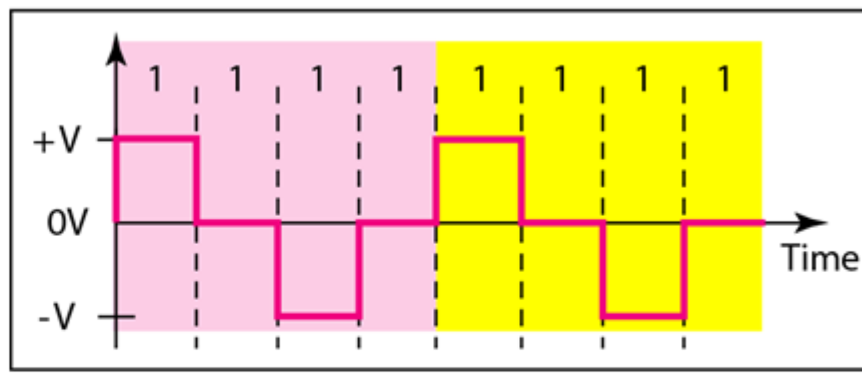


Multi-transition Coding: MLT-3

- Multiline Transmission, three level (MLT 3) scheme uses three levels (+V, 0, -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 non-zero level.



Typical case



Worst case

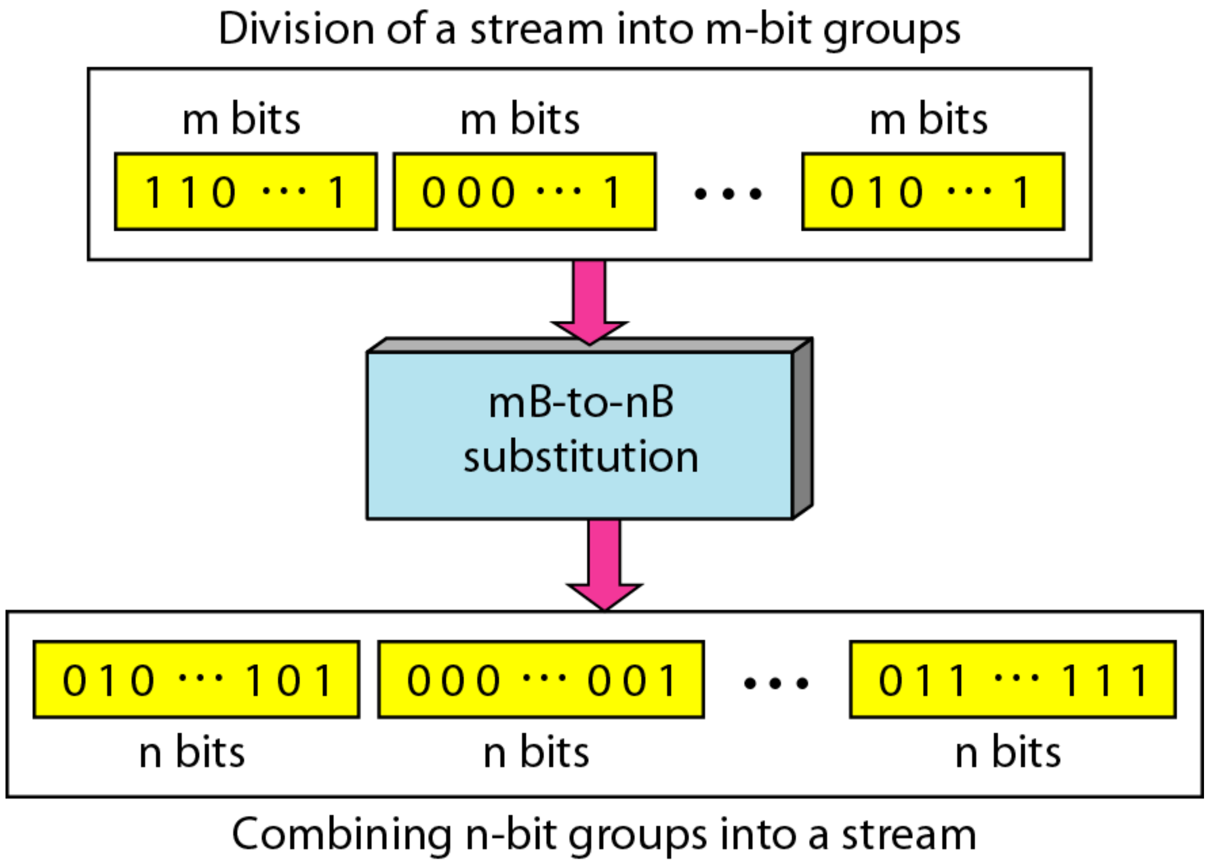
Summary of line coding schemes

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

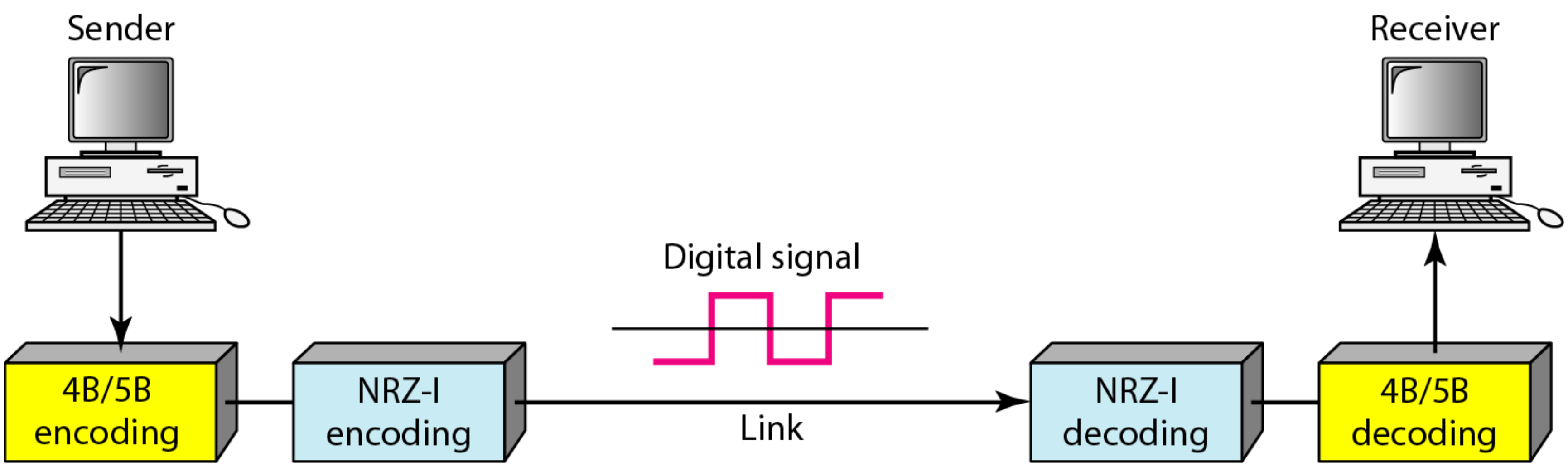
- Block coding provides the redundancy and improves the performance of line coding.
- It changes a block of *m* bits into a block of *n* bits, where *n* is larger than *m*.
- It is also referred to as an ***mB/nB*** encoding technique
- It involves in three steps: division, substitution and combination

Block Coding Concept



4B/5B (Four binary/five binary)

- It was designed to be used in combination with NRZ-I.
- To solve the synchronization problem, 4B/5B changes the bit stream prior to encoding with NRZ-I, so that it does not have a long stream of 0s.

