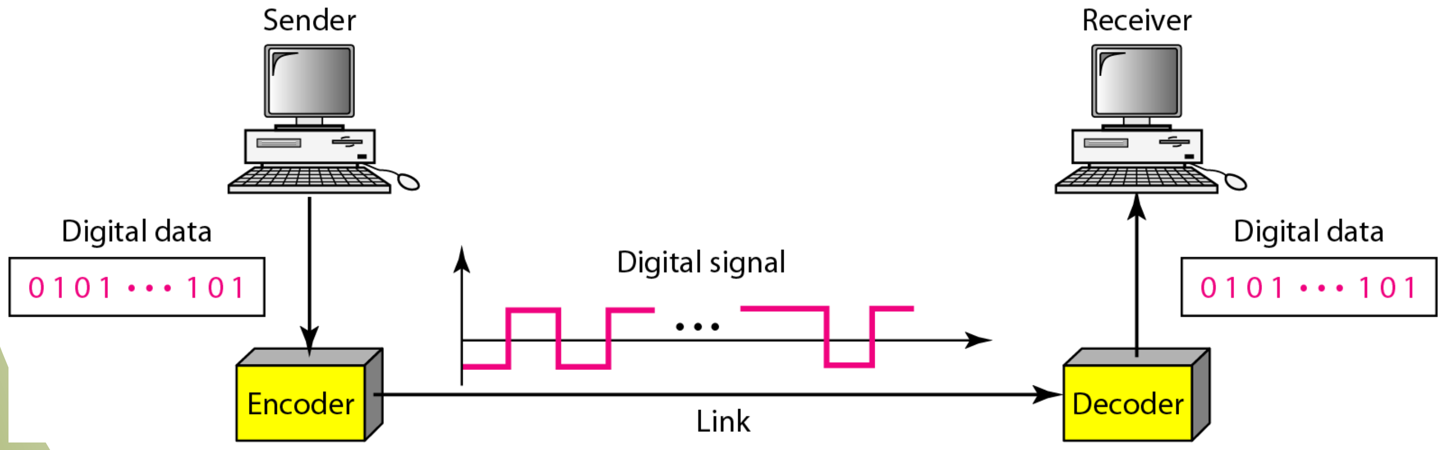
Chapter 4. Digital Transmission

1. Digital-to-Digital Conversion
2. Analog-to-Digital Conversion
3. Transmission Mode

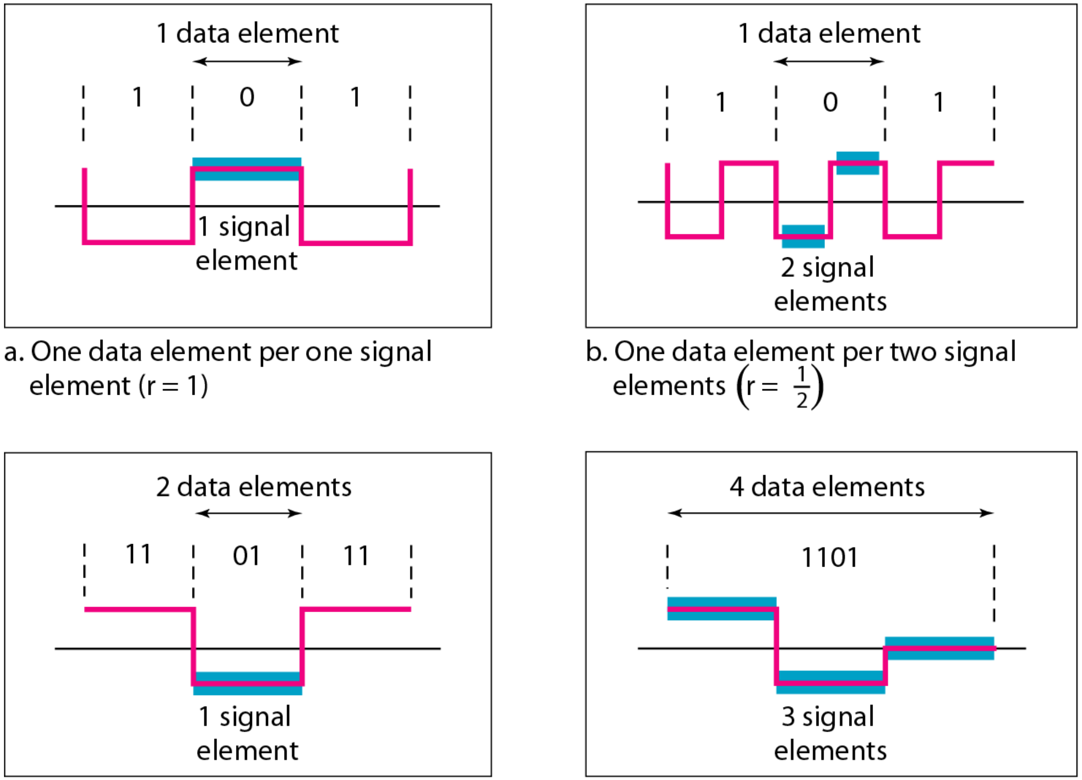
Digital-to-Digital Conversion

- Involves three techniques:
  - Line coding (always needed), block coding, and scrambling
- Line coding: the process of converting digital data to digital signals



Signal Element and Data Element

- Data elements are what we need to send; signal elements are what we can send



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

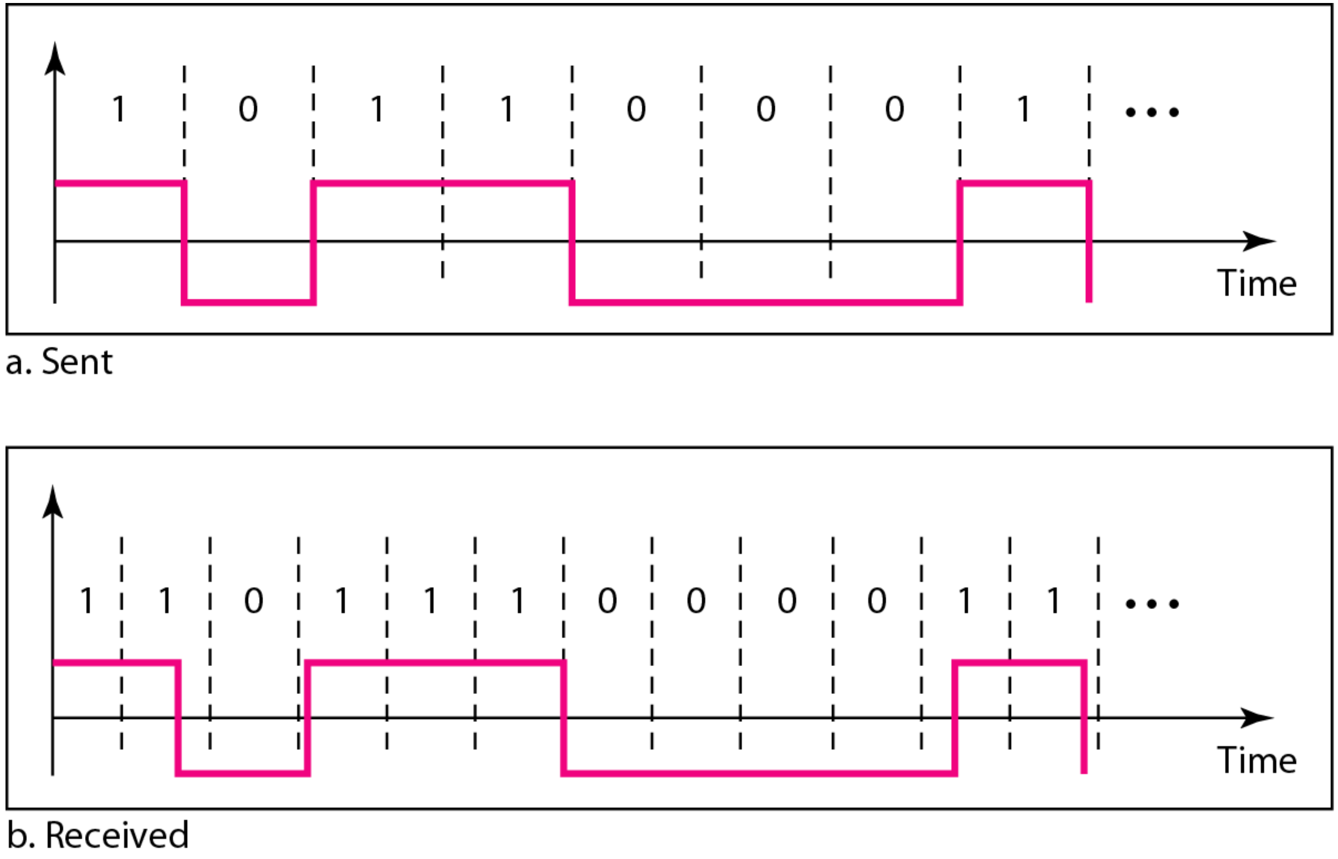
Data Rate Versus Signal Rate

- Data rate defines the number of data elements (bits) sent in 1s: bps
- Signal rate is the number of signal elements sent in 1s: baud
- Data rate = bit rate, signal rate = pulse rate, modulation rate, baud rate
- S = c x N x 1/r, where N is the date rate; c is the case factor, S is the number of signal elements; r is the number of data elements carried by each signal element
- Although the actual bandwidth of a digital signal is infinite, the effective bandwidth is finite
- The bandwidth is proportional to the signal rate (baud rate)
- The minimum bandwidth: $B_{min} = c \times N \times 1/r$
- The maximum data rate: $N_{max} = 1/c \times B \times r$

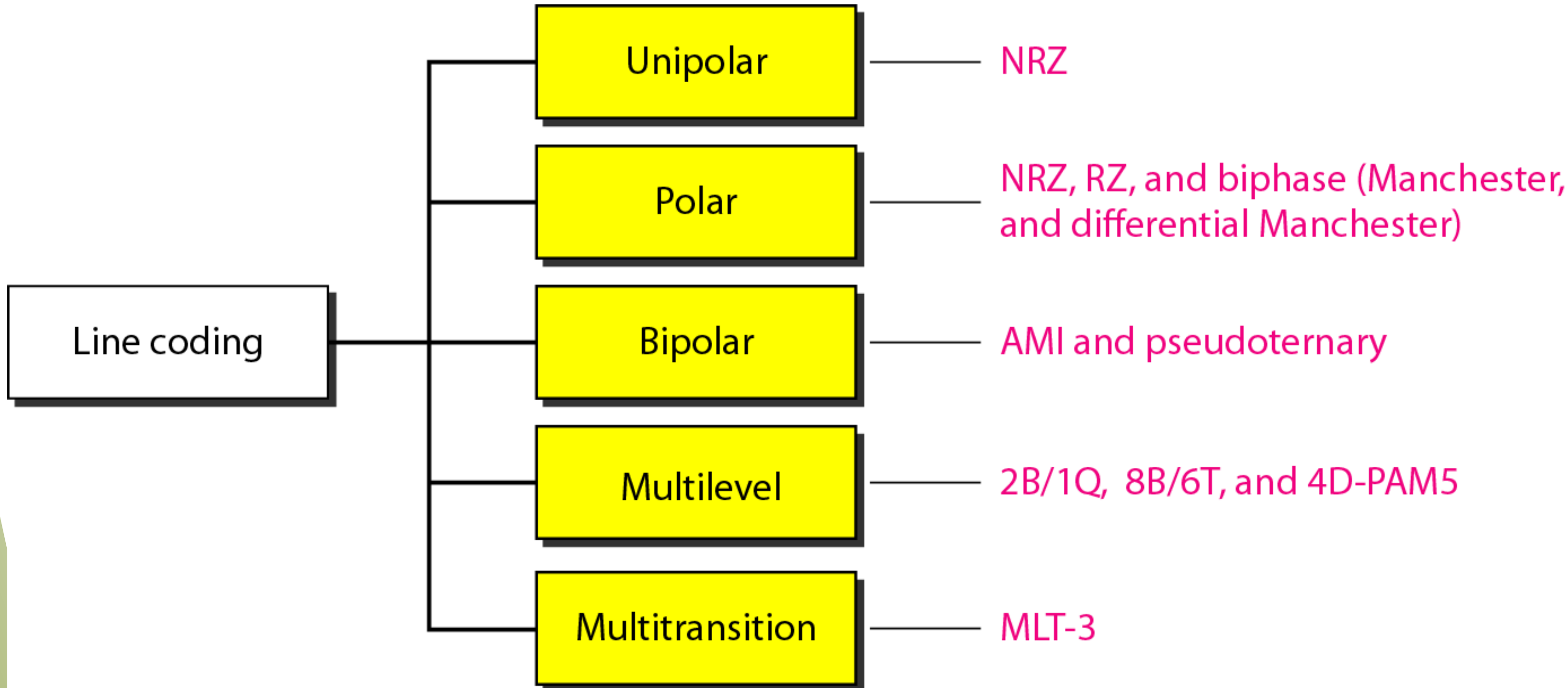
Design Consideration for Line Coding Scheme

