Content Outline – Unit 2

- **Physical Layer**
  - **Transmission Media**
    - **Transmission Impairments**
  - **Channel capacity of a transmission media**
  - **Line coding techniques**

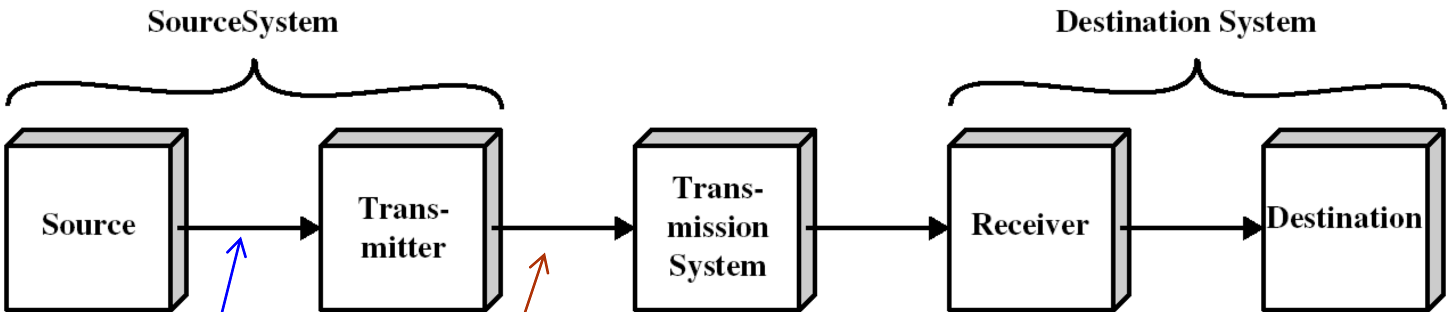
Objectives of Unit 2

- Describe different physical transmission medium and the impairments during transmission
- Describe the design factors when choosing an appropriate transmission medium for sending data
- Show how to estimate the maximum possible data rate, i.e., the channel capacity, of a communication channel under the perfect noiseless or noisy environment
- Introduce different line coding techniques for converting the data into some digital signals suitable for transmission over the medium

Data Transmission

- Terminology:
  - Data transmission occurs between a transmitter & receiver via some medium
  - Data
    - Entities that convey meaning
  - Signals & signalling
    - Electric or electromagnetic representations of data, physically propagates along medium
  - Transmission
    - Communication of data by propagation and processing of signals

Data Transmission



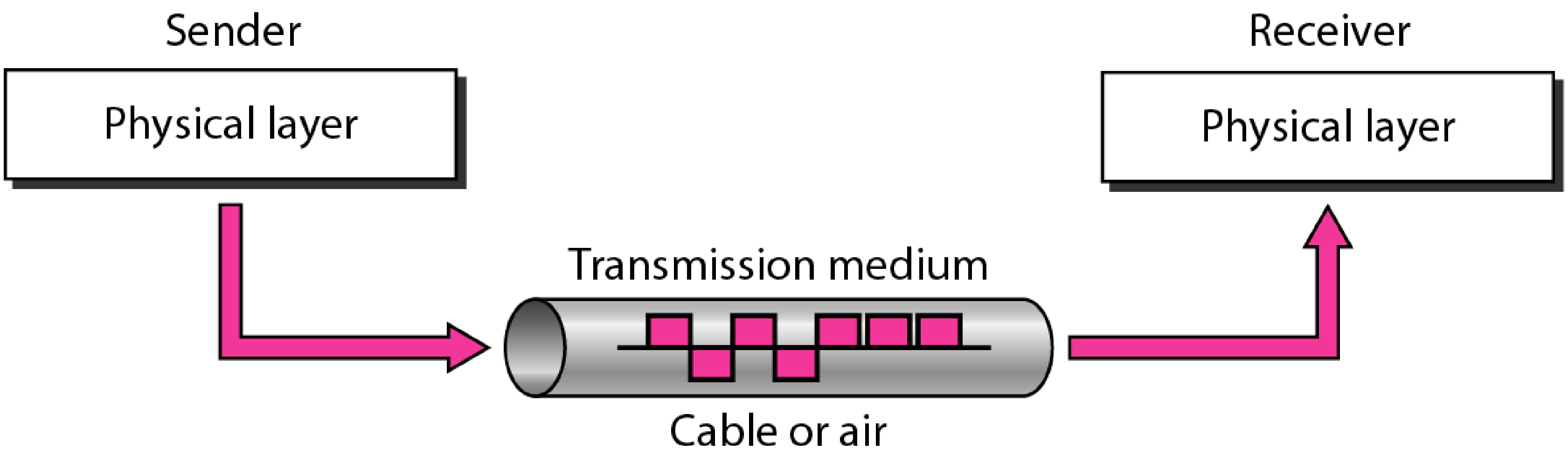
- Source Data:
  - Digital data: discrete, e.g., text and integers
  - Analog data: continuous, e.g., audio
- Transmitted Signal:
  - Digital signal: a sequence of voltage pulses transmitted over a medium
  - Analog signal: a continuously varying electromagnetic wave

Data Transmission

- Four possible combinations
  - Analog Transmission
    - Analog data, analog signal: Amplitude Modulation (AM), FM, PM.
    - Digital data, analog signal: Amplitude Shift Keying (ASK), FSK, PSK.
  - Digital Transmission
    - Digital data, digital signal: NRZ-L, NRZI, Bipolar-AMI, …
    - Analog data, digital signal: Pulse Code Modulation (PCM)