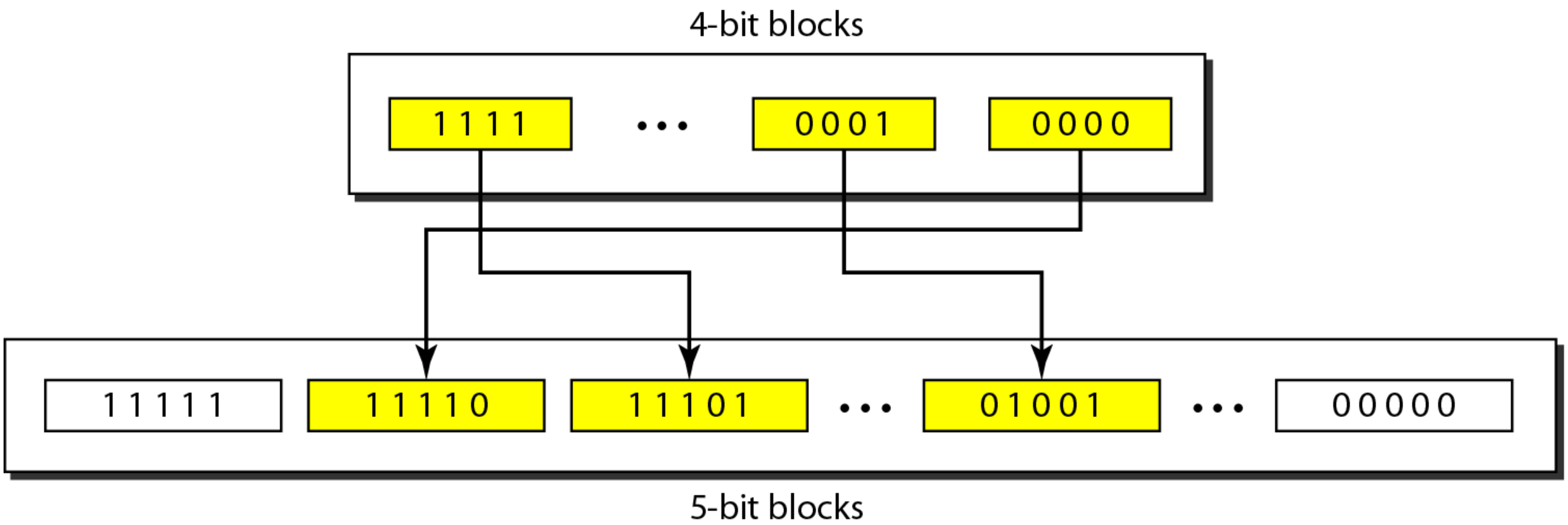


4B/5B Mapping codes

Data Sequence	Code	Data Sequence	Code
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1010	10110
0011	10101	1011	10111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

Control Sequence	Code
Q (Quiet)	00000
I (Idle)	11111
H (Halt)	00100
J (start delimiter)	11000
K (start delimiter)	10001
T (end delimiter)	01101
S (Set)	11001
R (Reset)	00111

Substitution in 4B/5B block coding



Example 4.5

We need to send data at a 1-Mbps rate. What is the minimum required bandwidth, using a combination of 4B/5B and NRZ-I or Manchester coding?

Solution

→First 4B/5B block coding increases the bit rate to 1.25 Mbps.

→The minimum bandwidth using NRZ-I is N/2 or 625 kHz.

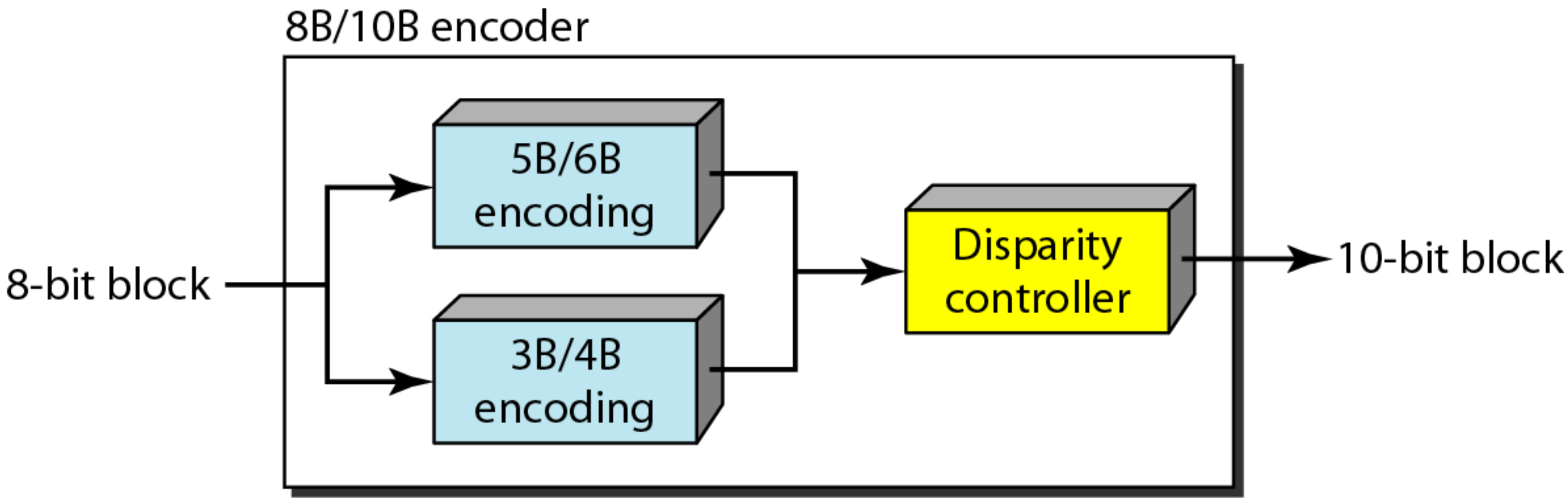
→The Manchester scheme needs a minimum bandwidth of 1 MHz.

→ The first choice needs a lower bandwidth, but has a DC component problem; the second choice needs a higher bandwidth, but does not have a DC component problem.

8B/10B

- More bits - better error detection
- The 8B/10B block code adds more redundant bits and can thereby choose code words that would prevent a long run of a voltage level that would cause DC components.
- 8 bits of data; substituted by a 10-bit code

8B/10B

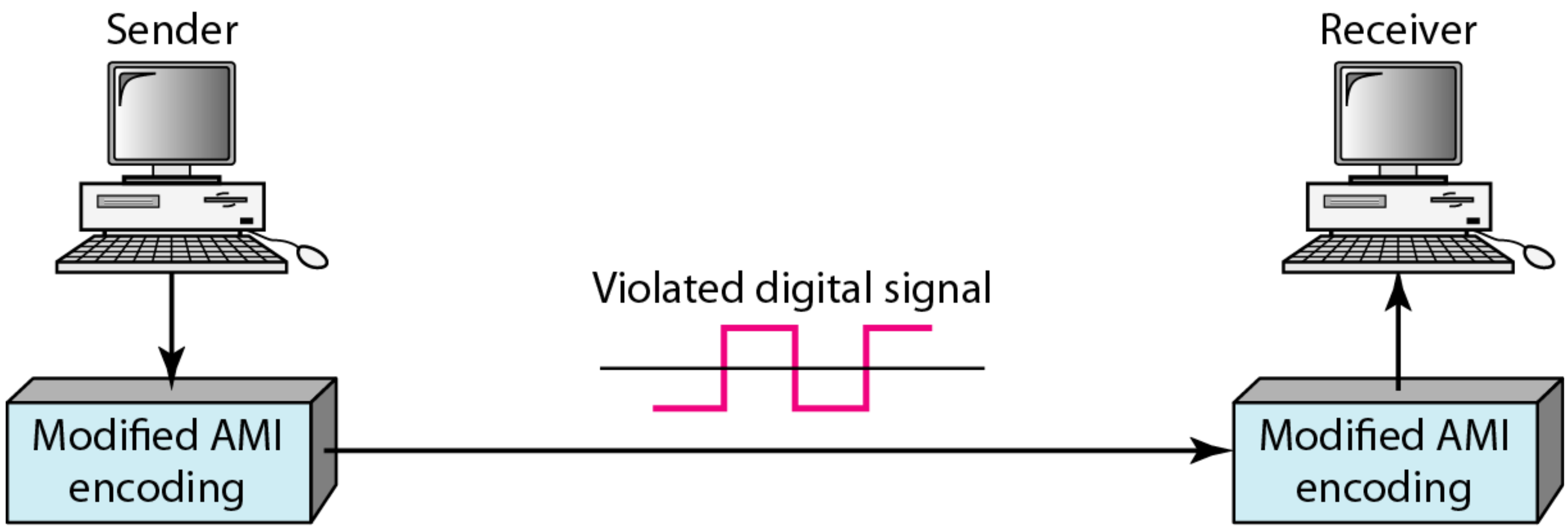


- It is a combination of 5B/6B and 3B/4B encoding.
- The five most significant bits of a 10-bit block are fed into the 5B/6B encoder
- The three least significant bits are fed into the 3B/4B encoder
- A disparity controller is used to prevent a long run of consecutive 0s or 1s.