- Baseline wandering
  - Long string of 0s and 1s can cause a drift in the baseline
- DC components
  - DC or low frequencies cannot pass a transformer or telephone line (below 200 Hz)
- Self-synchronization
- Built-in error detection
- Immunity to noise and interference
- Complexity

Lack of Synchronization

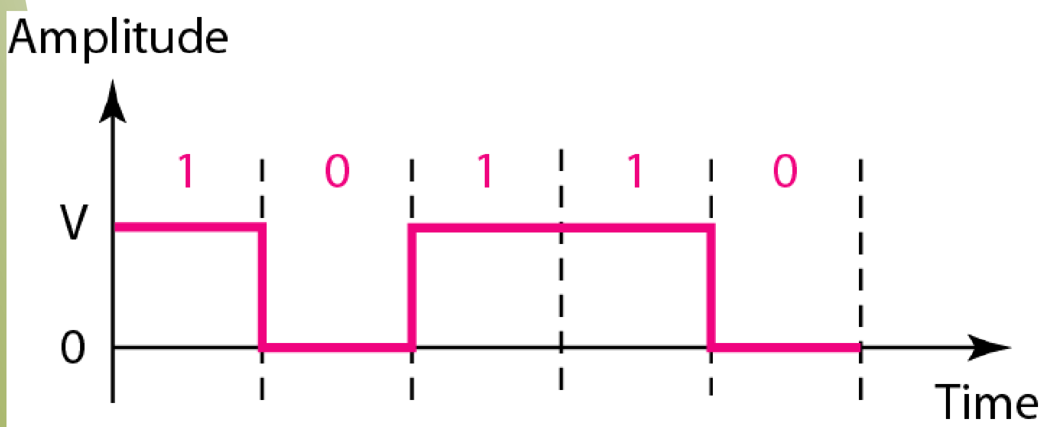


Line Coding Schemes



Unipolar Scheme

- One polarity: one level of signal voltage
- Unipolar NRZ (None-Return-to-Zero) is simple, but
  - DC component : Cannot travel through microwave or transformer
  - Synchronization : Consecutive 0's and 1's are hard to be synchronized → Separate line for a clock pulse
  - **Normalized power** is double that for polar NRZ

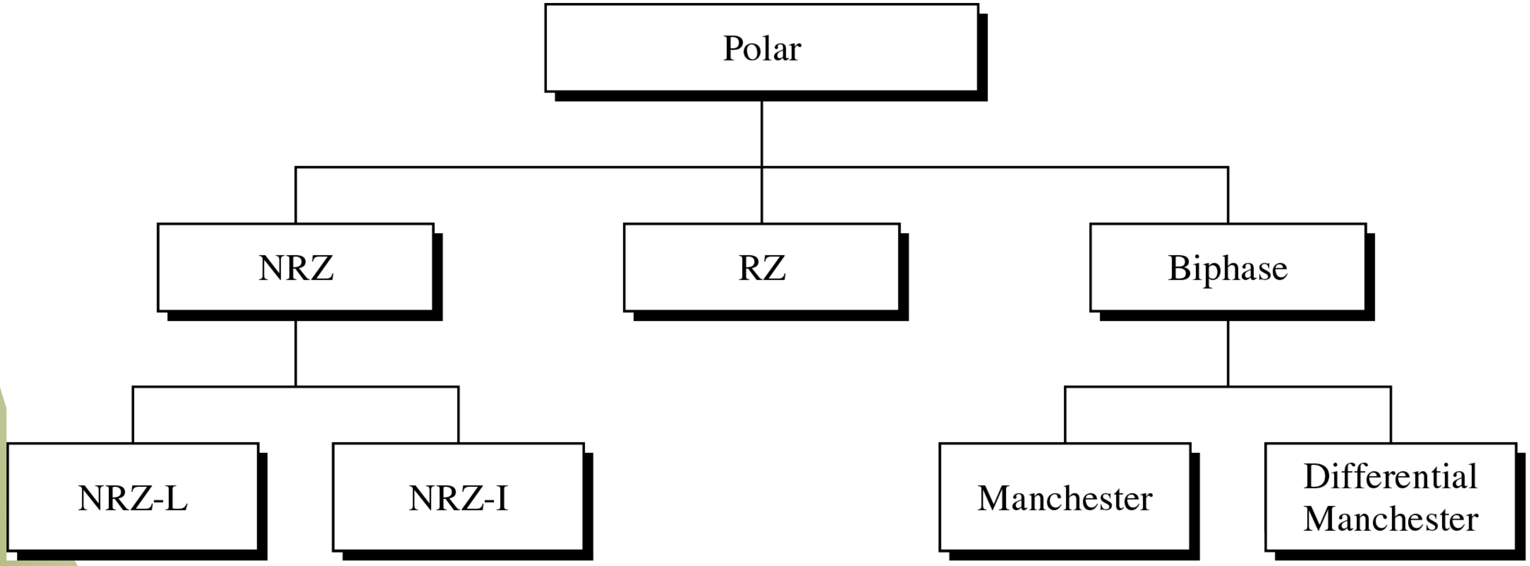


$$\frac{1}{2}V^2 + \frac{1}{2}(0)^2 = \frac{1}{2}V^2$$

Normalized power

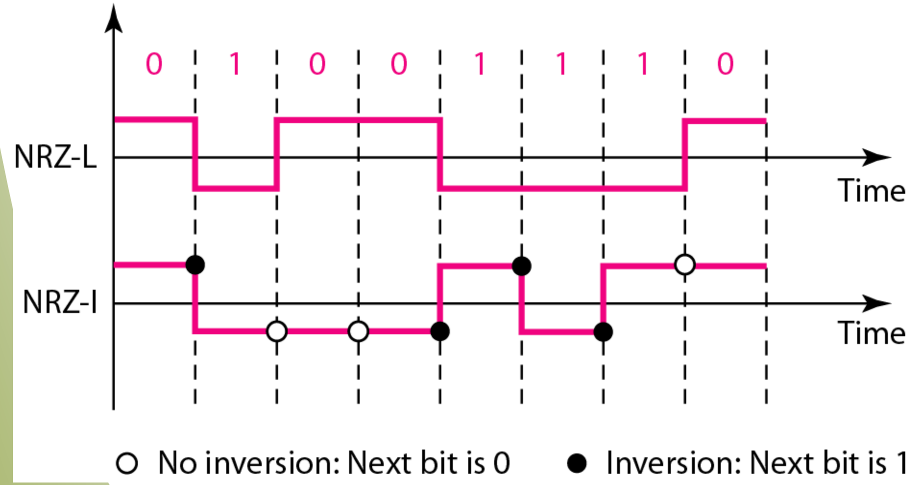
Polar Scheme

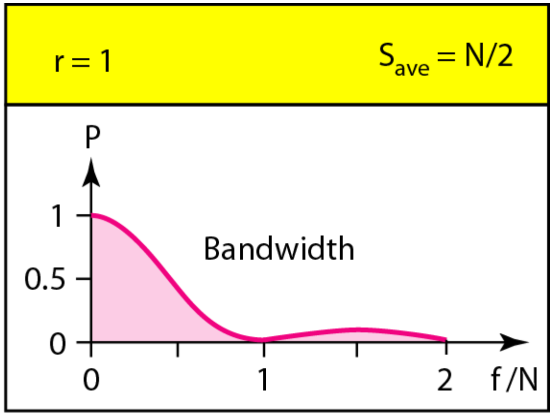
- Two polarity: two levels of voltage
- Problem of DC component is alleviated (NRZ,RZ) or eliminated (Biphaze)



Polar NRZ

- NRZ-L (Non Return to Zero-Level)
  - Level of the voltage determines the value of the bit
- NRZ-I (Non Return to Zero-Invert)
  - Inversion or the lack of inversion determines the value of the bit



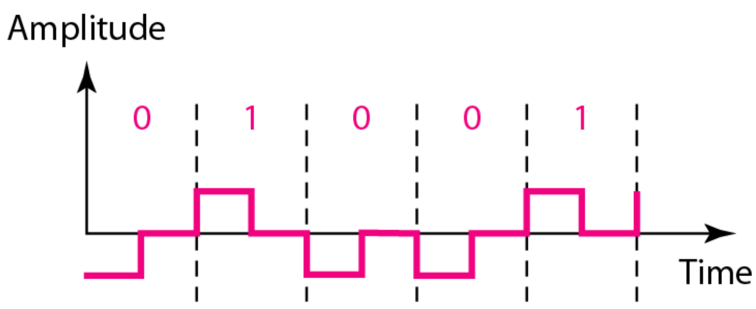


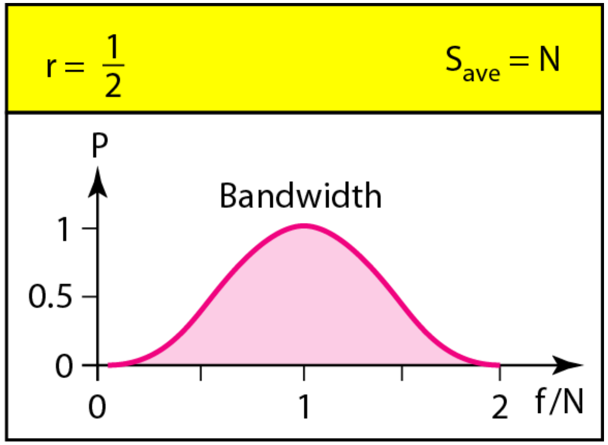
Polar NRZ: NRZ-L and NRZ-I

- Baseline wandering problem
  - Both, but NRZ-L is twice severe
- Synchronization Problem
  - Both, but NRZ-L is more serious
- NRZ-L and NRZ-I both have an average signal rate of N/2 Bd
- Both have a DC component problem

RZ

- Provides synchronization for consecutive 0s/1s
- Signal changes during each bit
- Three values (+, -, 0) are used
  - Bit 1: positive-to-zero transition, bit 0: negative-to-zero transition