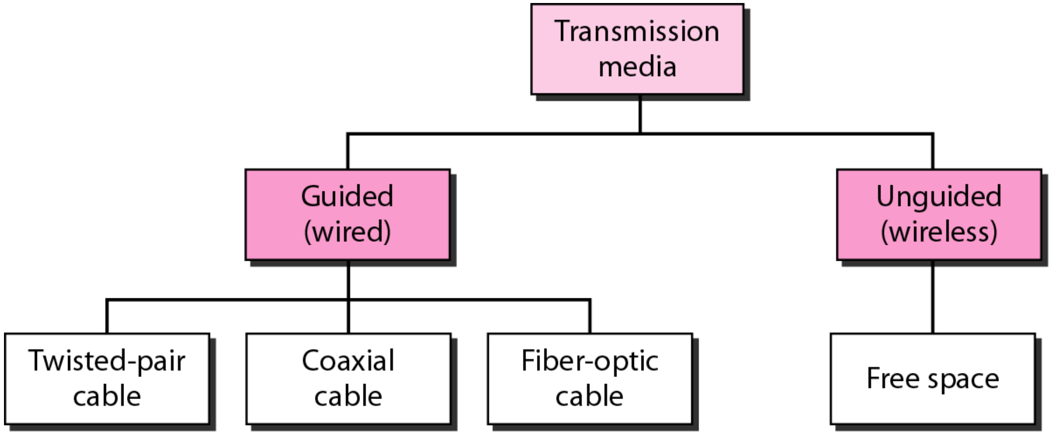
Transmission Media

- The physical medium that carries the transmitted signals



Transmission Media

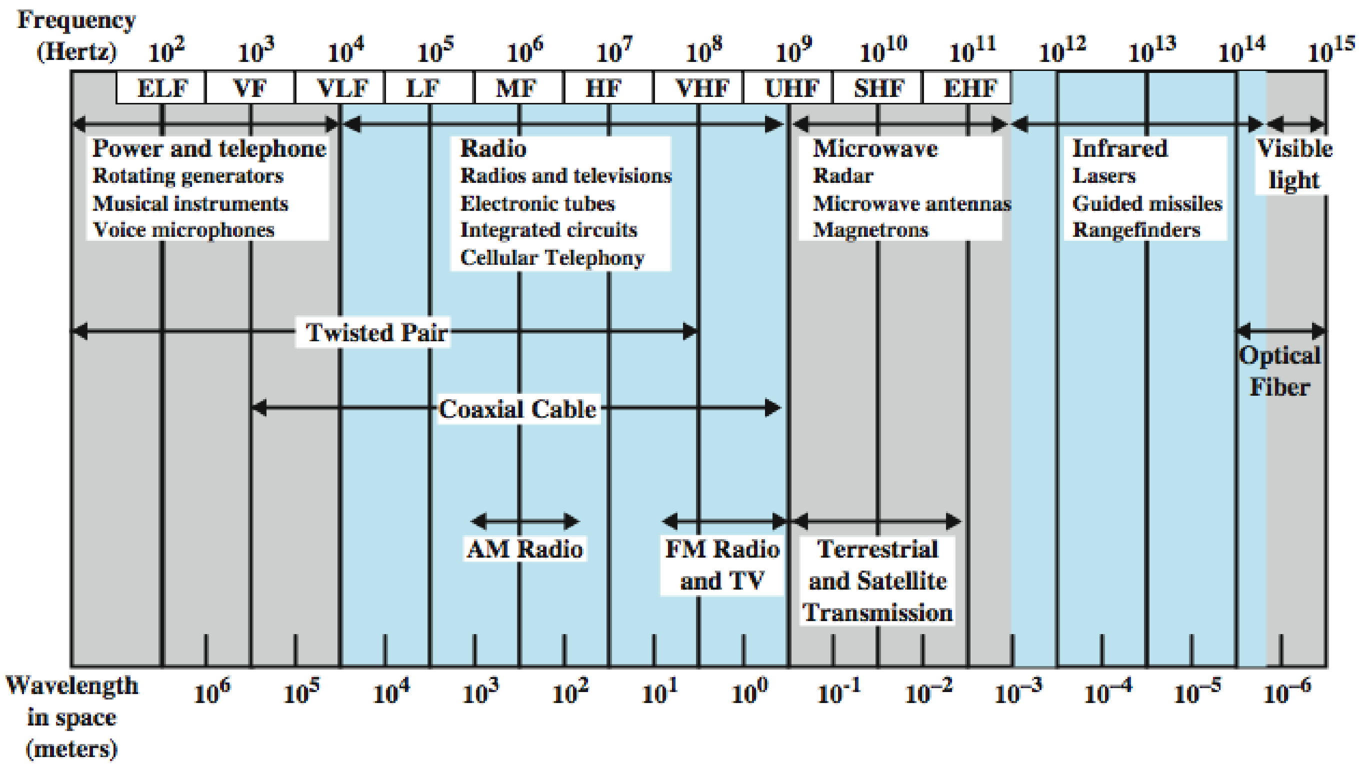
- Transmission Media:
  - Guided media - which are those that provide a conduit from one device to another, include twisted-pair cable, coaxial cable, and fiber-optic cable.
  - Unguided media - transport electromagnetic waves without using a physical conductor. This type of communication is often referred to as wireless communication.
- Key concerns are data rate and distance



Transmission Media

- Design factors
  - Bandwidth
    - Higher bandwidth gives higher data rate
  - Transmission impairments
    - e.g., attenuation
  - Interference
  - Number of receivers in guided media
    - More receivers introduces more attenuation

Transmission Media

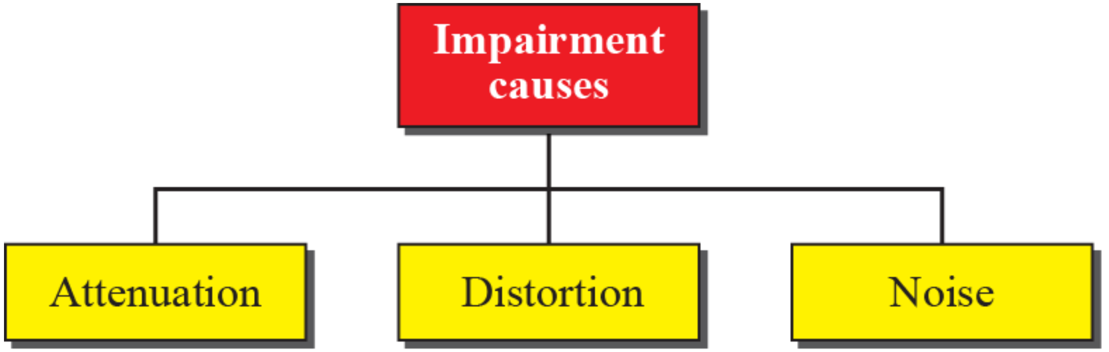


ELF = Extremely low frequency
VF = Voice frequency
VLF = Very low frequency
LF = Low frequency
MF = Medium frequency
HF = High frequency
VHF = Very high frequency
UHF = Ultrahigh frequency
SHF = Superhigh frequency
EHF = Extremely high frequency

Transmission Impairments

- Signal received may differ from signal transmitted causing:
  - Analog - degradation of signal quality
  - Digital - bit errors

- Most significant impairments are
  - Attenuation
  - Distortion
  - Noise

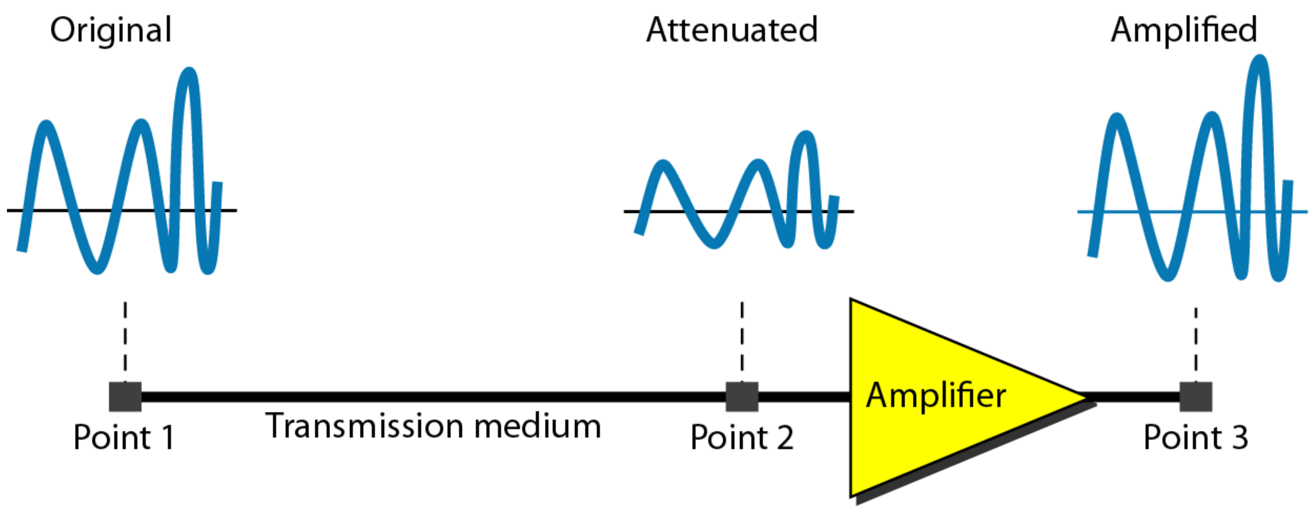


Transmission Impairments

- **Attenuation**
  - Attenuation means a loss of energy where signal strength falls off with distance
  - Depends on medium
  - Mainly resistance loss
  - Received signal strength must be:
    - Strong enough to be detected
    - Sufficiently higher than noise to receive without error
    - Attenuation varies with frequency