Scrambling

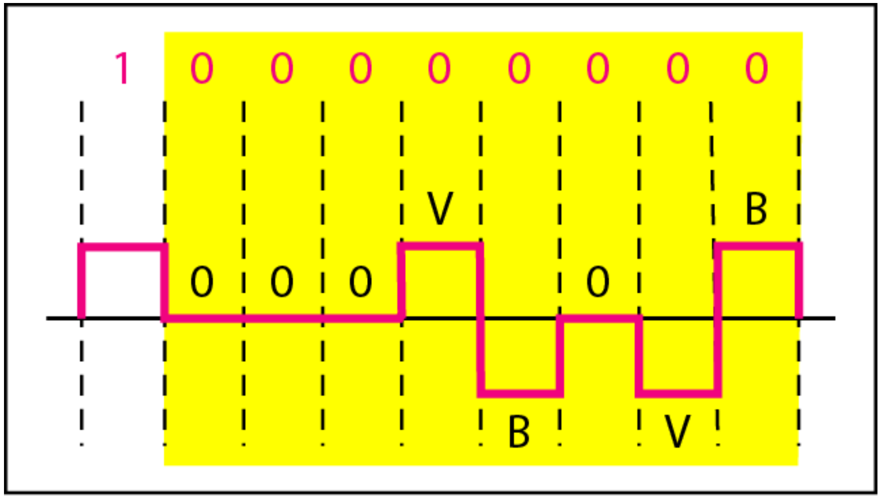
- Biphase schemes are not suitable for long-distance communication because of their wide bandwidth requirement.
- The combination of block coding and NRZ line coding is not suitable for long-distance communication either, because of the DC component.
- Bipolar AMI encoding has a narrow bandwidth and does not create a DC component. However, a long sequence of 0s upsets the synchronization.
- The solution is *Scrambling*.
- It is implemented at the same time as encoding (as opposed to block coding).

AMI used with Scrambling

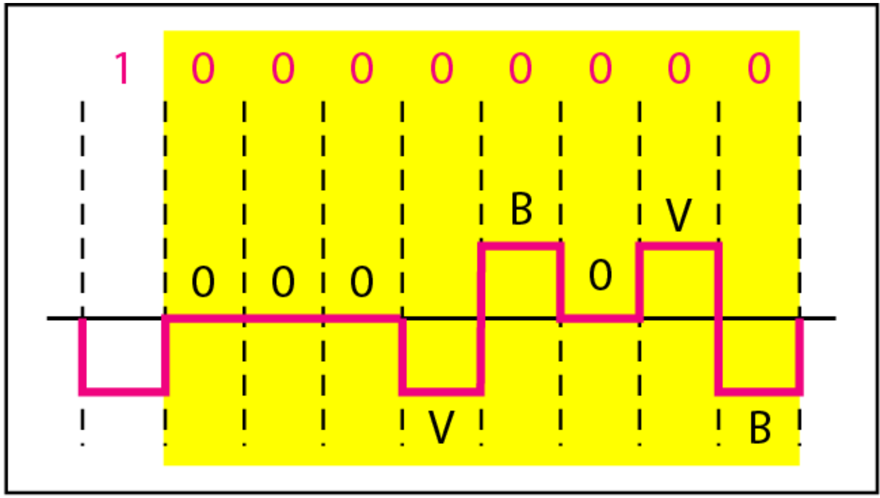


B8ZS

- B8ZS (Bipolar with 8-zero substitution) substitutes eight consecutive zeros with 000VB0VB.
- The V stands for violation, it violates the AMI rule of encoding; B stands for bipolar, it implements the AMI bipolar encoding rule.



a. Previous level is positive.



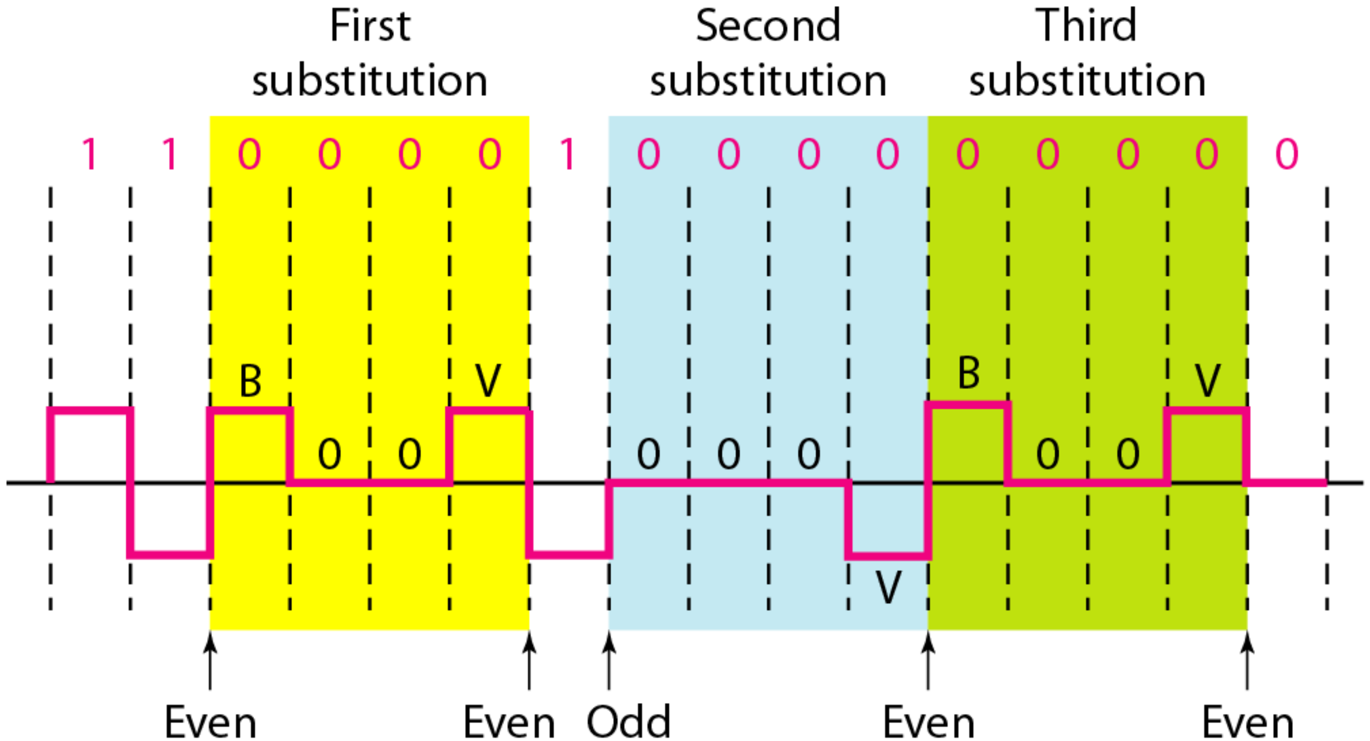
b. Previous level is negative.

HDB3

- HDB3 (High density bipolar 3-zero) substitutes four consecutive zeros with 000V or B00V depending on the number of nonzero pulses after the last substitution.
- There are two rules :
  - If the number of non zero pulses is odd the substitution is 000V to make total number of non zero pulses even.
  - If number of non zero pulses is even the substitution is B00V to make total number of non zero pulses even.

HDB3

- If the number of non zero pulses is odd the substitution is 000V to make total number of non zero pulses even.
- If number of non zero pulses is even the substitution is B00V to make total number of non zero pulses even.