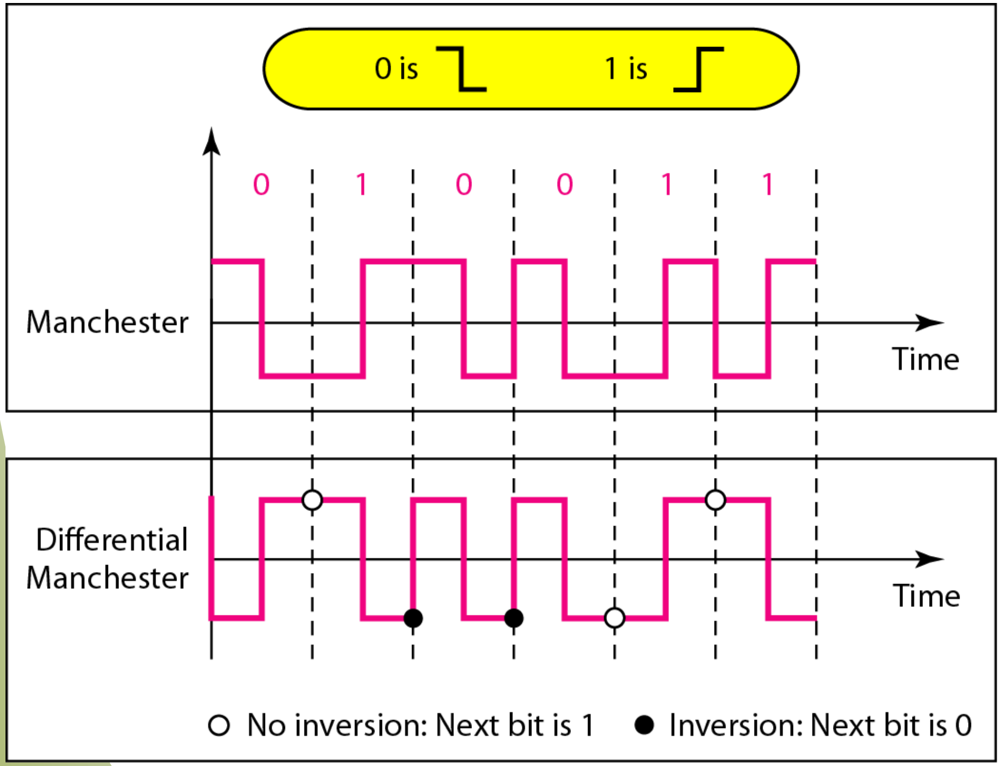


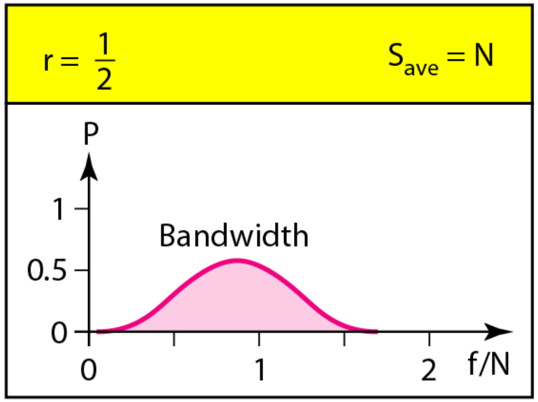
Biphase

- Combination of RZ and NRZ-L ideas
- Signal transition at the middle of the bit is used for synchronization
- Manchester
  - Used for Ethernet LAN
  - Bit 1: negative-to-positive transition
  - Bit 0: positive-to-negative transition
- Differential Manchester
  - Used for Token-ring LAN
  - Bit 1: no transition at the beginning of a bit
  - Bit 0: transition at the beginning of a bit

Polar Biphase

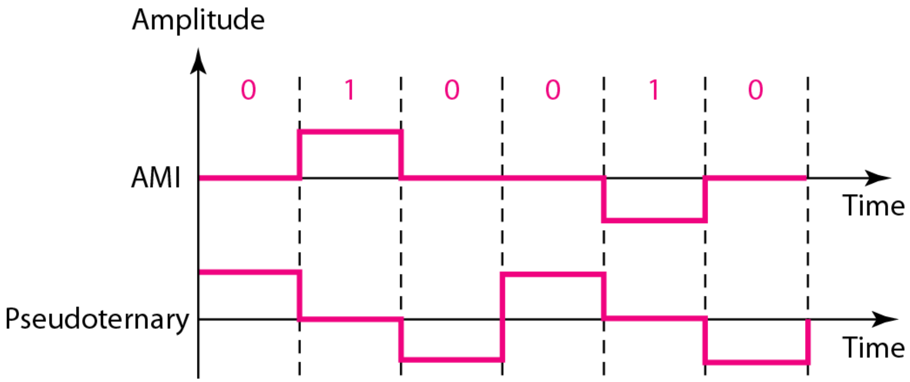
- Minimum bandwidth is 2 times that of NRZ

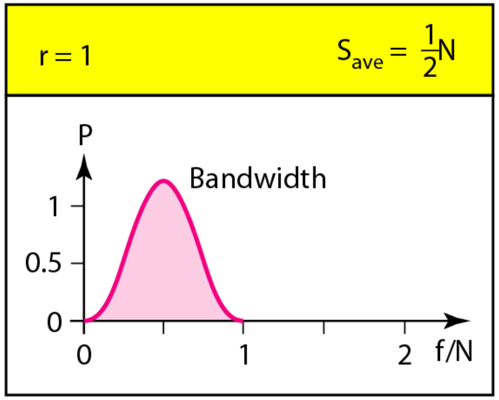




Bipolar Scheme

- Three levels of voltage, called "multilevel binary"
- Bit 0: zero voltage, bit 1: alternating +1/-1
  - (Note) In RZ, zero voltage has no meaning
- AMI (Alternate Mark Inversion) and pseudoternary
  - Alternative to NRZ with the same signal rate and no DC component problem





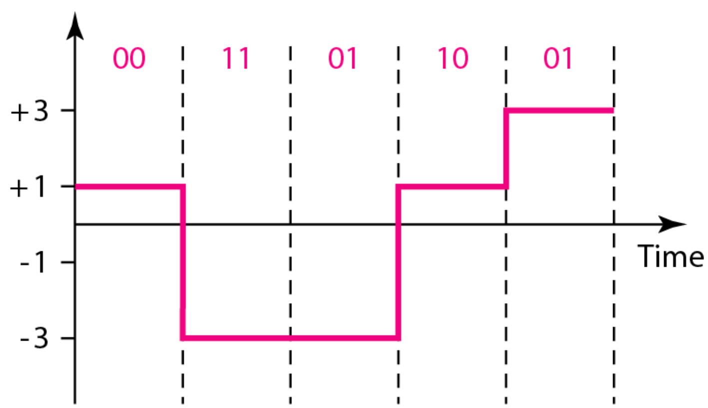
Multilevel Scheme

- 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 $2^m \leq L^n$
- 2B1Q (two binary, one quaternary)
- 8B6T (eight binary, six ternary)
- 4D-PAM5 (four-dimensional five-level pulse amplitude modulation)

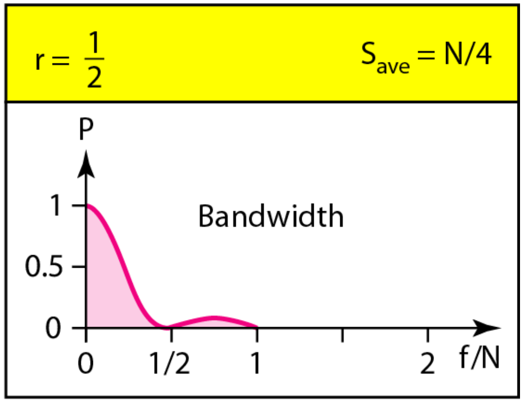
2B1Q: for DSL

	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

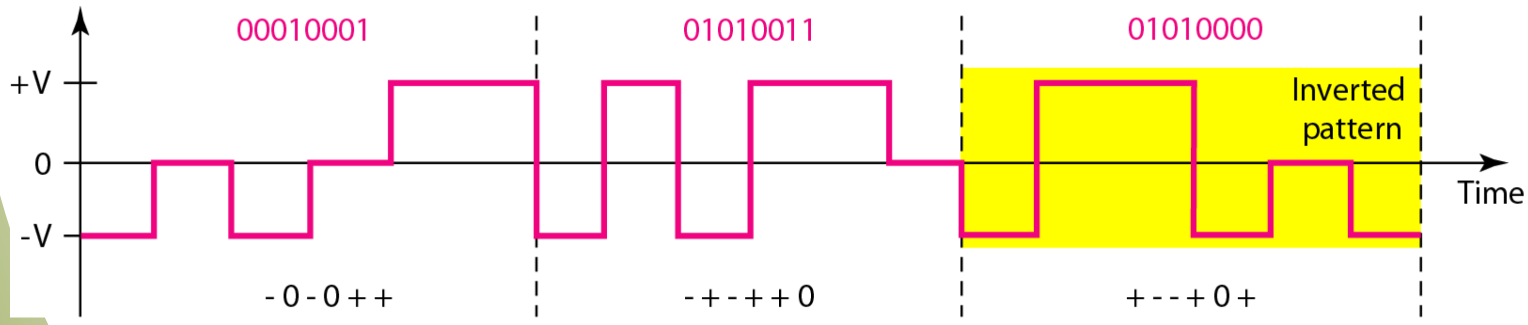


Assuming positive original level

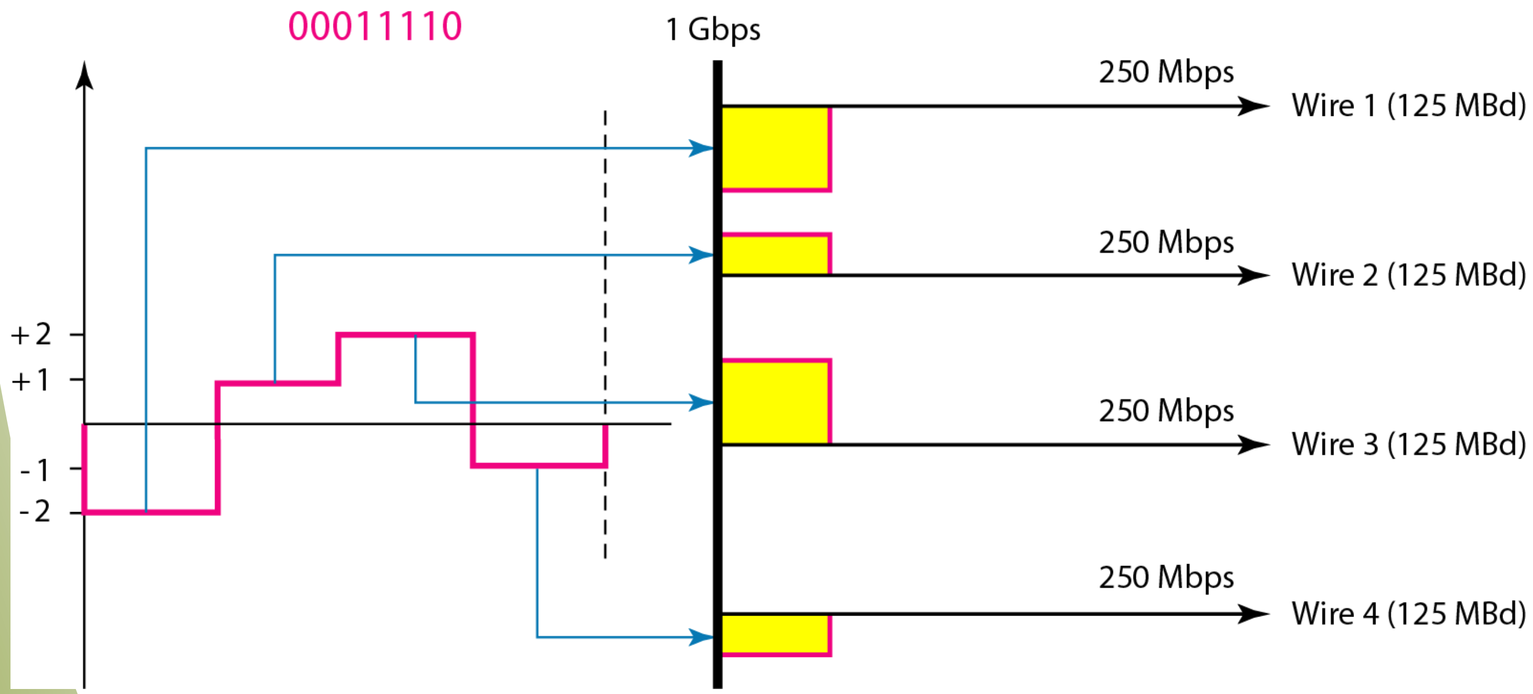


8B6T

- Used with 100Base-4T cable
- Encode a pattern of 8 bits as a pattern of 6 (three-levels) signal elements
- 222 redundant signal element = 3^6(478 among 729) - 2^8(256)
- The average signal rate is theoretically, $S_{ave} = 1/2 \times N \times 6/8$; in practice the minimum bandwidth is very close to 6N/8