Transmission Impairments

- **Solutions to Attenuation**
  - For the first and second problems, increase strength using amplifiers/repeaters
  - For the third problem, equalize attenuation across a band of frequencies



Example

Suppose a signal travels through a transmission medium and its power is reduced to one half. This means that $P_2 = 0.5\ P_1$. In this case, the attenuation (loss of power) can be calculated as

$$\boxed{10 \log_{10} P_2/P_1 = 10 \log_{10} (0.5\ P_1)/P_1 = 10 \log_{10} 0.5 = 10 \times (-0.3) = -3 \text{ dB.}}$$

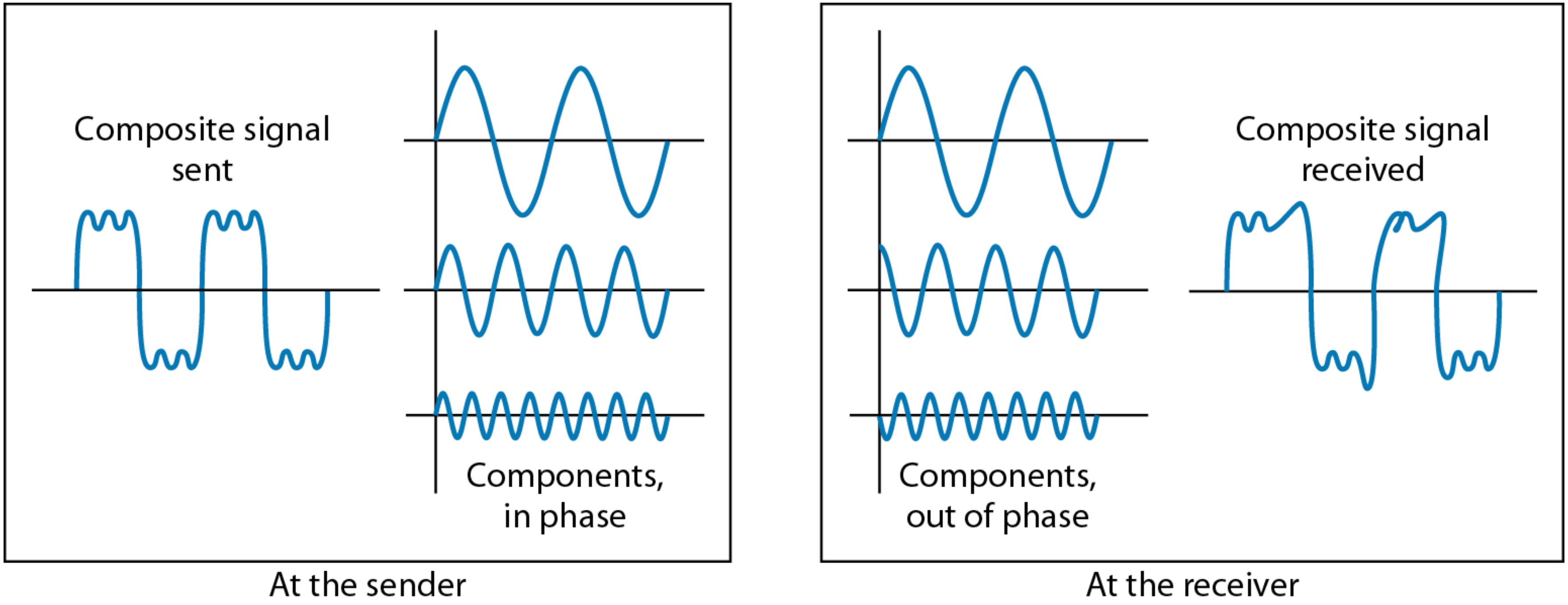
A loss of 3 dB (−3 dB) is equivalent to losing one-half the power.

Transmission Impairments

- **Delay distortion**
  - Propagation velocity varies with frequency
  - Hence various frequency components arrive at different times
  - Particularly critical for digital data
  - Inter-symbol interference: Parts of one bit spill over into others