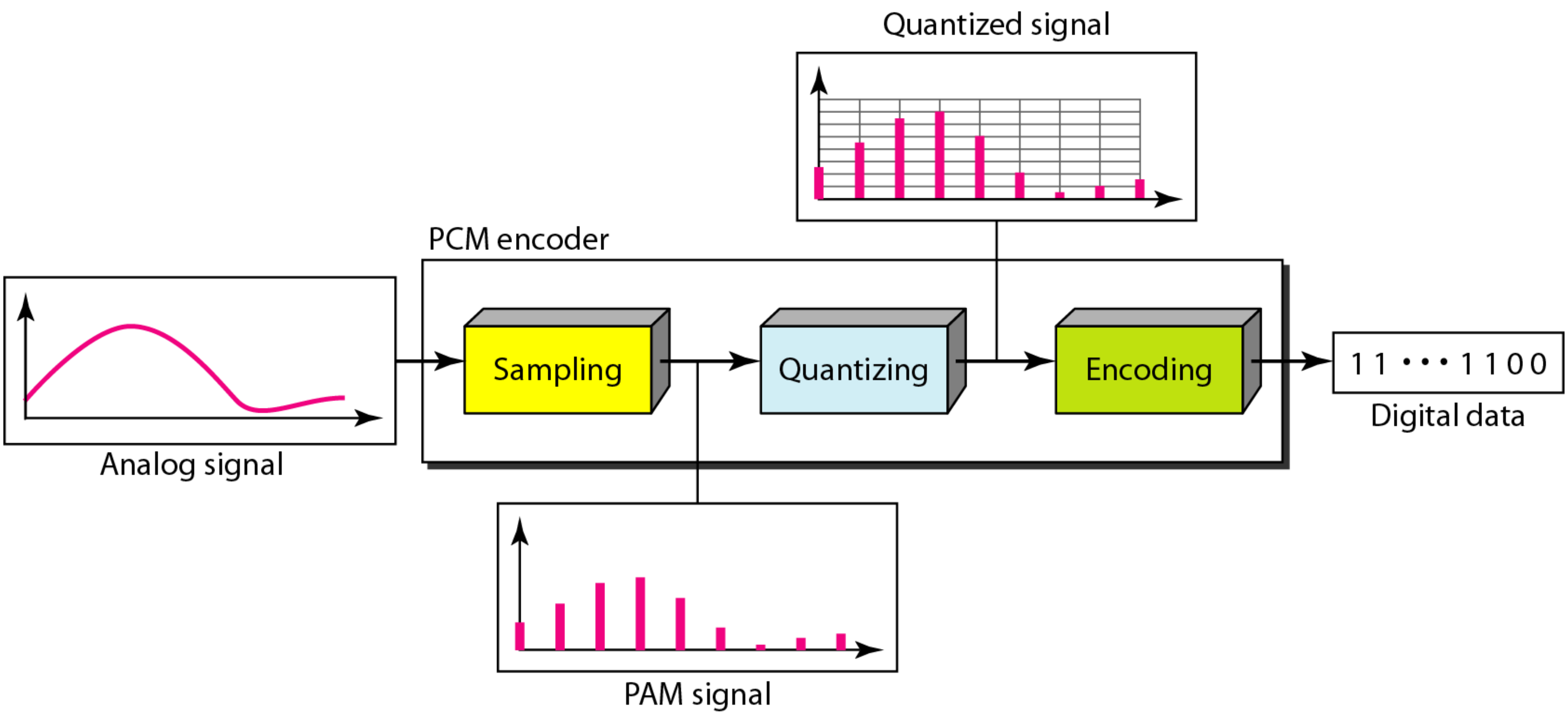
Analog-to-Digital Conversion

- A digital signal is superior to an analog signal. The tendency today is to change an analog signal to digital data.
- Two techniques of analog signal to digital data are:
  - Pulse Code Modulation (PCM)
  - Delta Modulation (DM)

Pulse Code Modulation (PCM)

- The most common technique to change an analog signal to digital data (digitization) is called PCM.
- A PCM encoder has three processes:
  1. The analog signal is sampled.
  2. The sampled signal is quantized.
  3. The quantized values are encoded as streams of bits.

Components of PCM encoder

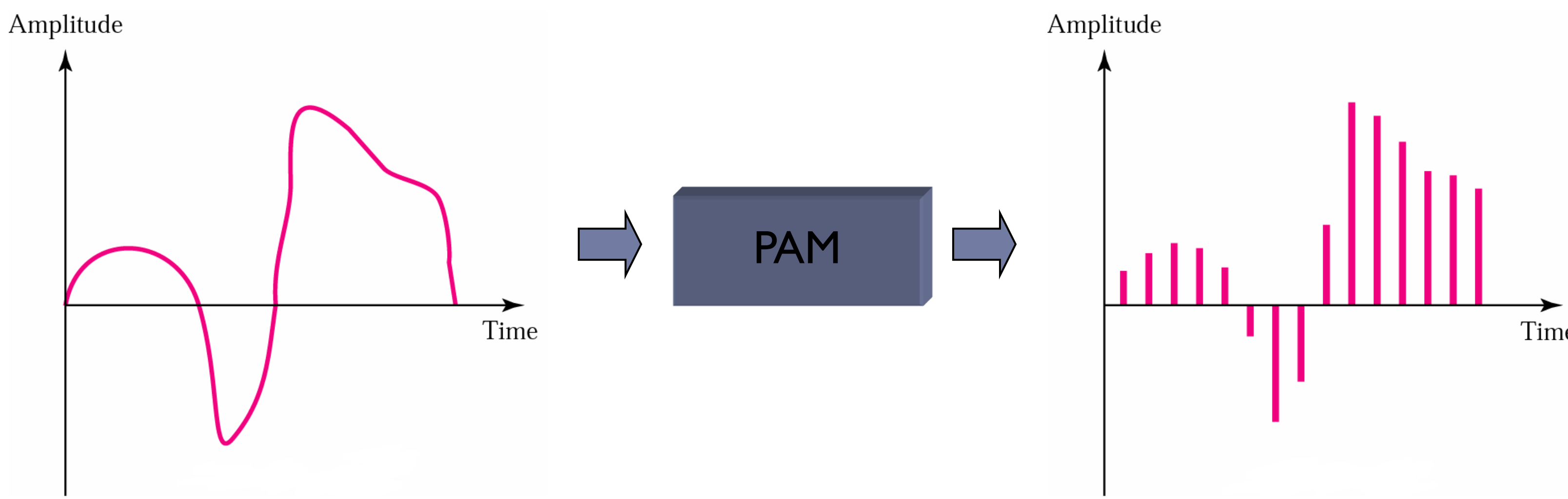


Sampling

- The analog signal is sampled every ***Ts***, where ***Ts*** is *the **sample interval*** or ***period***.
- The inverse of the sampling interval is called the ***sampling rate*** or ***sampling frequency*** and denoted by ***fs***, where ***fs = 1/Ts***.
- The sampling process is sometimes referred to as ***Pulse Amplitude Modulation (PAM).***