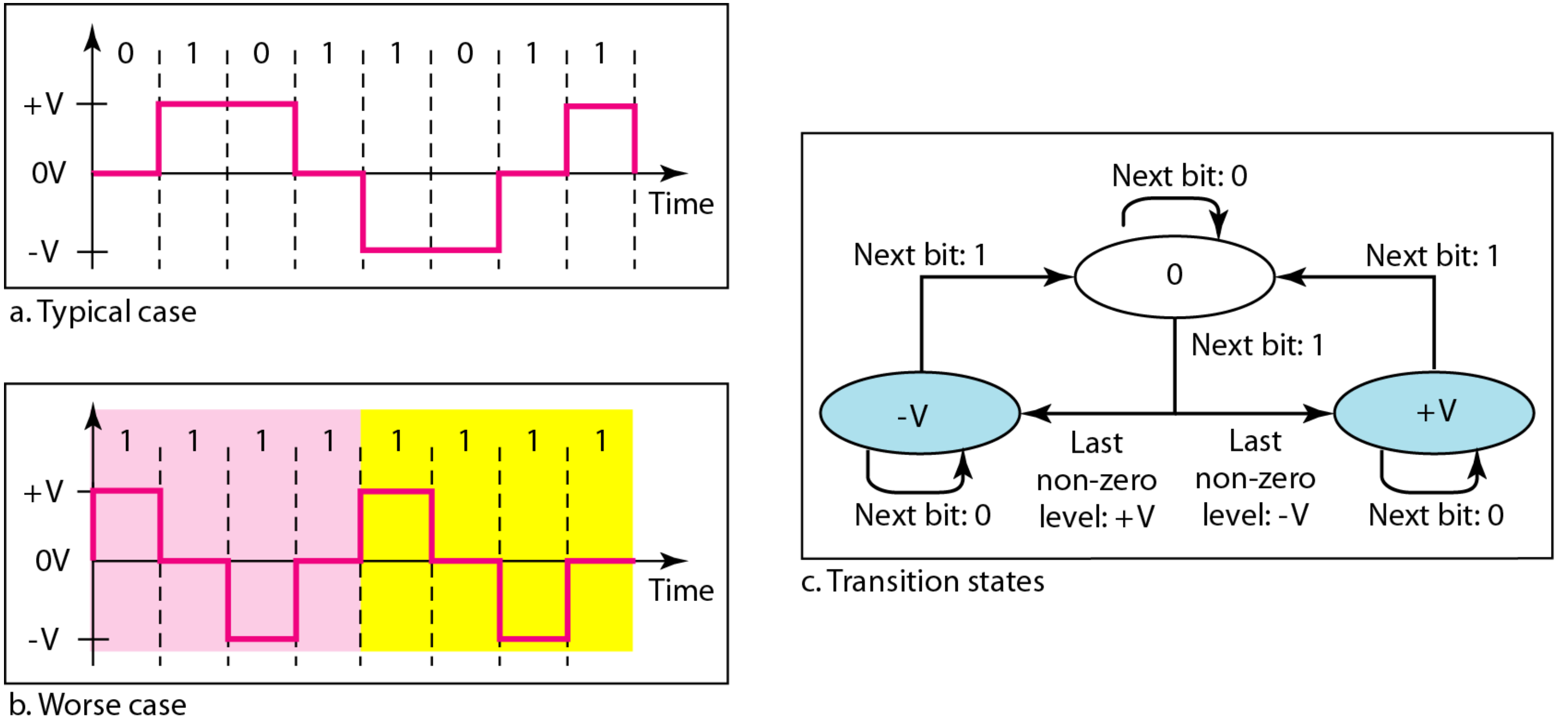
4D-PAM5: for Gigabit LAN



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
- The MLT-3 uses three different voltage levels (+v, 0, -v) and three transition rules to move between the levels:
  - If the next bit is 0, there is no transition
  - If the next bit is 1 and the current level is not 0, the next level is 0.
  - If the next bit is 1 and the current level is 0, the next level is the opposite of last nonzero level.

Multiline Transmission: MLT-3

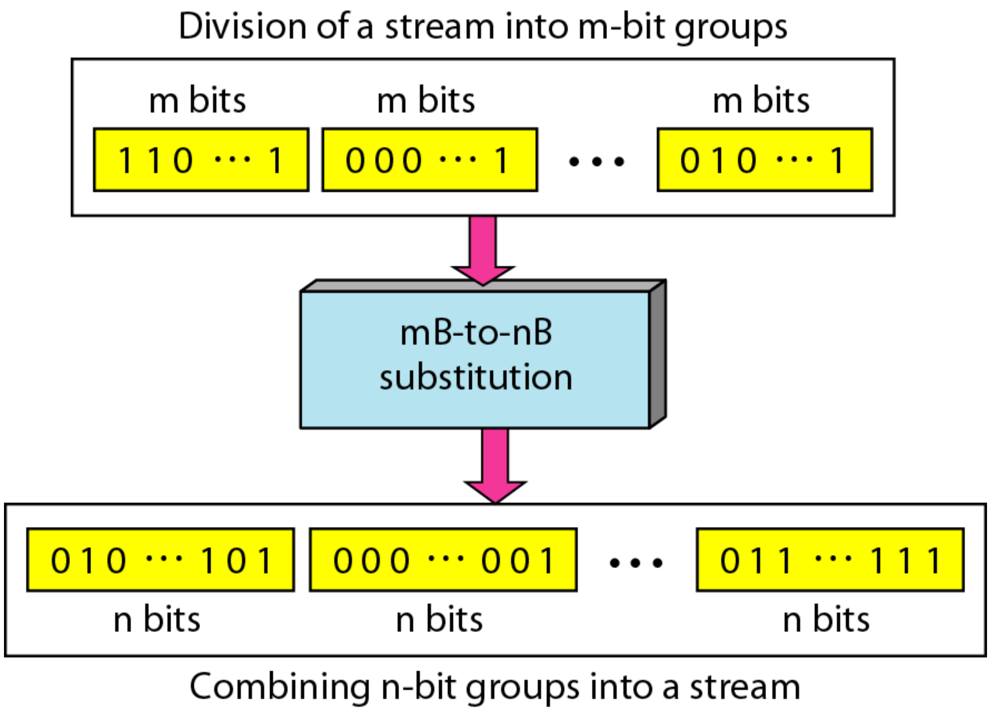


Summary of Line Coding Schemes

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

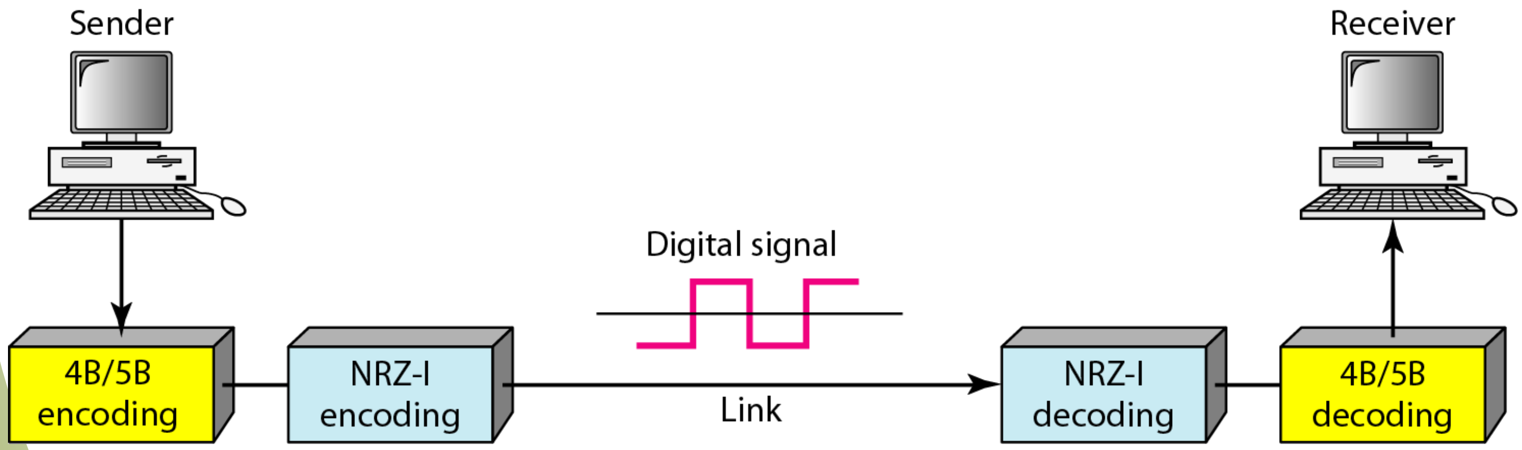
Block Coding

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



4B/5B

- Solve the synchronization problem of NRZ-I
- 20% increase the signal rate of NRZ-I (Biphase scheme has the signal rate of 2 times that of NRZ-I
- Still DC component problem