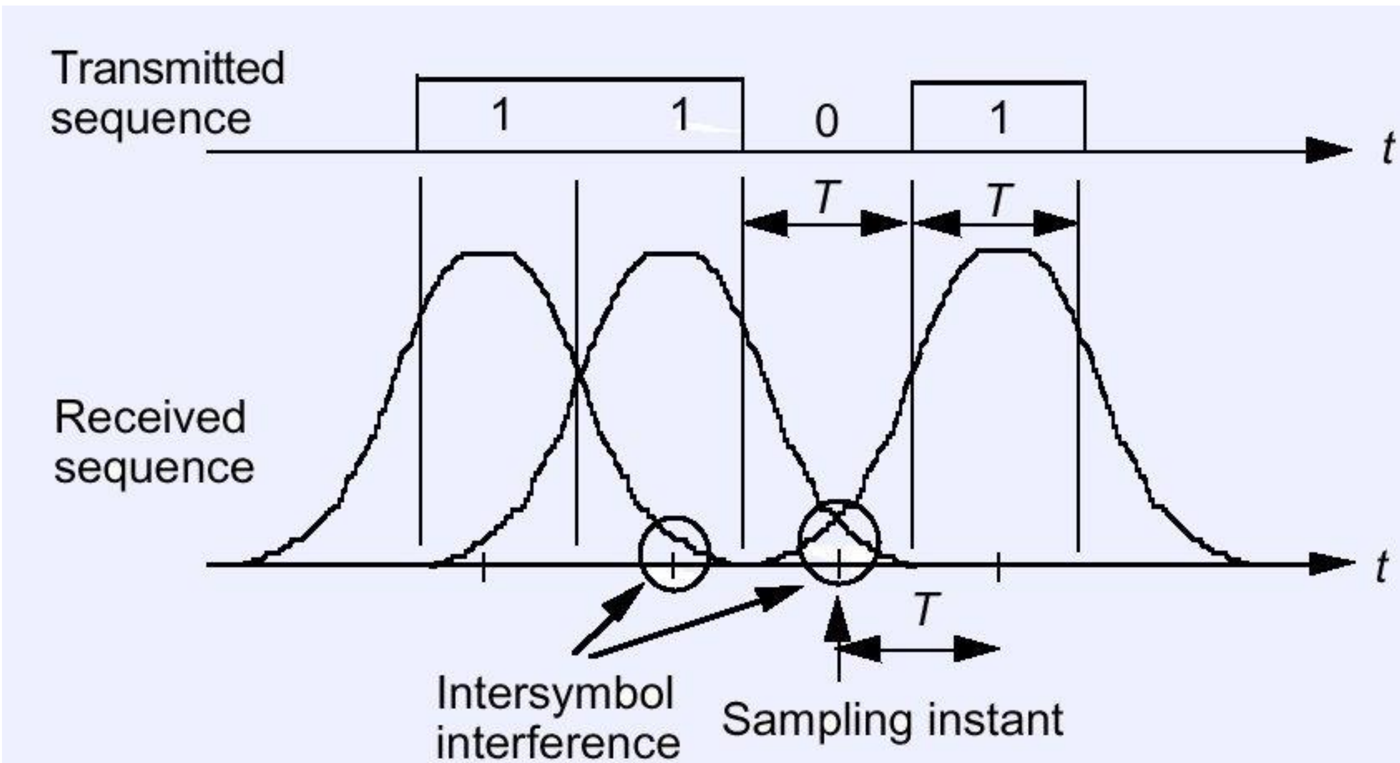
Transmission Impairments

- **Delay distortion**



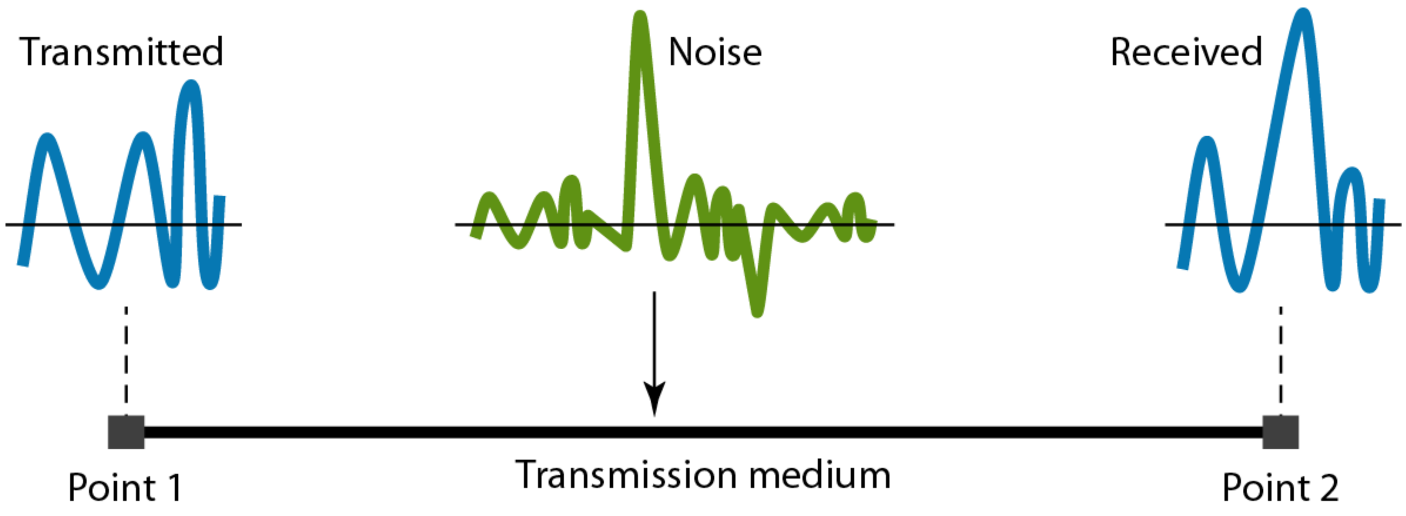
Transmission Impairments

- **Inter-Symbol Interference (ISI)**



Transmission Impairments

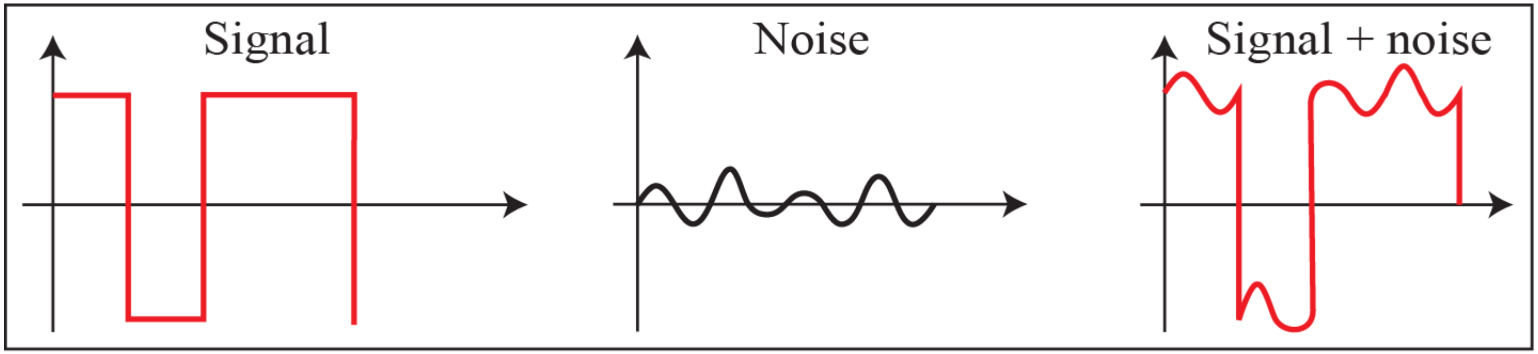
- **Noise**
  - Additional signals inserted between transmitter and receiver



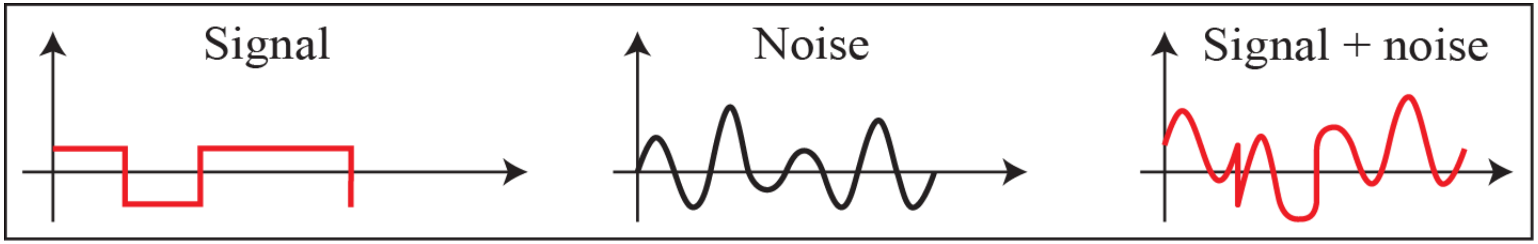
Transmission Impairments

- Thermal Noise
  - Due to thermal agitation of electrons
  - Uniformly distributed, white noise
- Intermodulation Noise
  - Signals that are the sum and difference of original frequencies sharing a medium
- Crosstalk Noise
  - A signal from one line is picked up by another
- Impulse Noise
  - Irregular pulses or spikes, e.g., external electromagnetic interference
  - Short duration, high amplitude
  - A minor annoyance for analog signals but a major source of error in digital data
  - A noise spike could corrupt many bits