PAM

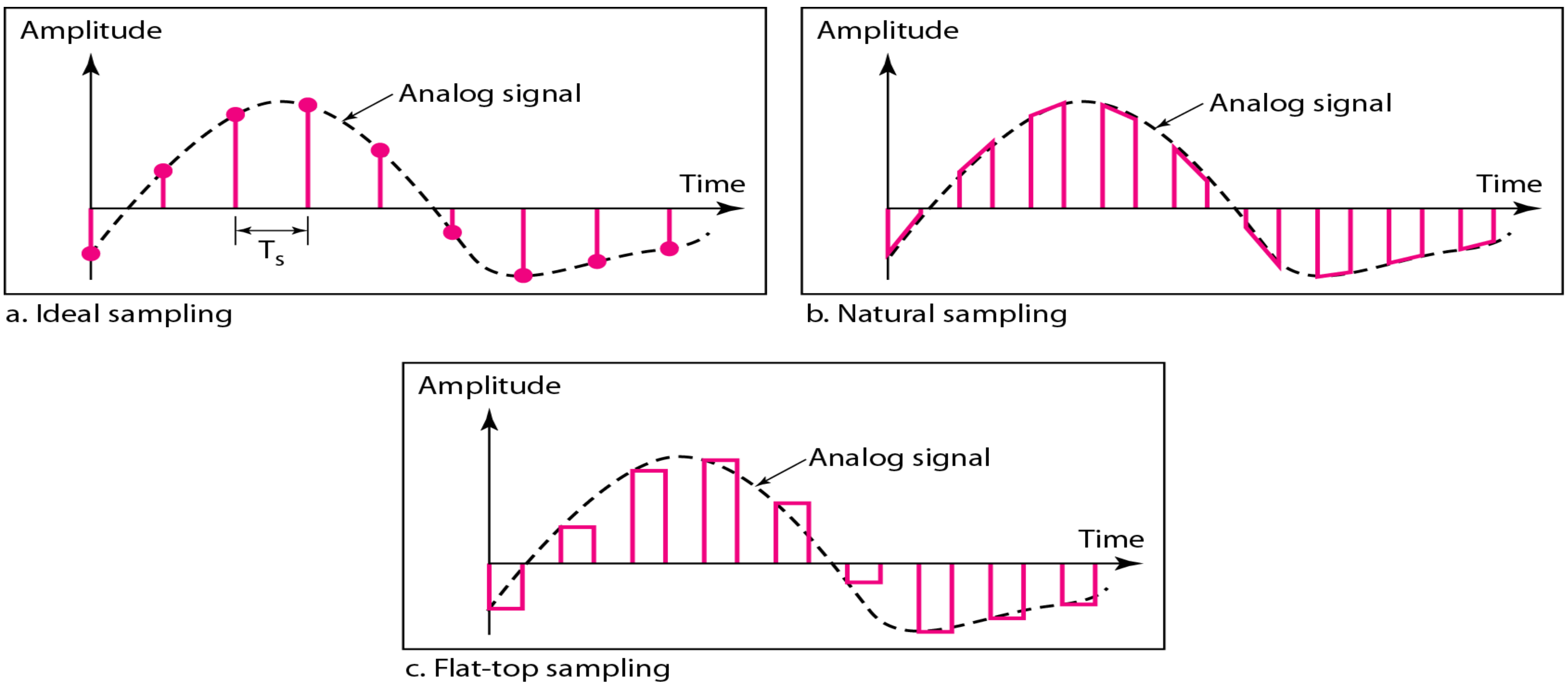
- Pulse Amplitude Modulation (PAM)
  - Converts an analog signal into a series of pulses by sampling



Analog signal

PAM signal
(Sampled analog data)

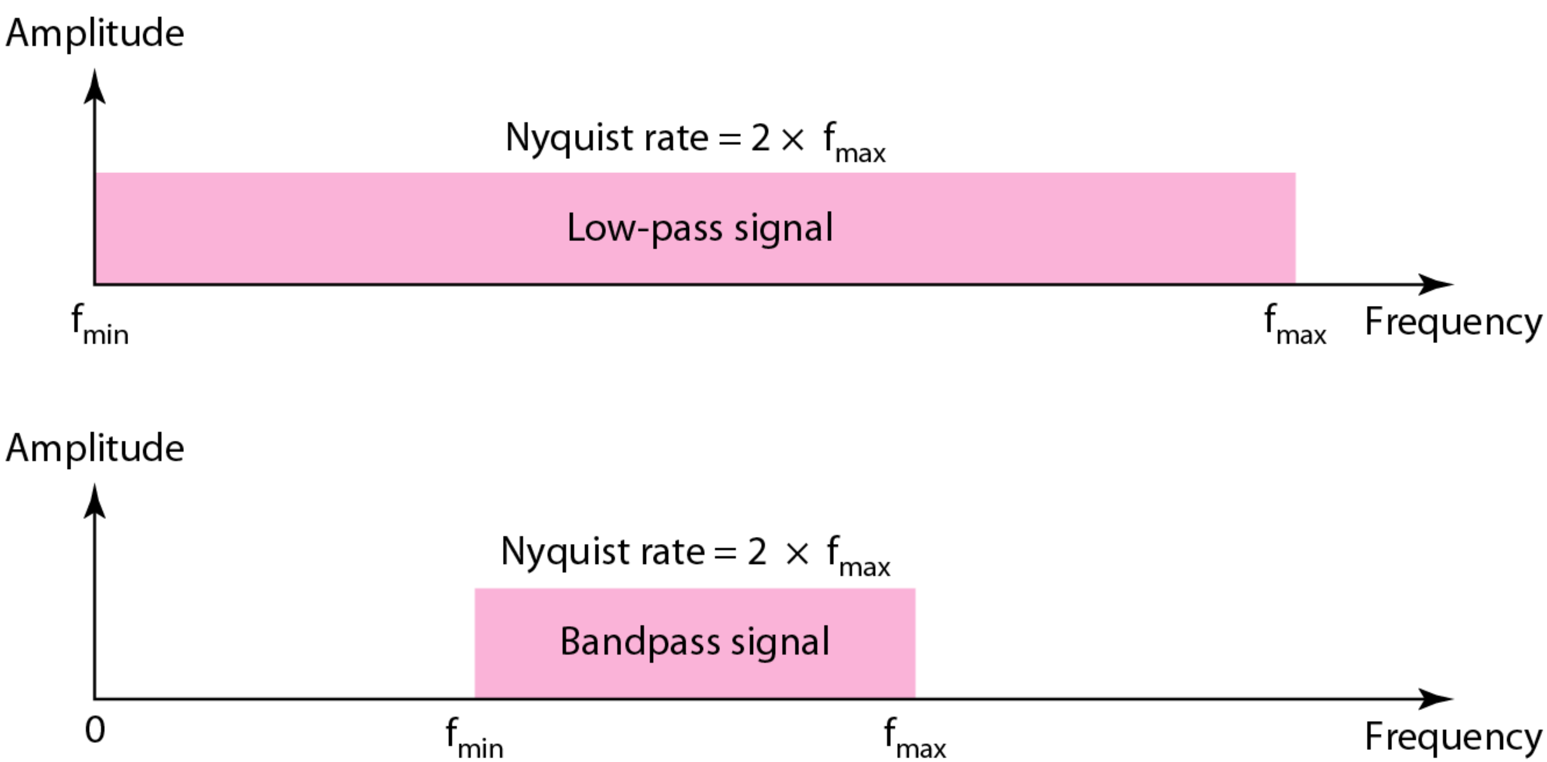
Different Sampling Methods



Sampling Rate

- According to the ***Nyquist theorem***, the sampling rate must be at least 2 times the highest frequency contained in the signal.
- We can sample a signal only if the signal is band-limited. In other words, a signal with an infinite bandwidth cannot be sampled.
- The sampling rate must be at least 2 times the highest frequency, not the bandwidth.
- If the analog signal is low-pass, the bandwidth and the highest frequency are the same value. If the analog signal is bandpass, the bandwidth value is lower than the value of the maximum frequency.

Nyquist Sampling Rate for low-pass and band-pass



Home work

- Example 4.6 – 4.11

Quantization

- Quantization is the process of converting, or digitizing, the almost enormously variable amplitude of an analog waveform to one of a finite series of discrete levels.
- The steps of the quantization process are:

1. We assume that the original analog signal has instantaneous amplitudes between V_{min} and V_{max}.

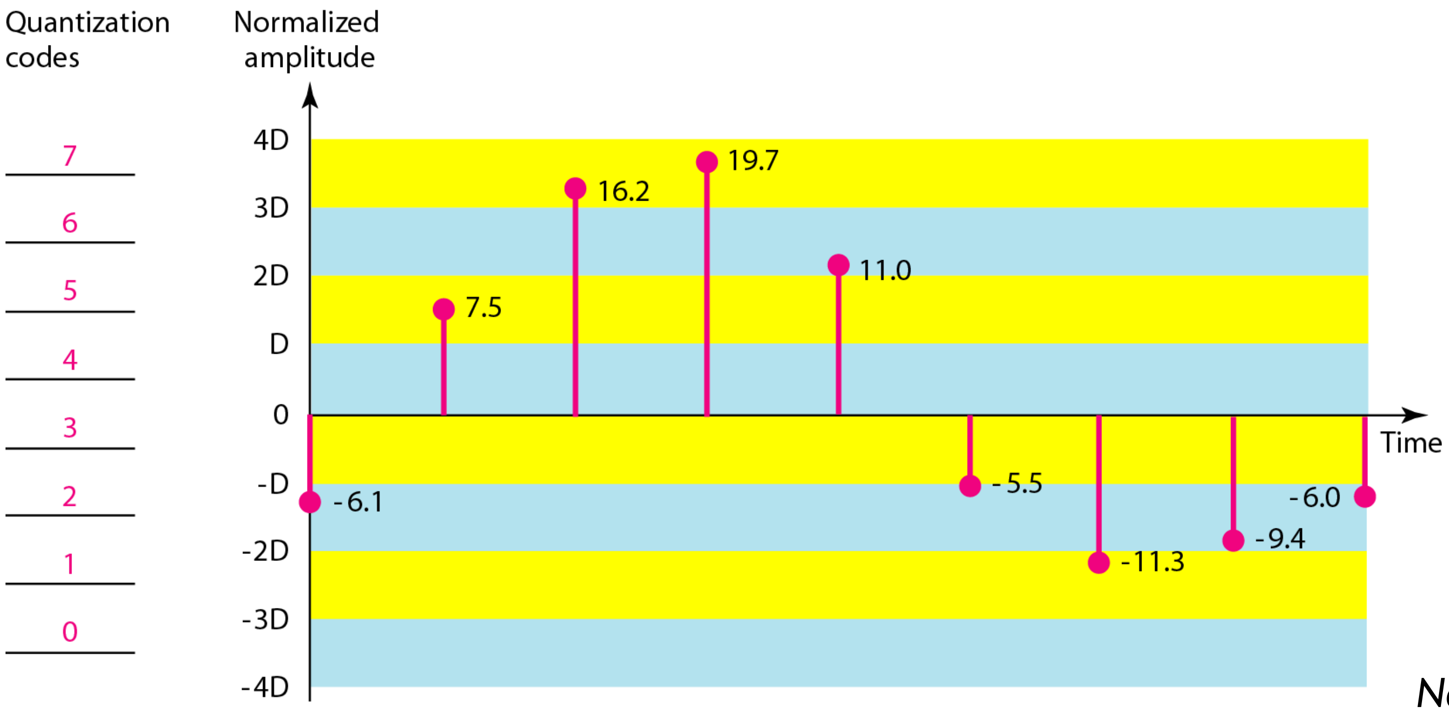
2. We divide the range into L zones, each of height Δ (delta).

$$\Delta = \frac{V_{max} - Vmin}{L}$$

3. We assign quantized values of 0 to $L-1$ to the midpoint of each zone.

4. We approximate the value of the sample amplitude to the quantized values.

Quantization



Vmax = +20V
Vmin = -20V
L = 8
Δ = 5 V

Normalized value = Actual amplitude/ Δ

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 Levels

- The choice of L depends on the range of the amplitudes of the analog signal and how accurately we need to recover the signal.
- If the amplitude of a signal fluctuates between two values only, we need only two levels.
- If the signal has many amplitudes, we need more quantization levels.

Quantization Error and Bit rate

- The value of the error for any sample is less than $\Delta/2$

$$- \Delta/2 \leq \text{error} \leq \Delta/2$$

- Quantization error to the SNR_{db} :

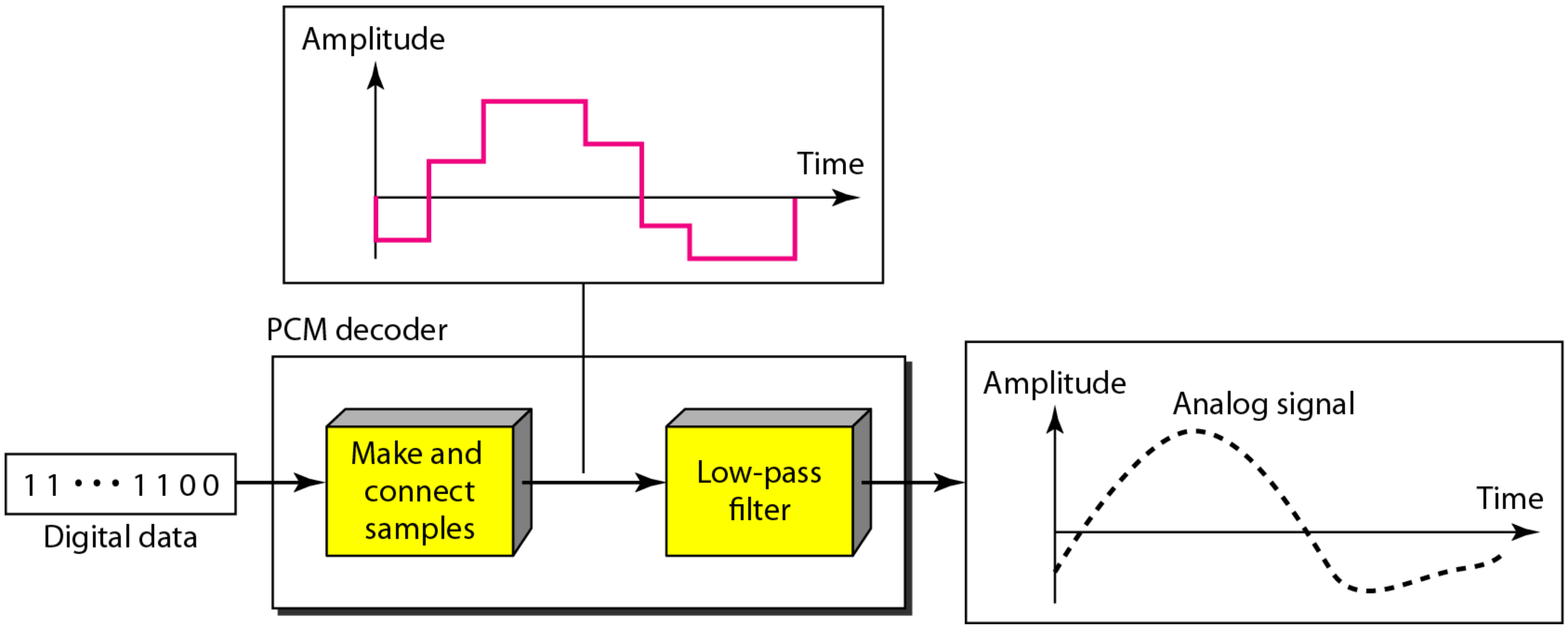
  $SNR_{db} = 6.02n_b + 1.76$ dB; where n_b is the bits per sample.

- Bit Rate = sampling rate x number of bits per sample

  $= f_s \times n_b$

Original Signal Recovery

- The recovery of the original signal requires the PCM decoder.



Components of a PCM decoder

PCM Bandwidth

- The minimum bandwidth of the digital signal is n_b times greater than the bandwidth of the analog signal.

$$B_{min} = n_b \times B_{analog}$$

- Maximum data rate of a channel:

$$N_{max} = 2 \times B \times \log_2 L \ \ \textbf{bps}$$

- Minimum required bandwidth:

$$B_{min} = N / (2 \times \log_2 L) \ \textbf{Hz}$$

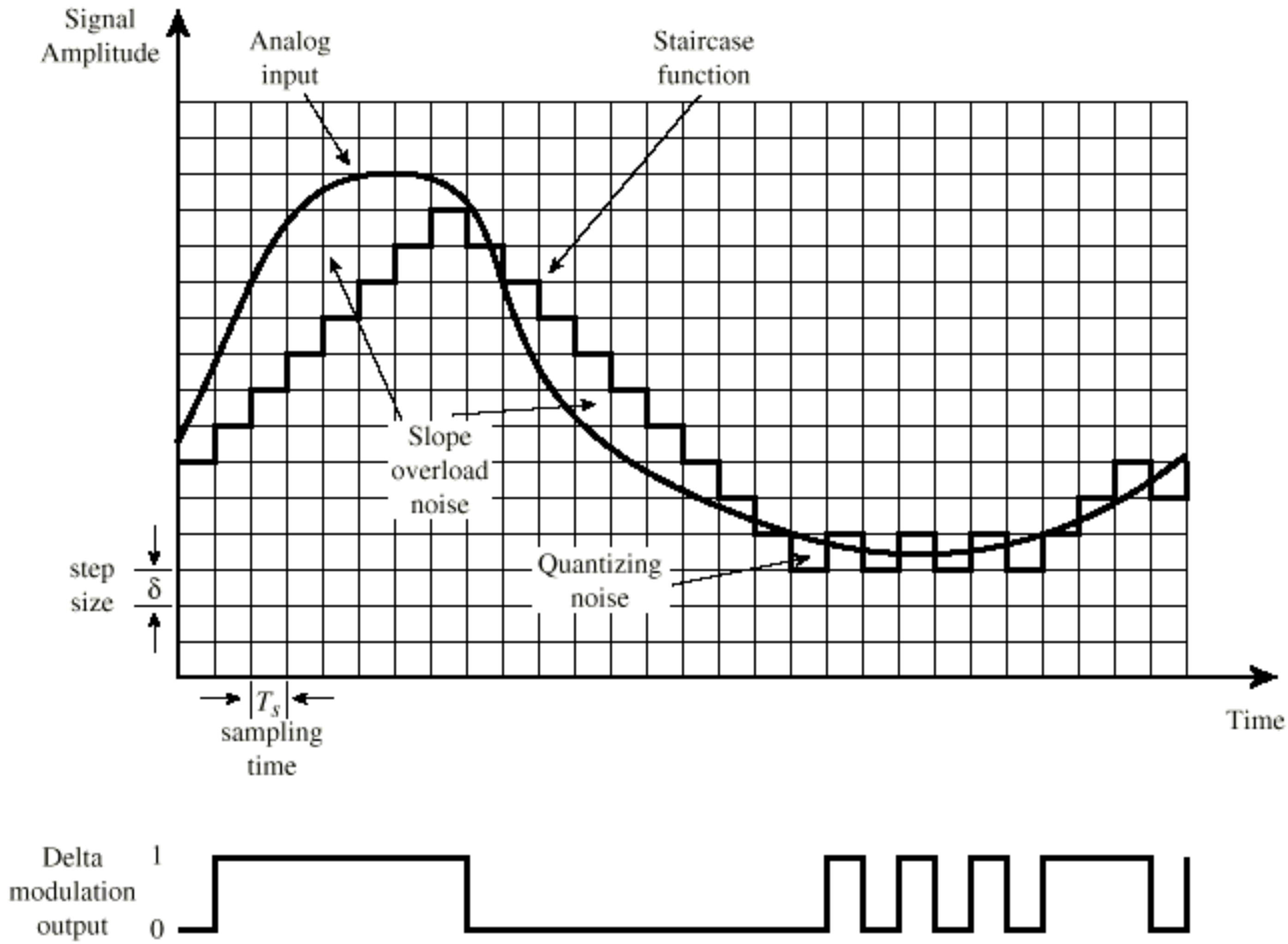
Home Work

- Example 4.12 – 4.15

Delta Modulation

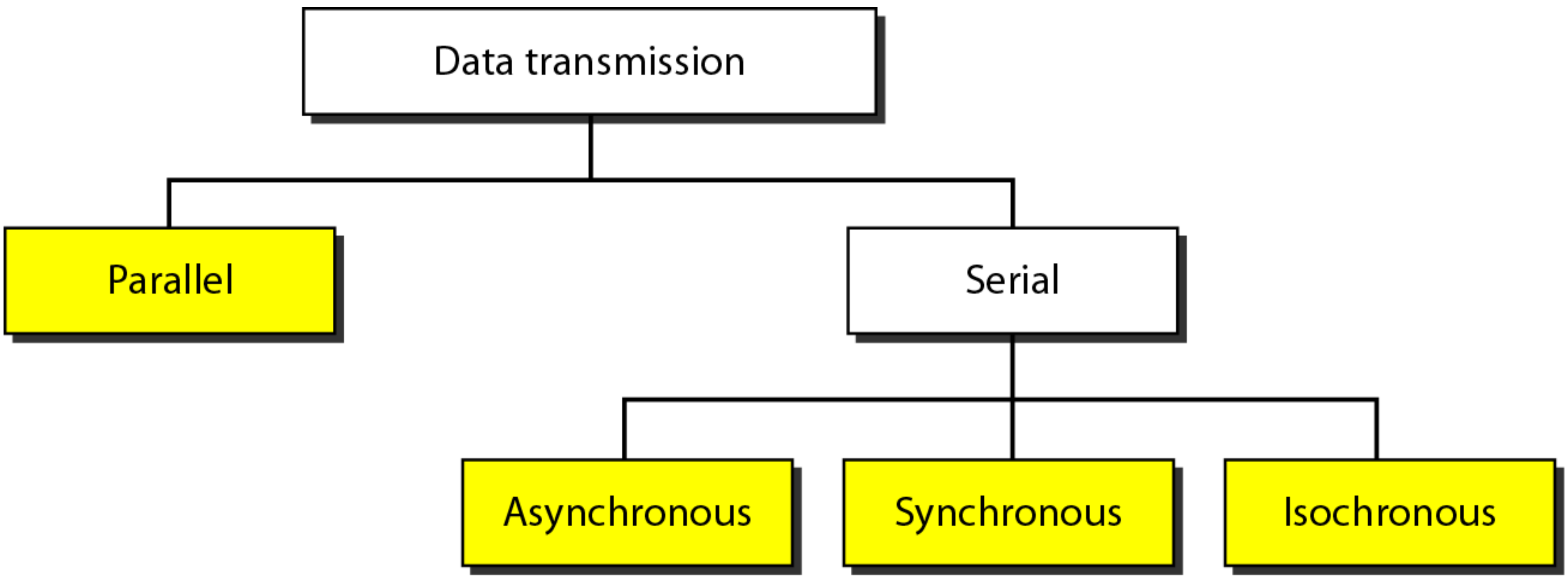
- PCM → complex
- Delta Modulation (DM) → simple
- PCM finds the value of the signal amplitude for each sample; whereas DM finds the change from the previous sample.
- There are no code words here; bits are sent one after another.

Delta Modulation



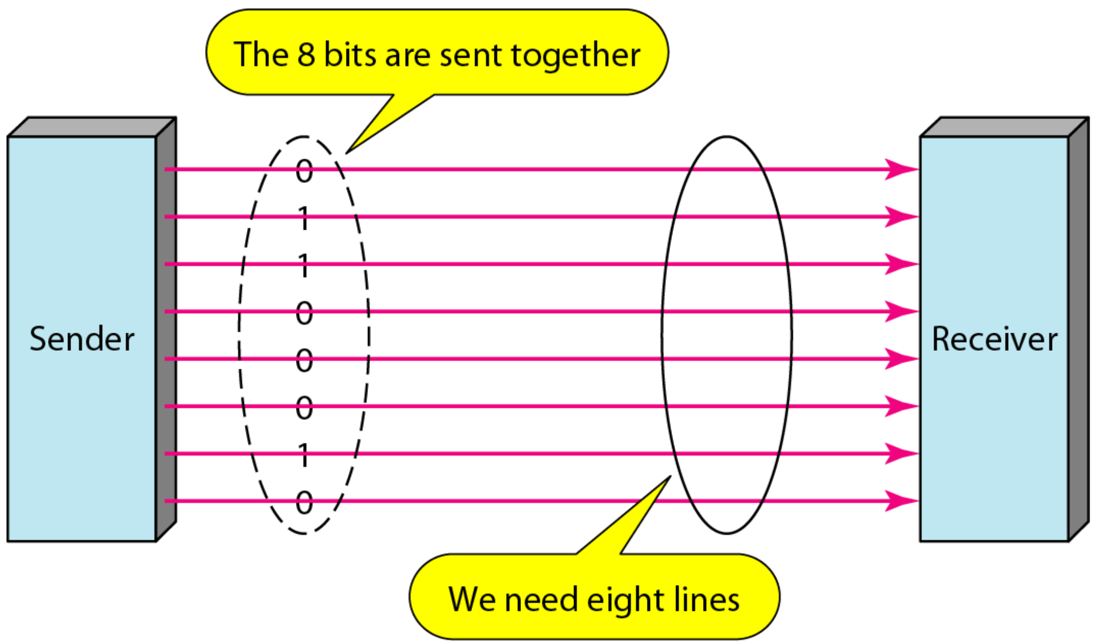
Transmission Modes

- The transmission of binary data across a link can be accomplished in either ***parallel*** or ***serial*** mode.