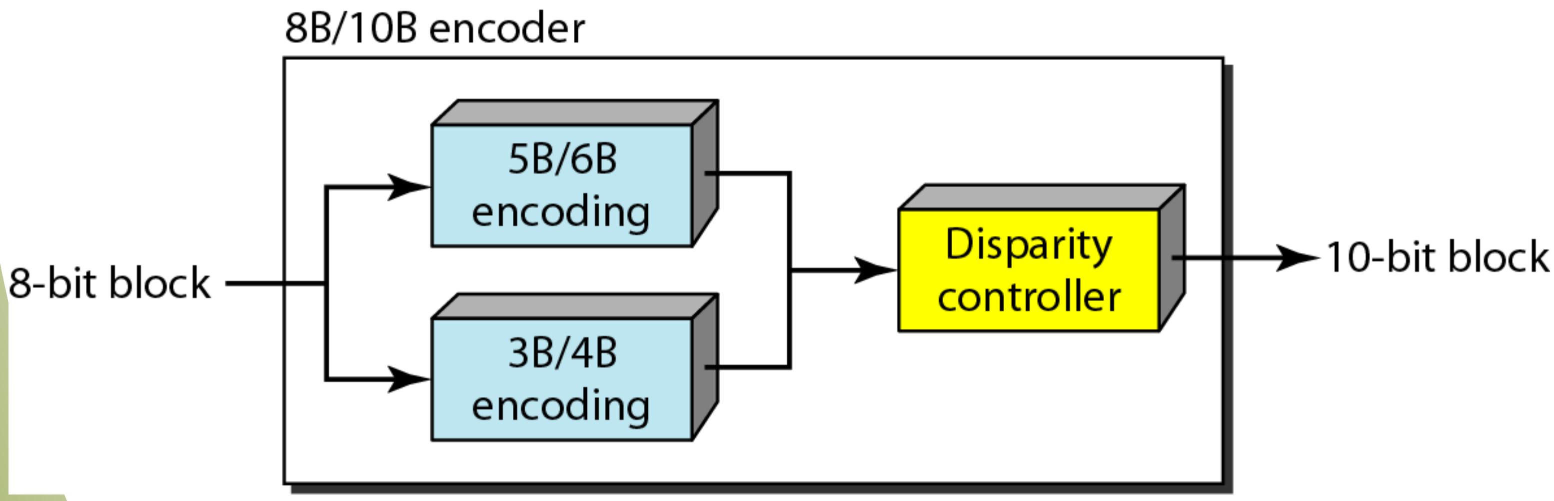


4B/5B Mapping Codes

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		

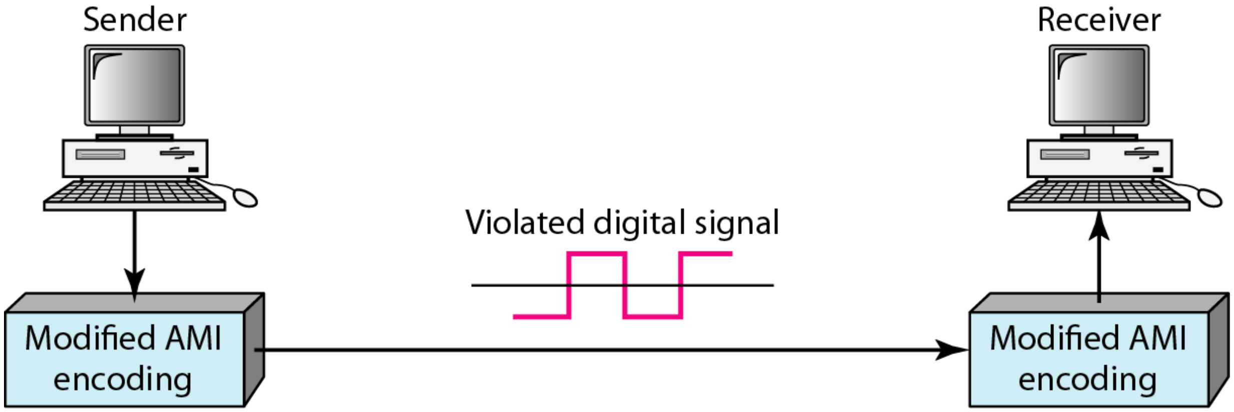
8B/10B

- $2^{10} - 2^{8} = 768$ redundant groups used for disparity checking and error detection



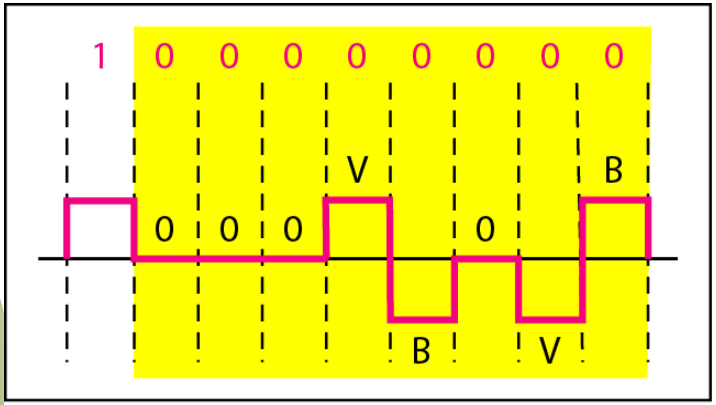
Scrambling

- Biphase : not suitable for long distance communication due to its wide bandwidth requirement
- Combination of block coding and NRZ: not suitable for long distance encoding due to its DC component problem
- Bipolar AMI: synchronization problem → Scrambling

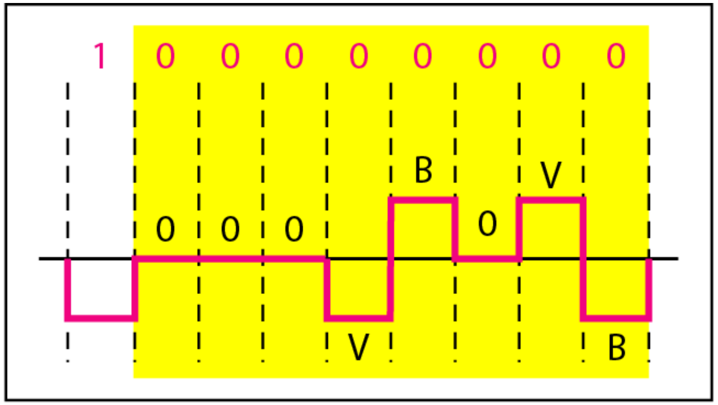


B8ZS

- Commonly used in North America
- Updated version of AMI with synchronization
- Substitutes eight consecutive zeros with **000VB0VB**
- **V** denotes "*violation*", **B** denotes "*bipolar*"



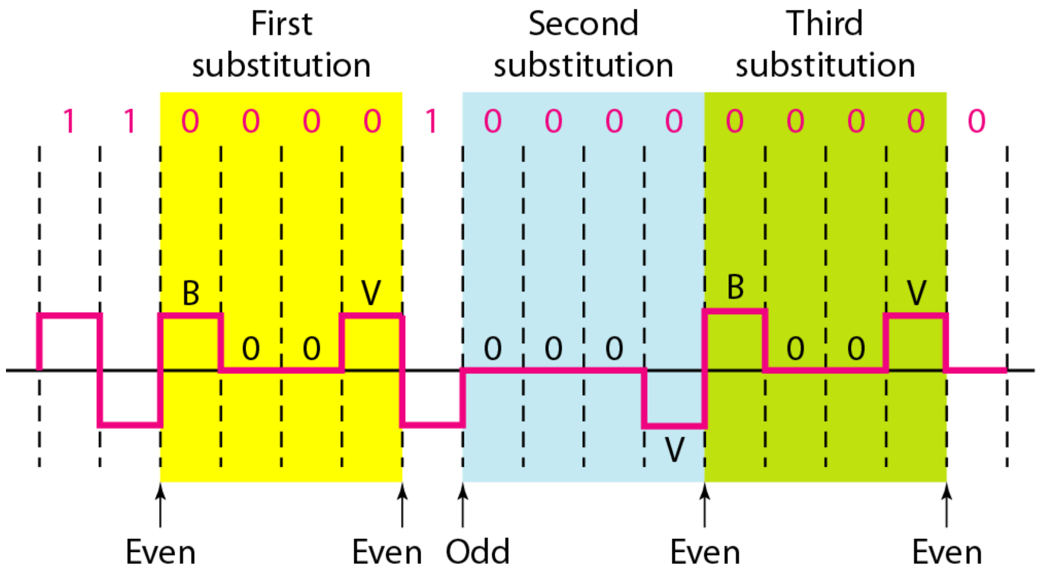
a. Previous level is positive.



b. Previous level is negative.

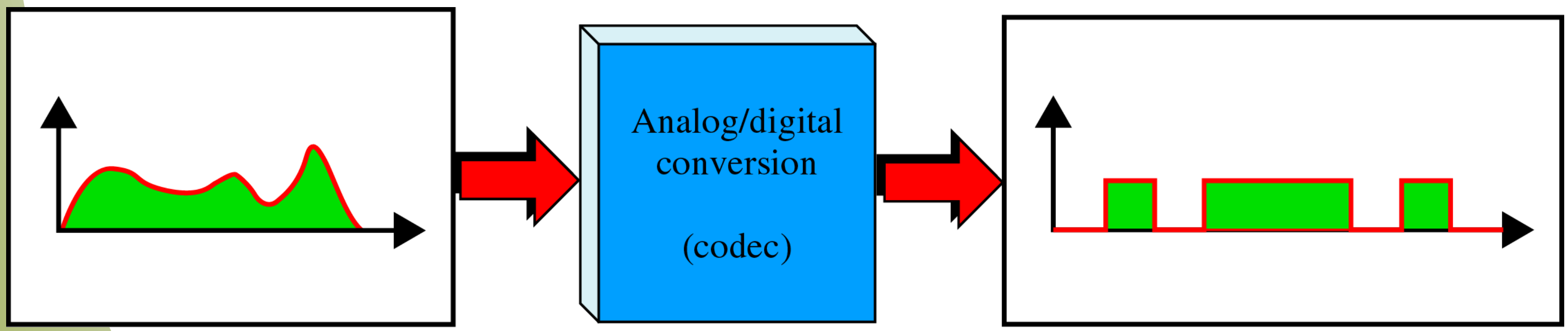
HDB3

- High-density bipolar 3-zero
- Commonly used outside of North America
- HDB3 substitutes four consecutive zeros with 000V or B00V depending on the number of nonzero pulses after the last substitution



Sampling: Analog-to-Digital Conversion

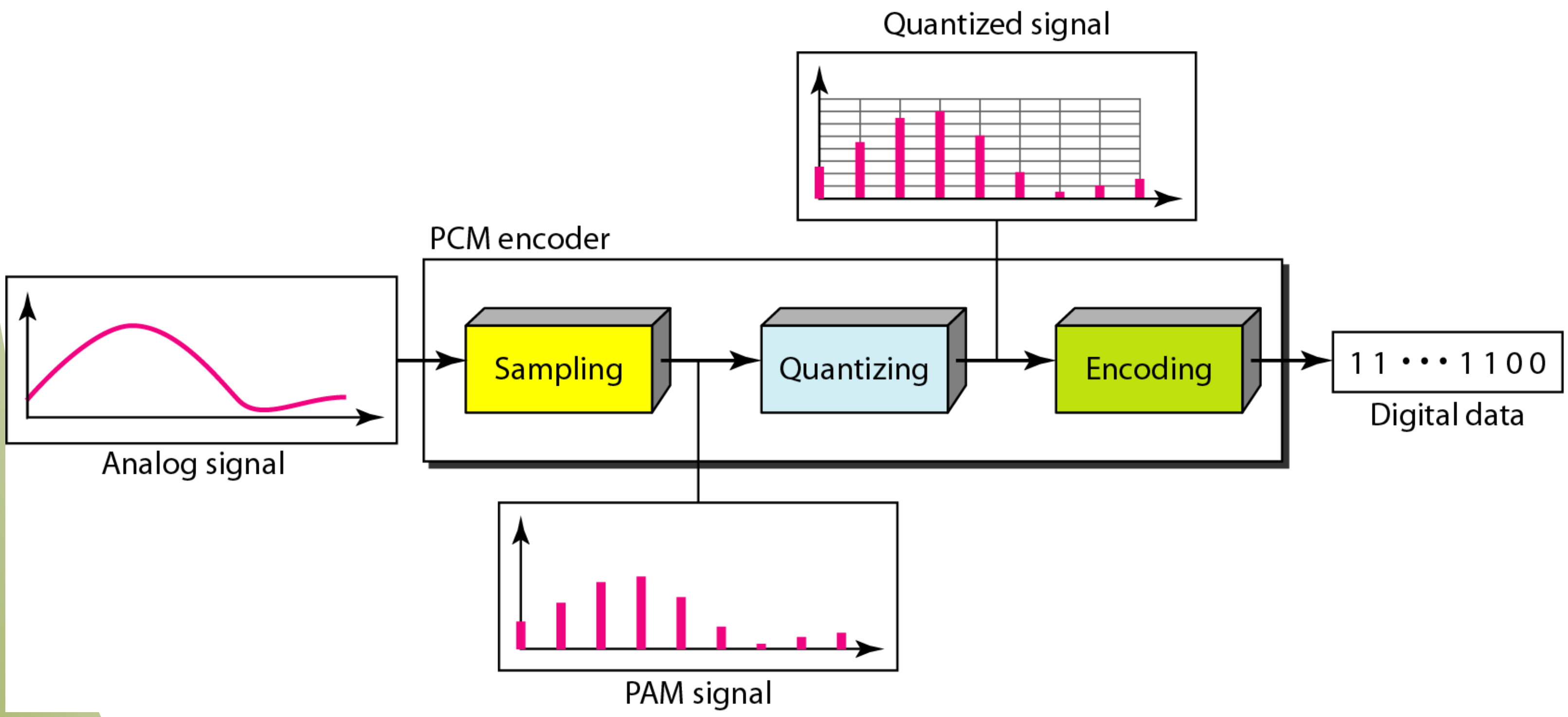
- Analog information (e.g., voice) → digital signal (e.g., 10001011…)
- Codec(Coder/Decoder): A/D converter