Signal to Noise Ratio (SNR)



a. High SNR



b. Low SNR

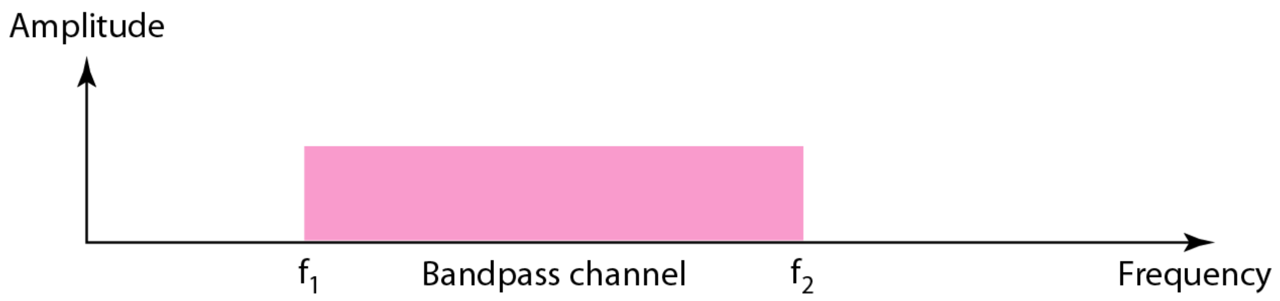
Channel Capacity

- A very important consideration in data communications is how fast we can send data, in bits per second, over a channel.
  - Channel capacity = Maximum possible data rate on communications channel

- Channel capacity depends on three factors:
  - The bandwidth available
  - The level of the signals we use
  - The quality of the channel (the level of noise)

Channel Capacity

- **Bandwidth**
  - Bandwidth in hertz (Hz), or cycles per second, refers to the range of frequencies in a composite signal or the range of frequencies that a channel can pass
  - The bandwidth is different for each type of transmission medium, e.g. twisted pair (300 kHz), coaxial cable (500 MHz), fiber optics (10 GHz)



- In computer networking, we use the term **"bandwidth"** in a different context, i.e., bandwidth in bits per second (bps), refers to the speed of bit transmission in a channel or link.

Channel Capacity

- Baud rate (signaling rate): number of signal elements per second on a channel

- Baud rate ≠ bit rate (transmission rate)
  - For a binary level, baud rate = bit rate.
  - For a multi-level, baud rate < bit rate.

Channel Capacity

- **Noiseless Channel - Nyquist Bandwidth**
  - Nyquist showed that maximum signaling rate is equal to 2 × bandwidth.
  - The Nyquist Bitrate is given by

$$C = 2B \log_2 L \text{ bps}$$

where C = bitrate in bps

B = bandwidth in Hz

L = no. of levels per signaling element

Nyquist Formula

- Nyquist formula is used to determine the maximum information rate for noiseless channel.

- Example: a telephone voice channel has a bandwidth of 4 kHz, what is its bit rate if it is used to transmit binary signals?

  [Solution]

$$\begin{aligned} \text{bit rate} &= 2 \times 4000 \times \log_2 2 \text{ bps} \\ &= 8 \text{ kbps.} \end{aligned}$$

Nyquist Formula - Example

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

Solution

We can use the Nyquist formula as shown:

$$265{,}000 = 2 \times 20{,}000 \times \log_2 L \longrightarrow \log_2 L = 6.625 \longrightarrow L = 2^{6.625} = 98.7 \text{ levels}$$

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

Channel Capacity

- **Noisy Channel - Shannon Capacity Formula**

$$C = B \log_2(1 + S/N) \text{ bps}$$

where C = information rate in bps

B = bandwidth in Hz

S/N = signal to noise ratio

$$= \frac{\text{Signal Power}}{\text{Noise Power}}$$

Example

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

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

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

Example

We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000. The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as

$$C = B \log_2 (1 + \text{SNR}) = 3000 \log_2 (1 + 3162) = 3000 \log_2 3163$$
$$= 3000 \times 11.62 = 34{,}860 \text{ bps}$$

This means that the highest bit rate for a telephone line is 34.860 kbps. If we want to send data faster than this, we can either increase the bandwidth of the line or improve the signal-to-noise ratio.

Example

The signal-to-noise ratio is often given in decibels. Assume that $SNR_{dB} = 36$ and the channel bandwidth is 2 MHz. The theoretical channel capacity can be calculated as

$$SNR_{dB} = 10 \log_{10} SNR \rightarrow SNR = 10^{SNR_{dB}/10} \rightarrow SNR = 10^{3.6} = 3981$$

$$C = B \log_2 (1 + SNR) = 2 \times 10^6 \times \log_2 3982 = 24 \text{ Mbps}$$

Example

We have a channel with a 1-MHz bandwidth. The SNR for this channel is 63. What are the appropriate bit rate and signal level?

Solution

First, we use the Shannon formula to find the upper limit.

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

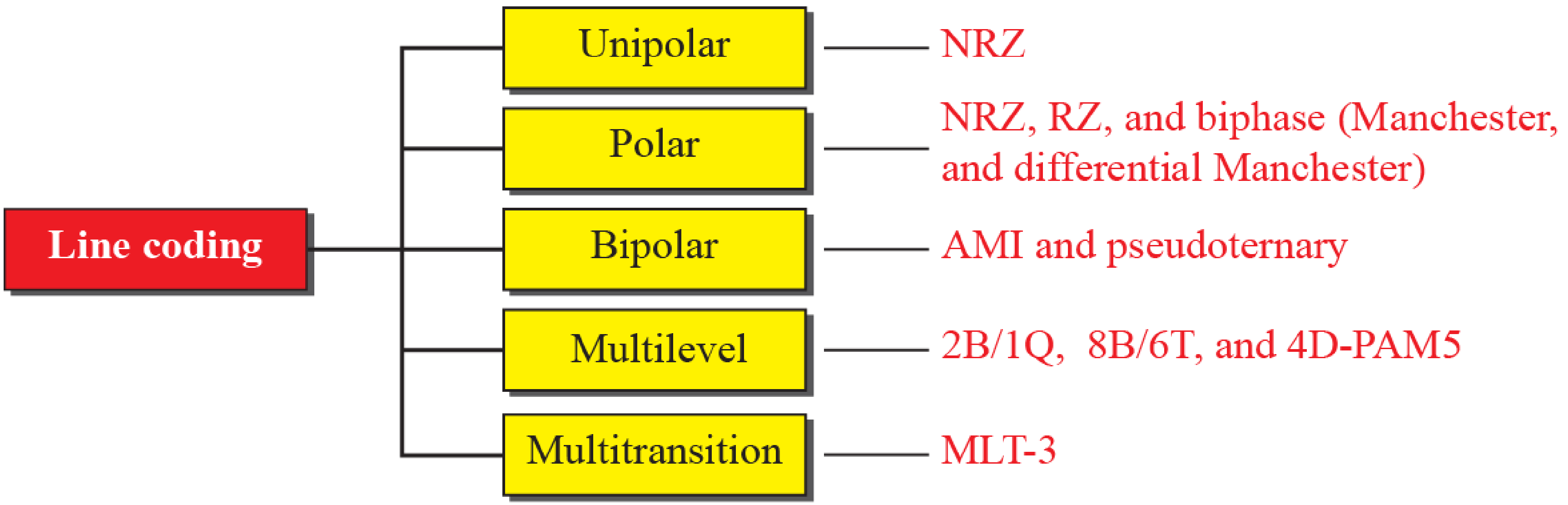
Example

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

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

The Shannon capacity gives us the upper limit; the Nyquist formula tells us how many signal levels we need.