Parallel Transmission

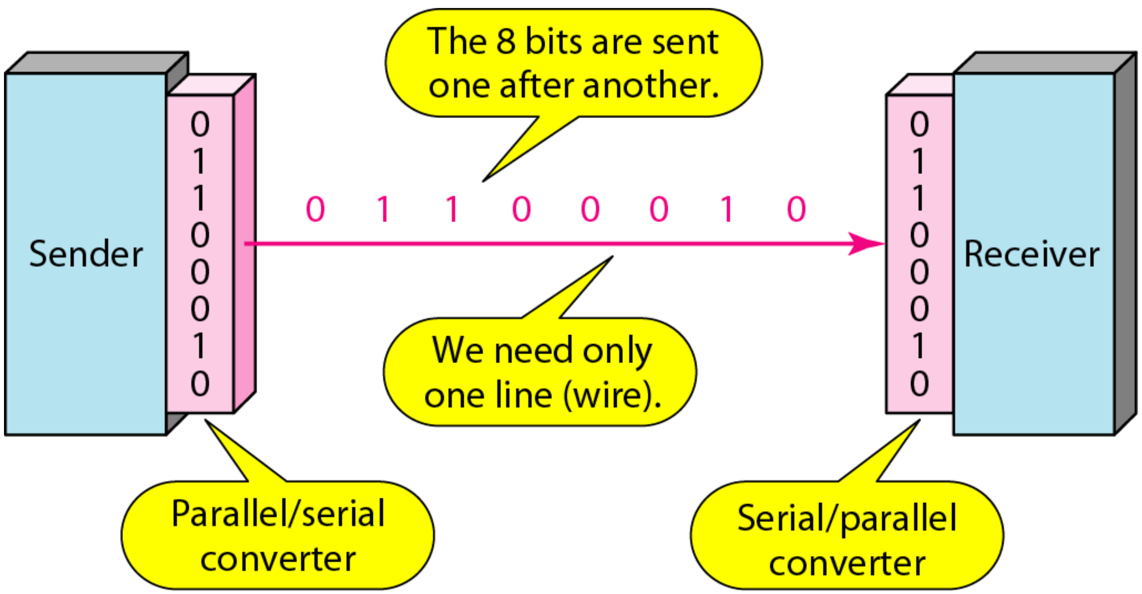
- A parallel communication device sends data in multiple bits to the same direction.
- For example, the eight bits are transferred in corresponding 8 channels, every channel transmits a bit, and a byte of data is received simultaneously.



- Speed
- Costly; requires *n* communication lines
- unsuitable for long distance transmission.

Serial Transmission

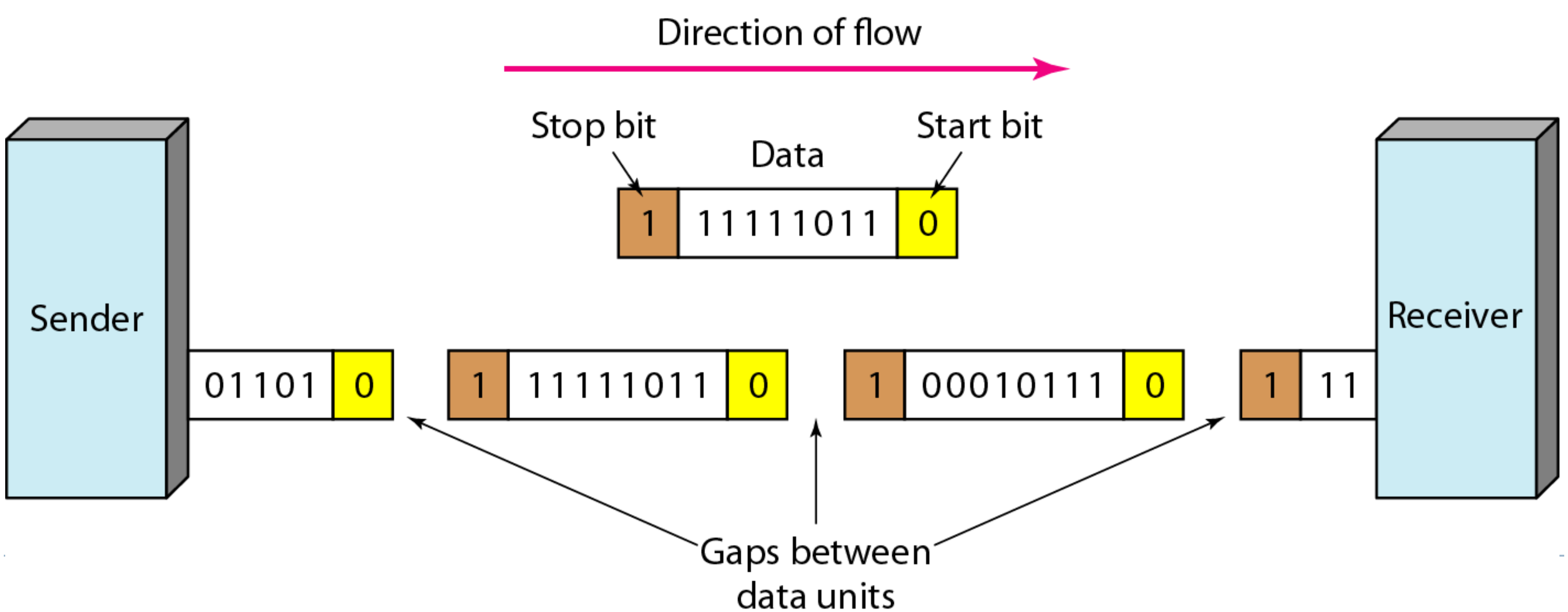
- A serial communication device transfers data in bits in the same direction.
- In serial communication a word of eight bits in length is sent sequentially, and is received after all eight bits are sent, one at a time.



- Requires *only one* communication line
- Suitable for long distance transmission.
- Requires conversion devices at the interface

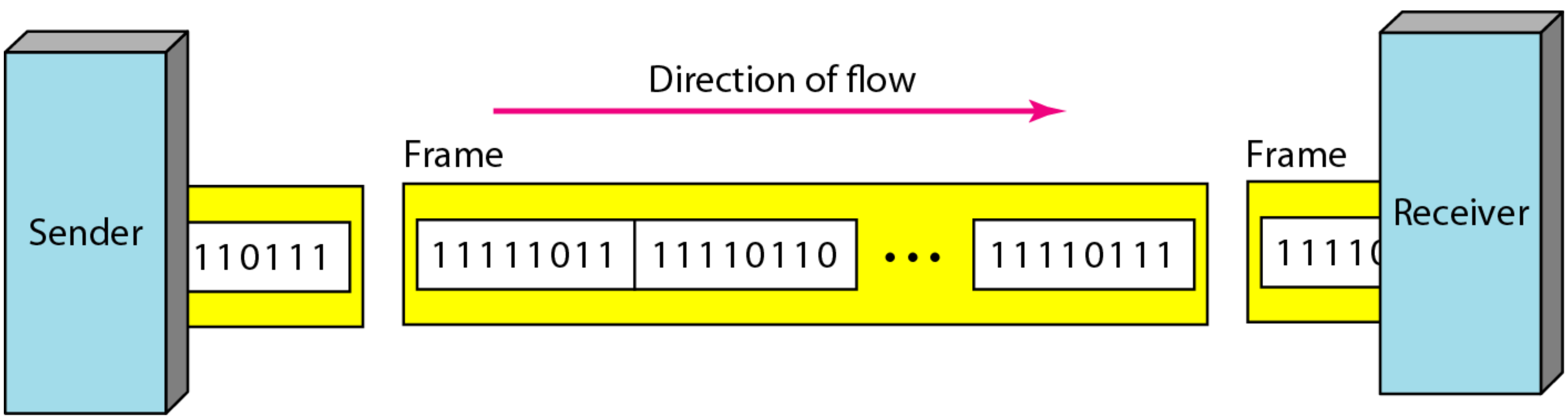
Asynchronous Transmission

- 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.
- Cheap and effective.
- Useful for low-speed communication such as the connection of a keyboard to a computer



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 timing is very important.
- Faster than asynchronous transmission.
- Useful for high-speed applications such as the transmission of data from one computer to another.



Isochronous Transmission

- In real-time audio and video, in which uneven delays between frames are not acceptable, synchronous transmission fails.
- For example, TV images are broadcast at the rate of 30 images per second; they must be viewed at the same rate.
- If each image is sent by using one or more frames, there should be no delays between frames.
- For this type of application, synchronization between characters is not enough; the entire stream of bits must be synchronized.
- The isochronous transmission guarantees that the data arrive at a fixed rate.