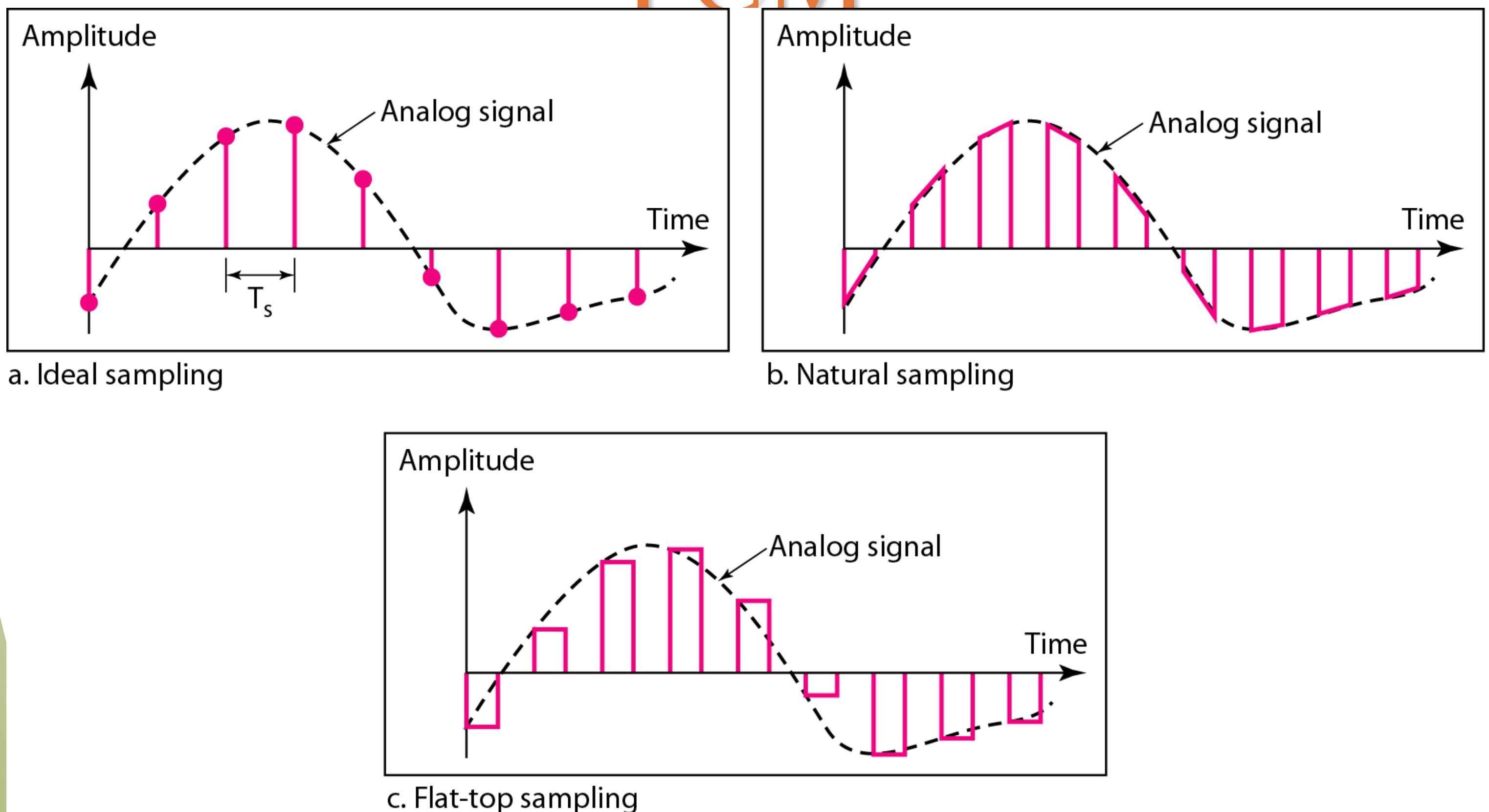
PCM

- Pulse Code Modulation
- Three processes
  - The analog signal is sampled
  - The sampled signal is quantized
  - The quantized values are encoded as streams of bits
- Sampling: PAM (Pulse amplitude Modulation)
  - According to the Nyquist theorem, the sampling rate must be at least 2 times the highest frequency contained in the signal.