Line Coding Schemes

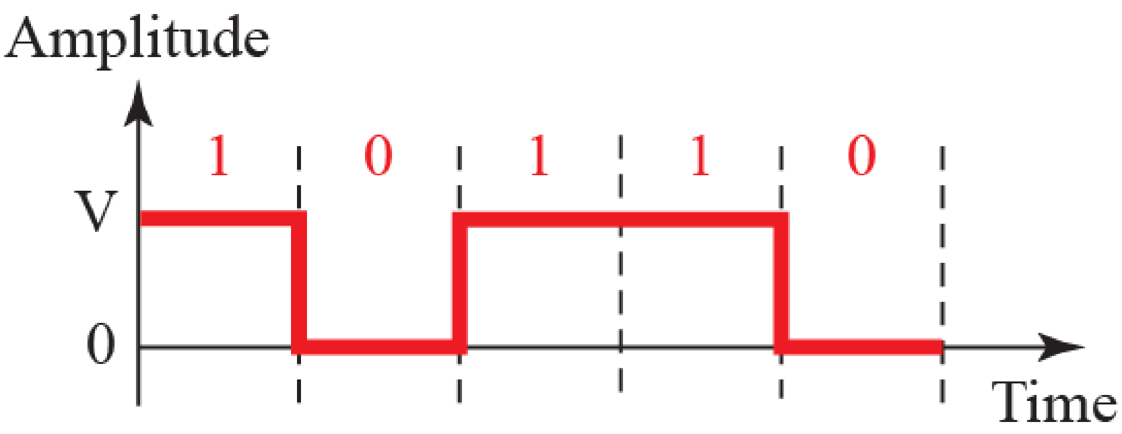


Line Coding Requirements

- Small transmission bandwidth
- Power efficiency: as small as possible for required data rate and error probability
- Error detection/correction
- Timing information: clock must be extracted from data
- No DC component: the DC component does not pass through some components of a communication system such as a transformer. This leads to distortion of the signal and may create error at the output. The DC component also results in unwanted energy loss on the line.

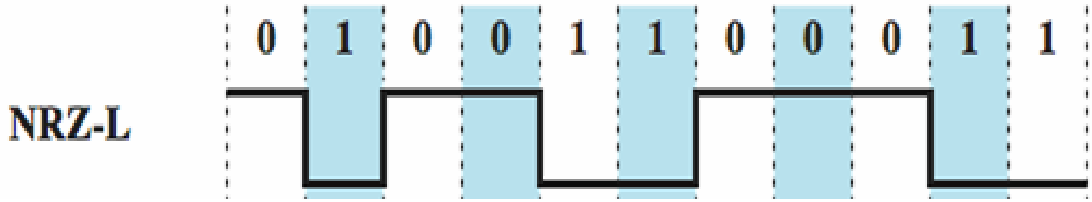
Unipolar: Non-Return to Zero-Level (NRZ-L)

- Voltage constant during bit interval
  - No transition i.e., no return to zero voltage at the middle of the bit
  - “0”: zero voltage, “1”: positive voltage



Polar: Non-Return to Zero-Level (NRZ-L)

- In polar schemes, the voltages are on both sides of the time axis (+ve and –ve)
- Two different voltages for 0 and 1 bits
- Voltage constant during bit interval
  - No transition i.e., no return to zero voltage
  - “0”: positive voltage, “1”: negative voltage

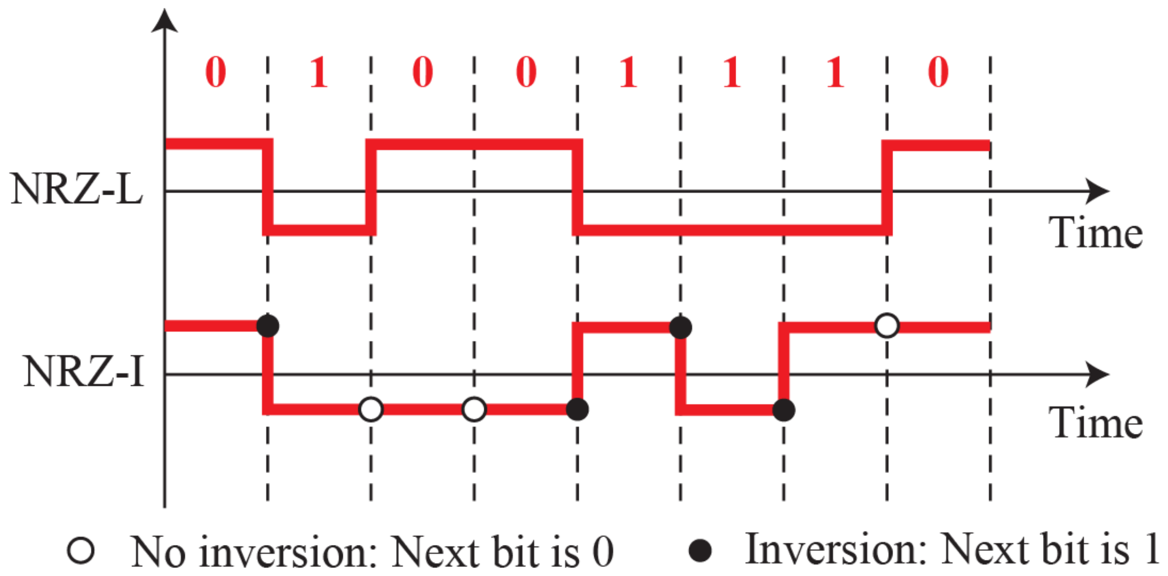


Polar: Non-Return to Zero, Inverted (NRZI)

- Non return to zero inverted on ones
- Constant voltage pulse for duration of bit
- Data encoded as presence or absence of signal transition at beginning of bit time
  - Transition denotes binary 1
    - Transition: low to high or high to low
  - No transition denotes binary 0

Non-Return to Zero, Inverted (NRZI)

- Example of differential encoding since have
  - Data represented by changes rather than levels
  - More reliable detection of transition rather than level
  - Easy to lose sense of polarity

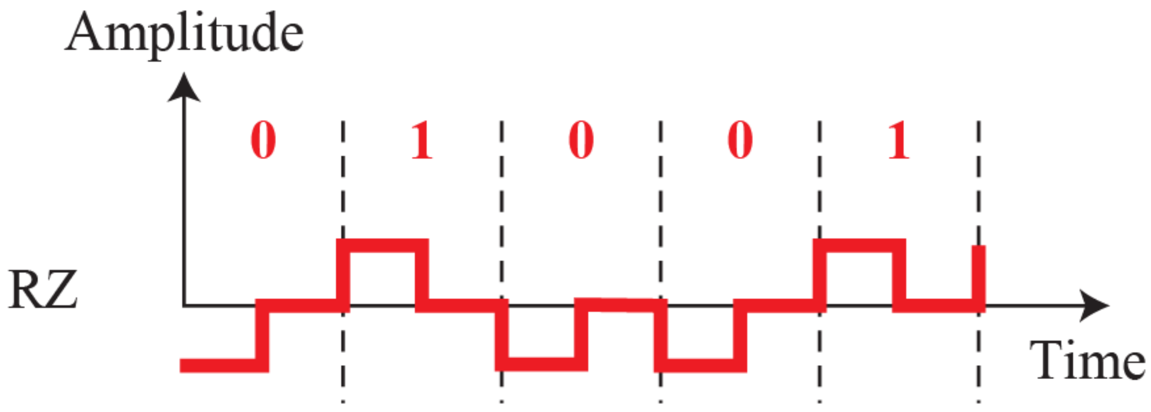


NRZ Pros & Cons

- Pros
  - easy to engineer
  - make good use of bandwidth
- Cons
  - dc component
  - lack of synchronization capability
- Used for magnetic recording
- Not often used for signal transmission