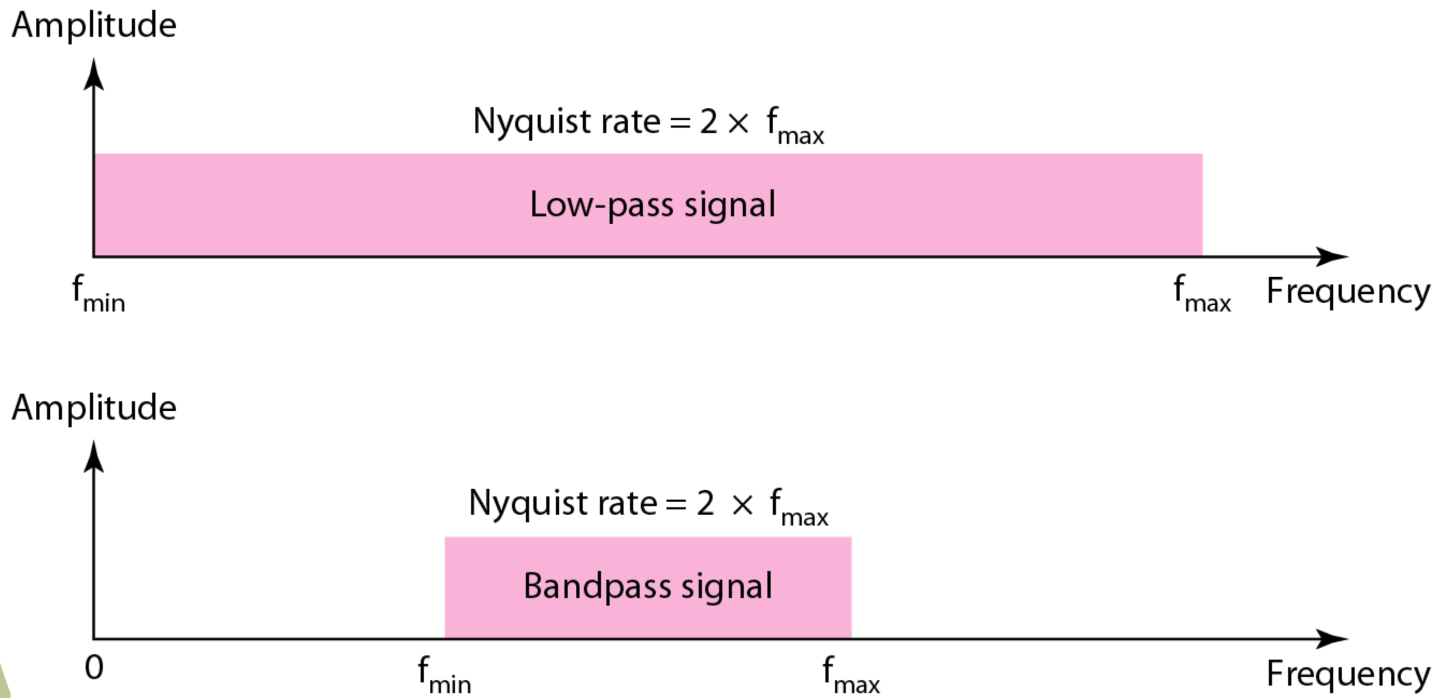
Components of PCM Encoder



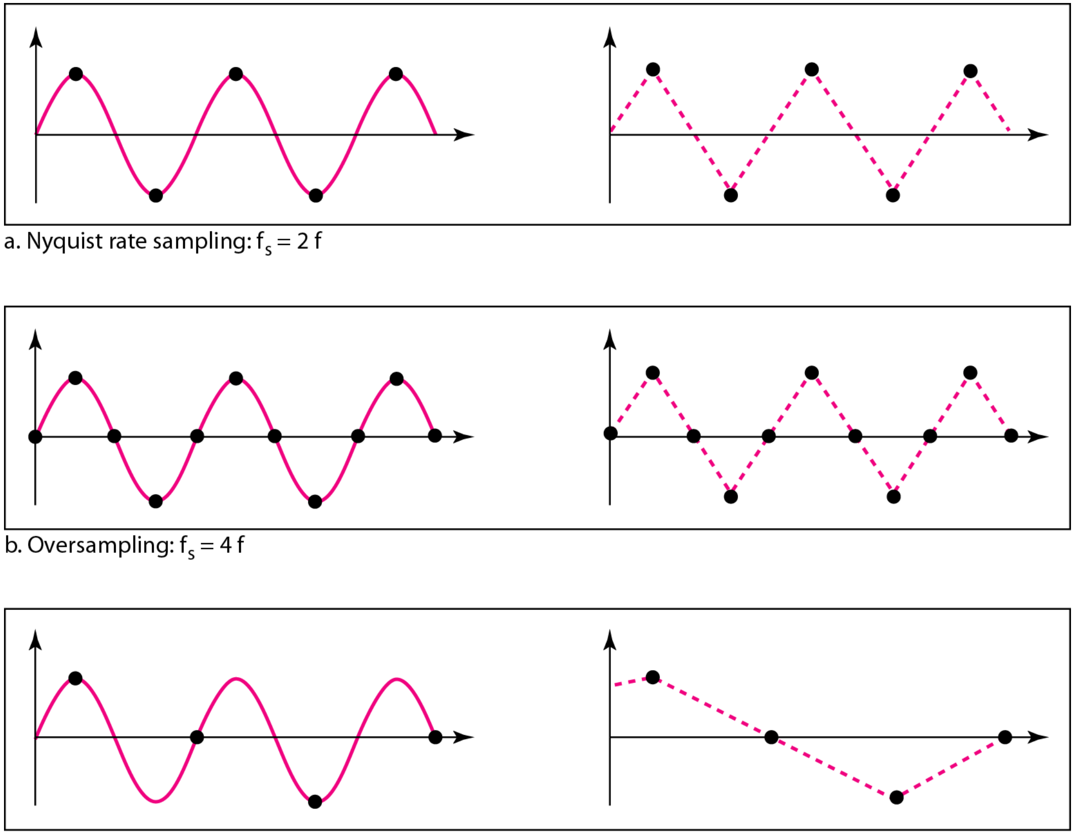
Different Sampling Methods for PCM



Nyquist Sampling Rate



Sampling Rate

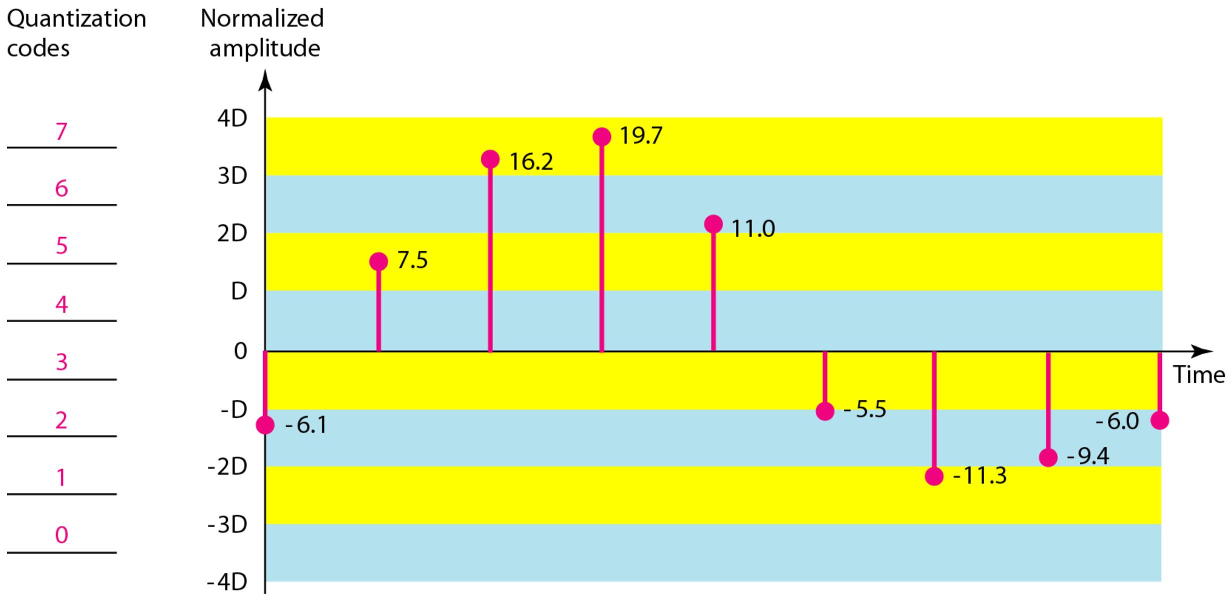


a. Nyquist rate sampling: $f_s = 2f$

b. Oversampling: $f_s = 4f$

c. Undersampling: $f_s = f$

Quantization

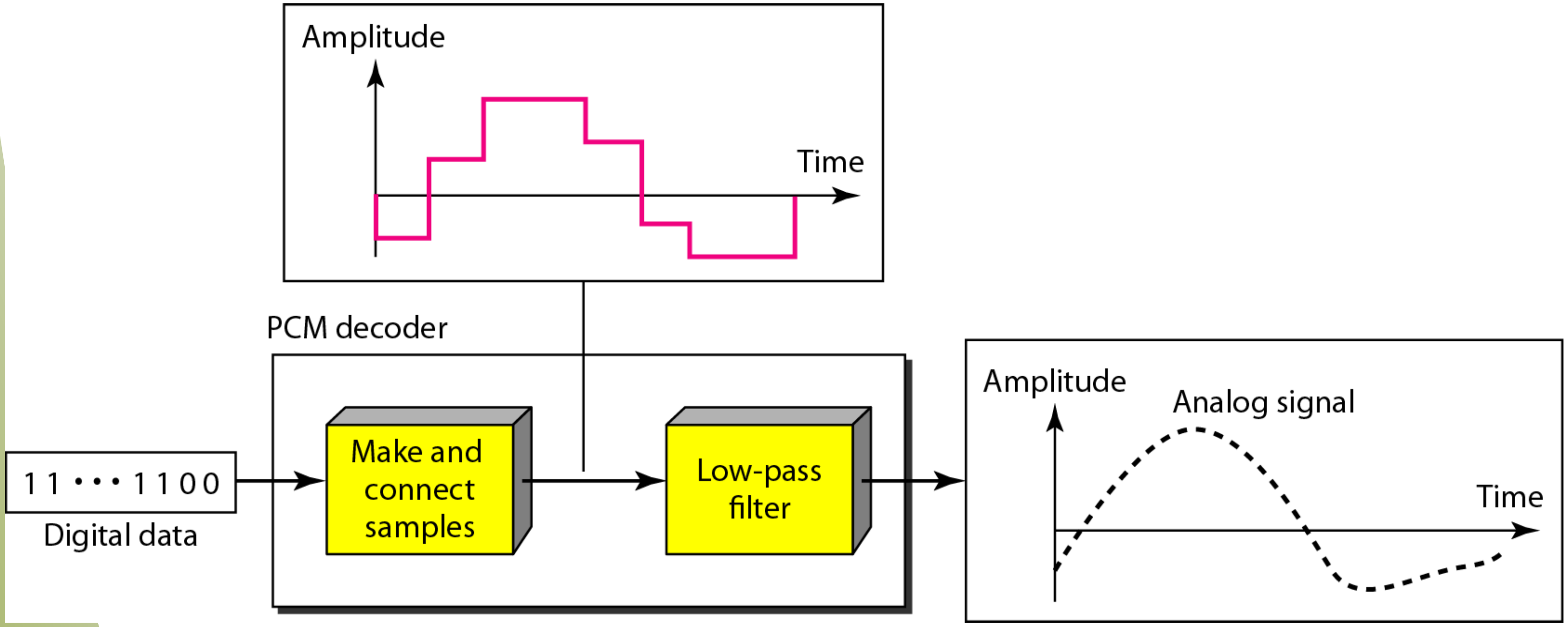


Normalized PAM values	-1.22	1.50	3.24	3.94	2.20	-1.10	-2.26	-1.88	-1.20
Normalized quantized values	-1.50	1.50	3.50	3.50	2.50	-1.50	-2.50	-1.50	-1.50
Normalized error	-0.38	0	+0.26	-0.44	+0.30	-0.40	-0.24	+0.38	-0.30
Quantization code	2	5	7	7	6	2	1	2	2
Encoded words	010	101	111	111	110	010	001	010	010

Quantization

- Quantization level (L)
- Quantization error : depending on L (or n_b)
  - $SNR_{dB} = 6.02n_b + 1.76$ dB
- Nonuniform quantization:
  - Companding and expanding
  - Effectively reduce the SNR_{dB}

Original Signal Recovery: PCM Decoder



PCM Bandwidth

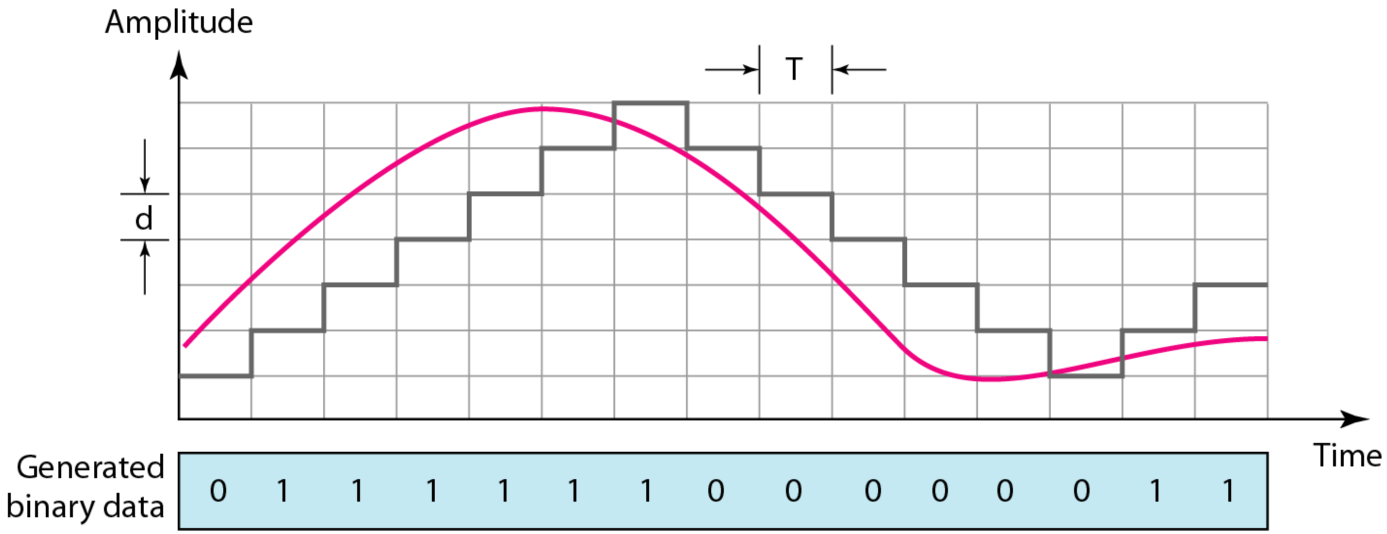
- The min. bandwidth of a line-encoded signal
  - $B_{min} = c \text{ x } N \text{ x } 1/r = c \text{ x } n_b \text{ x } f_s \text{ x } 1/r$

    $= c \text{ x } n_b \text{ x } 2 \text{ x } B_{analog} \text{ x } 1/r$

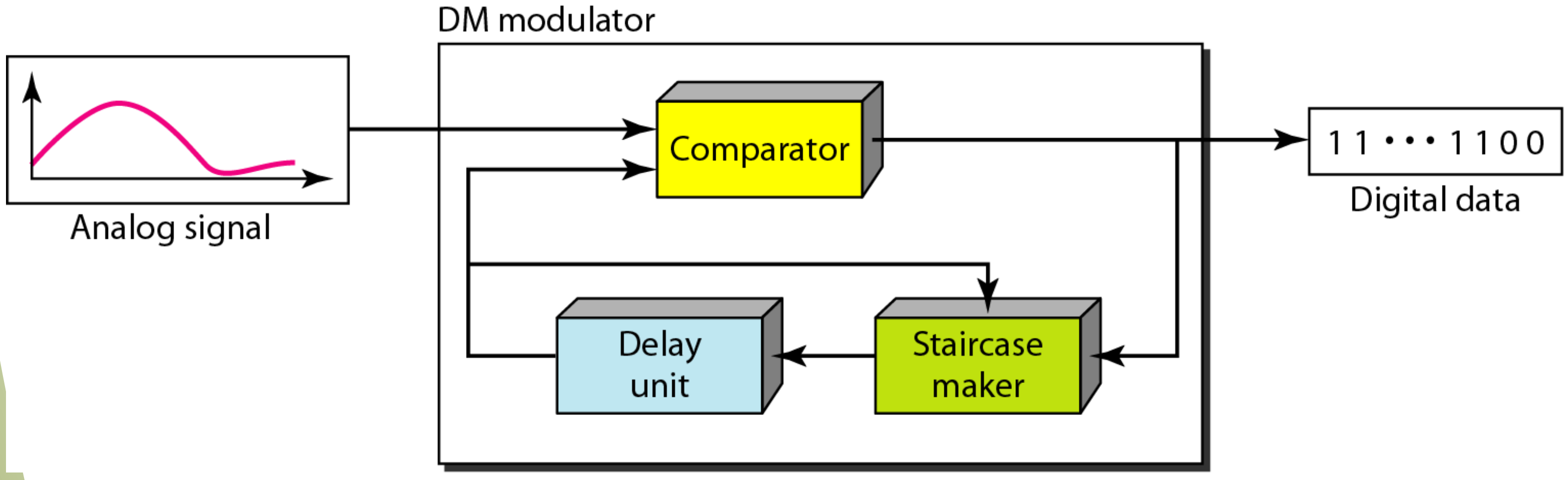
    $= n_b \text{ x } B_{analog}$ *where* $1/r = 1, c = 1/2$
- Max. data rate of a channel
  - $N_{max} = 2 \text{ x } B \text{ x } log_2 L$ bps
- Min. required bandwidth
  - $B_{min} = N/(2 \text{ x } log_2 L)$ Hz