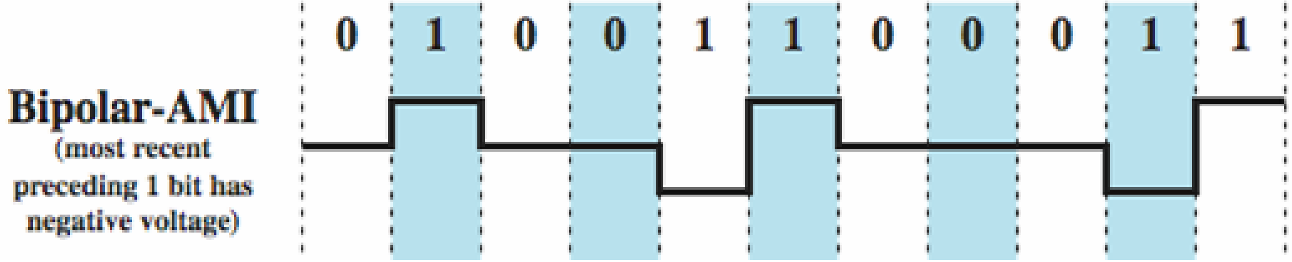
Polar: Return to Zero (RZ)

- In RZ, the signal changes not between bits but during the bit.
- The signal returns to zero in the middle of the bits.
- No DC component if numbers of "1" and "0" are the same



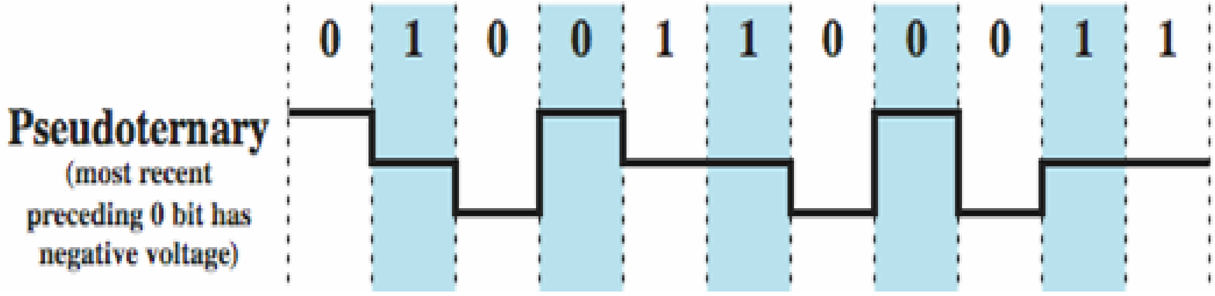
Bipolar - Alternate Mark Inversion (Bipolar-AMI)

- Bipolar-AMI
  - Zero represented by no line signal
  - One represented by positive or negative pulse
  - One pulses alternate in polarity
- No loss of sync if a long string of ones (zeros still a problem)
- No net dc component
- Lower bandwidth
- Easy error detection



Pseudoternary

- Pseudoternary
  - One represented by absence of line signal
  - Zero represented by alternating positive and negative
  - Very similar to bipolar-AMI
  - Each used in some applications



Bipolar Issues

- Synchronization with long runs of 0's or 1's
- Not as efficient as NRZ
  - Each signal element only represents one bit
    - Receiver distinguishes between three levels: +A, -A, 0
  - A 3 level system could represent $\log_2 3 = 1.58$ bits
  - Requires approx. 3dB more signal power for same probability of bit error

Biphase Techniques

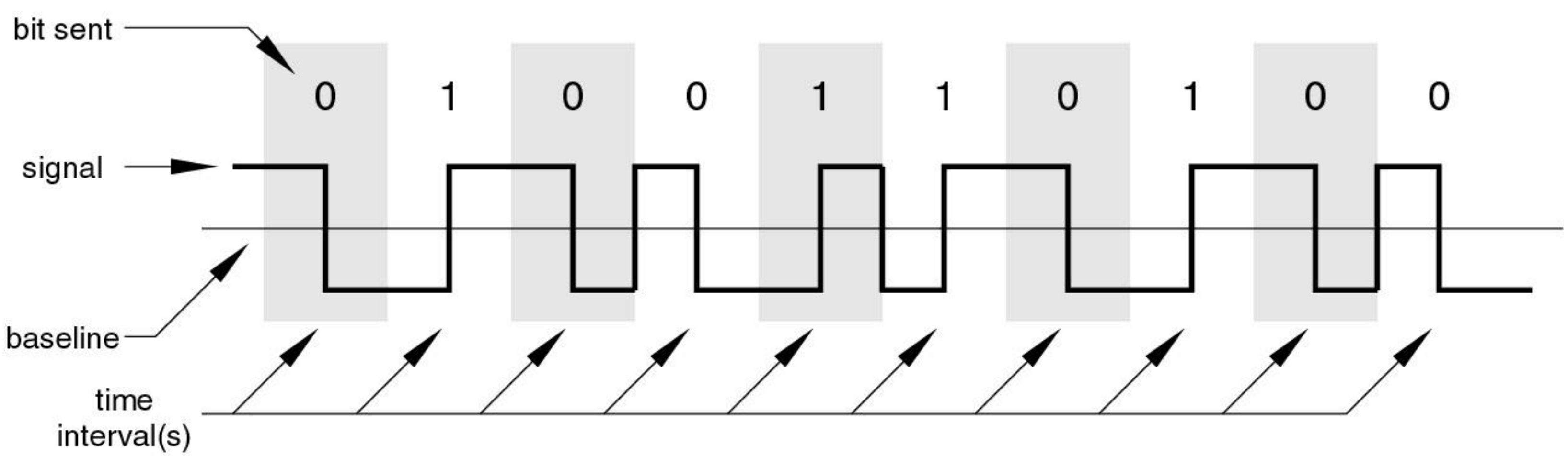
- Encoding technique: Biphase
  - Manchester encoding
  - Differentiated Manchester encoding

Manchester Encoding

- Manchester Encoding
  - Has transition in middle of each bit period
  - Transition serves as clock and data
  - Low to high represents one
  - High to low represents zero
  - Used by IEEE 802