Delta Modulation

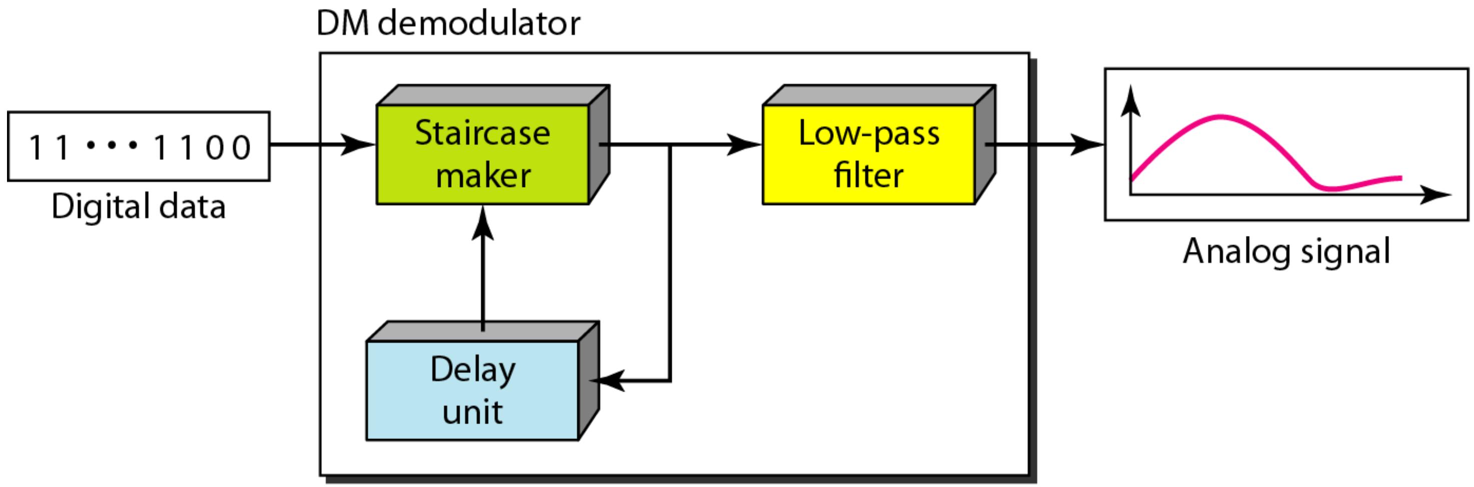
- To reduce the complexity of PCM



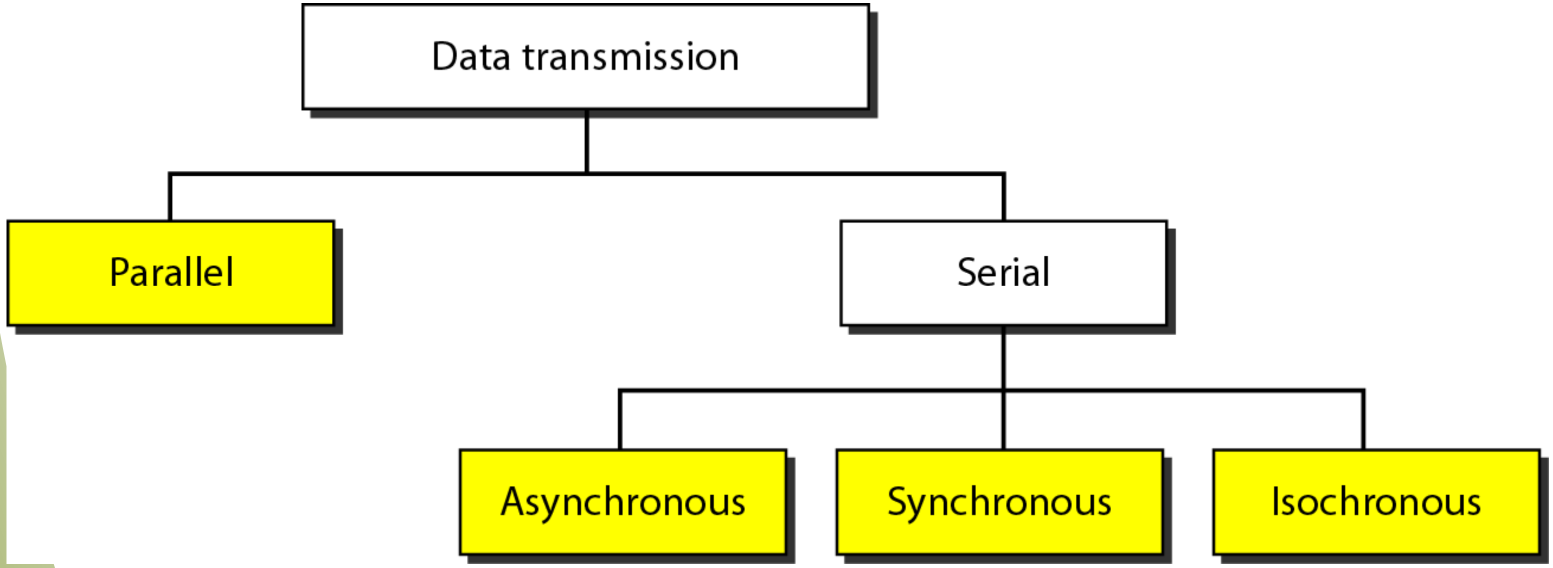
Delta Modulation Components



Delta Demodulation Components

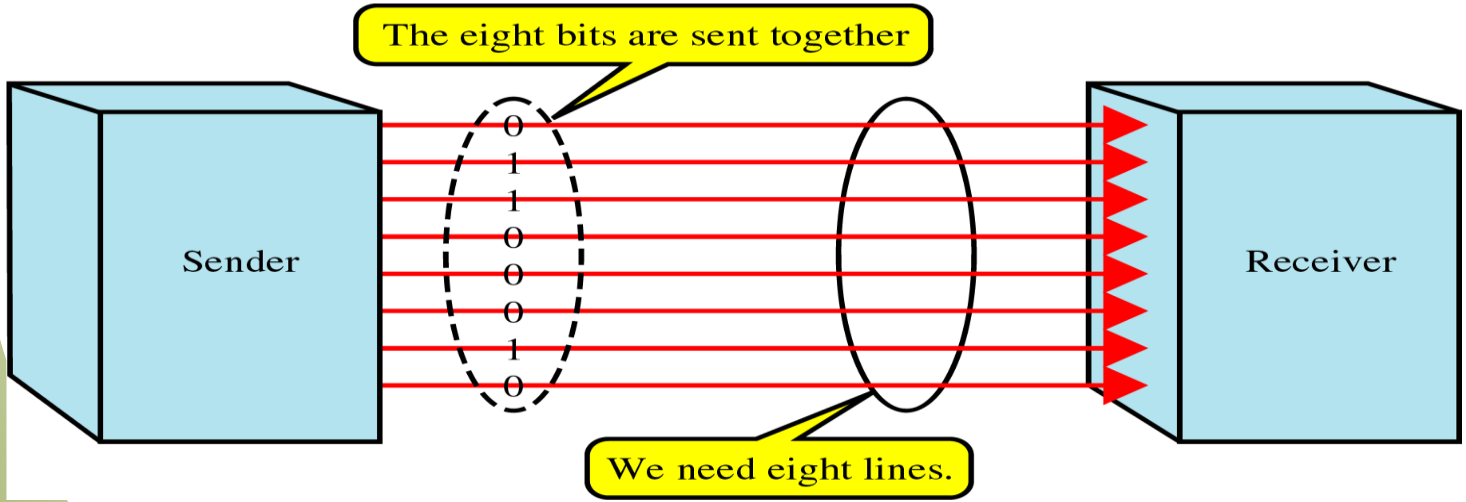


Transmission Modes



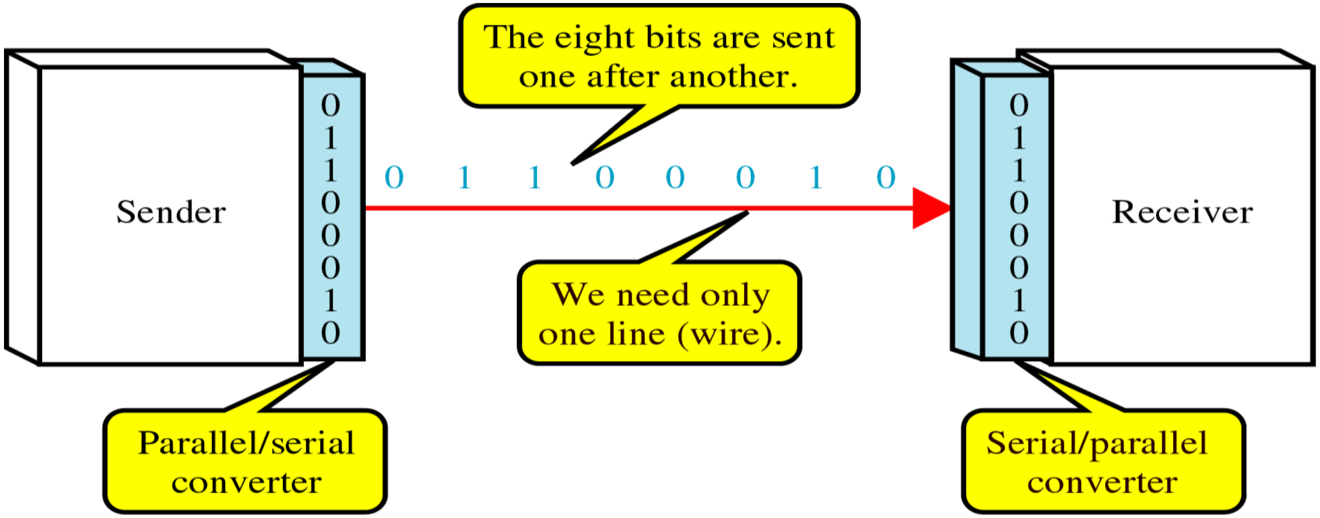
Parallel Transmission

- Use n wires to send n bits at one time synchronously
- Advantage: speed
- Disadvantage: cost $\Rightarrow$ Limited to short distances



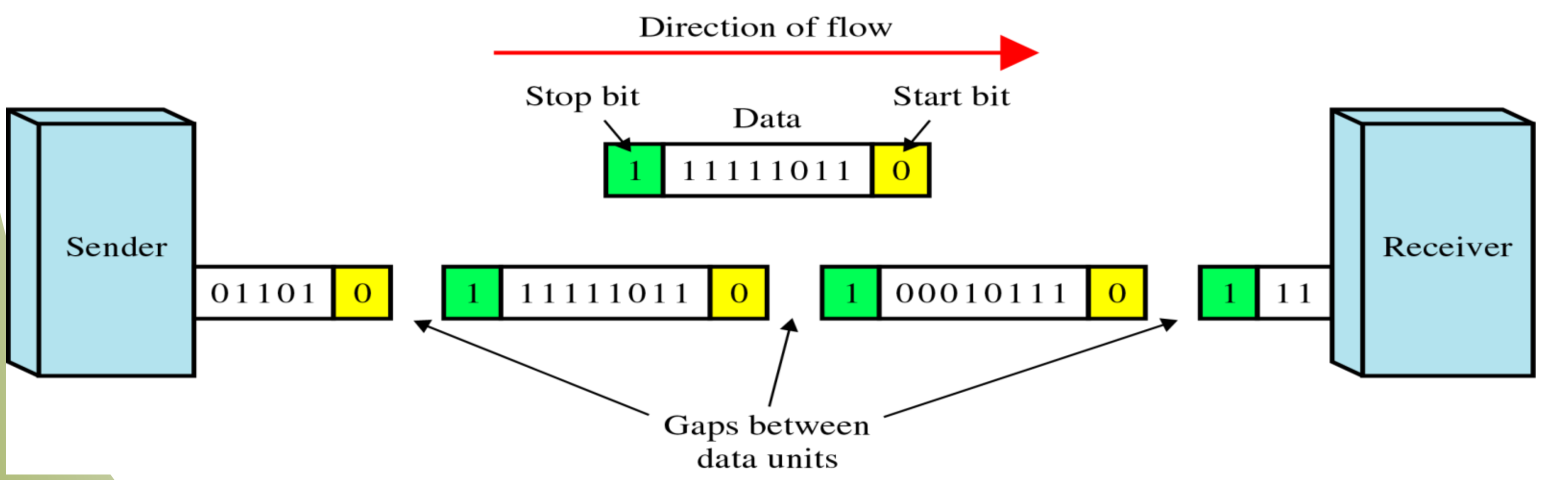
Serial Transmission

- On communication channel
- Advantage: reduced cost
- Parallel/serial converter is required
- Three ways: asynchronous, synchronous, or isochronous



Asynchronous Transmission

- Use *start bit* (0) and *stop bits* (1s)
- A gap between two bytes: idle state or stop bits
- It means asynchronous at byte level
- Must still be synchronized at bit level
- Good for low-speed communications (terminal)



Synchronous Transmission

- Bit stream is combined into “frames”
- Special sequence of 1/0 between frames: No gap
- Timing is important in midstream
- Byte synchronization in the data link layer
- Advantage: speed ⇒ high-speed transmission