Manchester Encoding

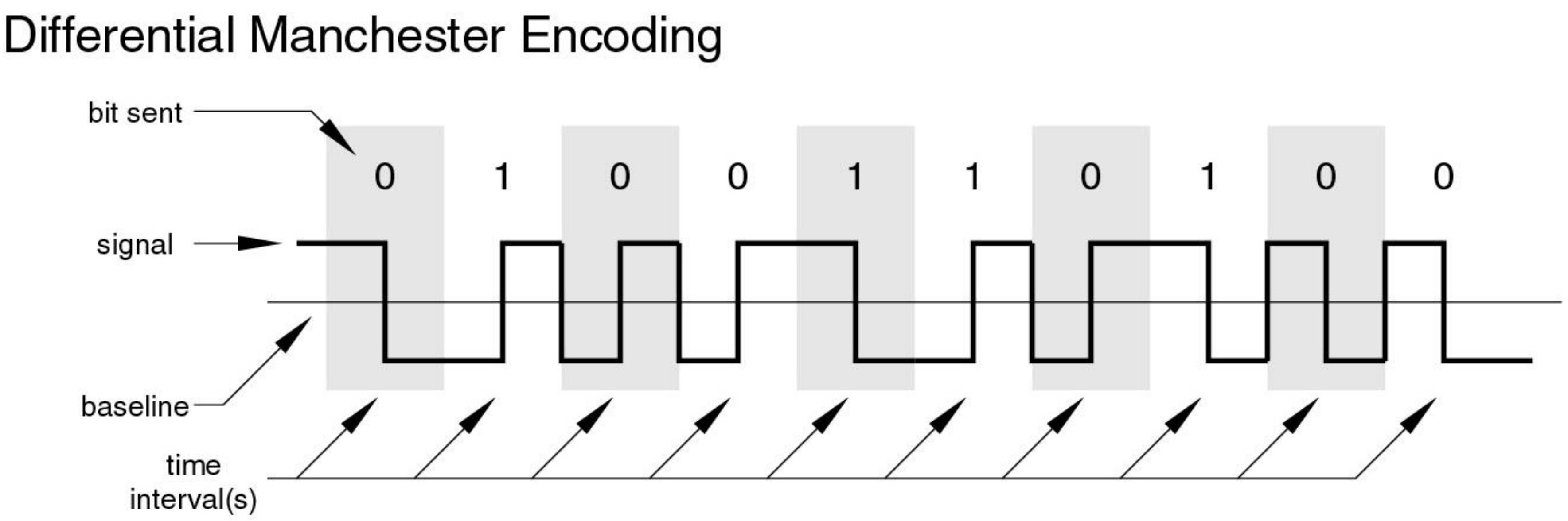
Manchester Encoding



Differential Manchester Encoding

- Differential Manchester Encoding
  - Midbit transition is clocking only
  - Transition at start of bit period representing 0
  - No transition at start of bit period representing 1
    - This is a differential encoding scheme
  - Used by IEEE 802.5

Differential Manchester Encoding

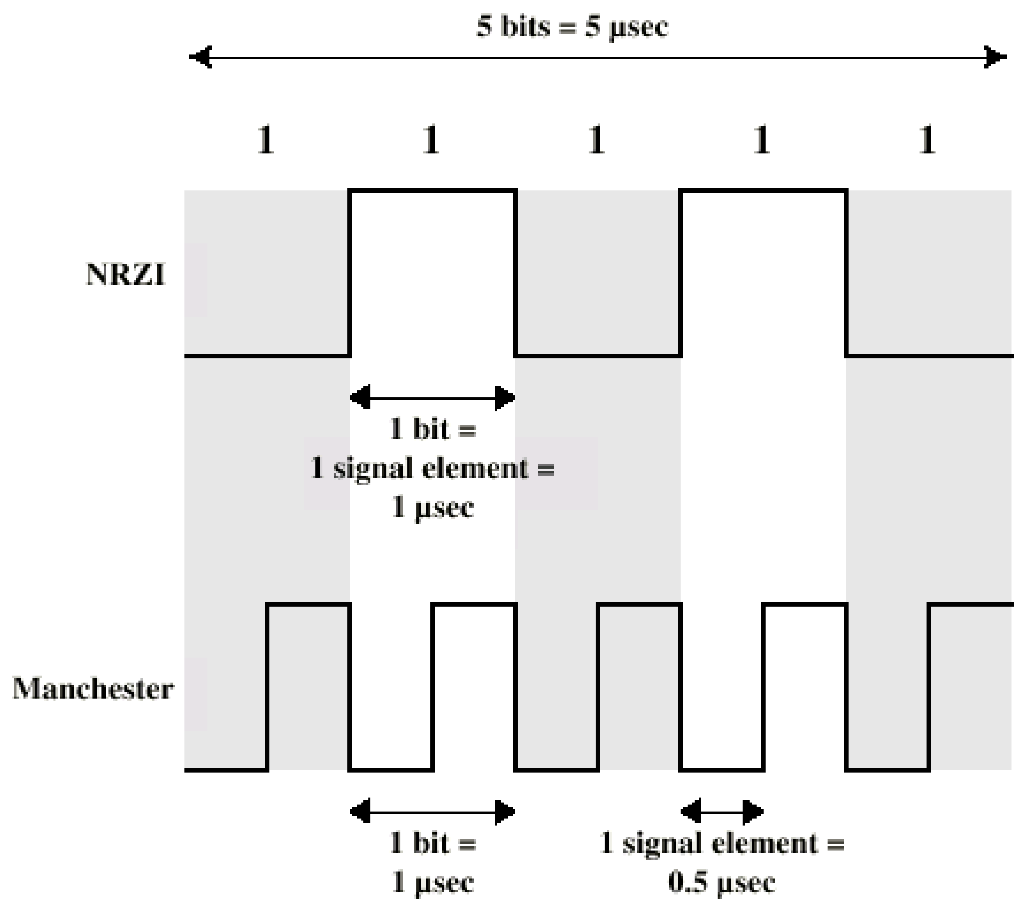


Biphase Pros and Cons

- Con
  - at least one transition per bit time and possibly two
  - maximum modulation rate is twice NRZ
  - requires more bandwidth
- Pros
  - synchronization on mid bit transition (self clocking)
  - has no dc component
  - has error detection (The absence of an expected transition can be used to detect errors)

Baud Rate

- A stream of binary ones at 1 Mbps
- Bit rate = 1Mbps
- Baud rate = ?

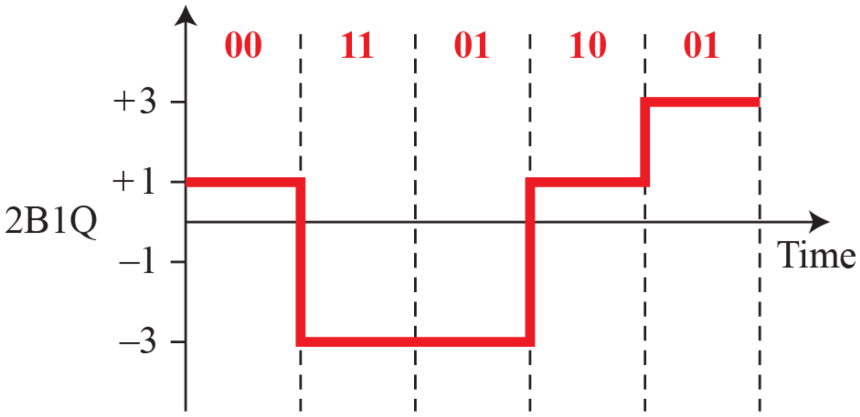


Multilevel: 2B1Q

- Two binary, one quaternary (2B1Q)
- It uses data patterns of size 2 and encodes the 2-bit patterns as one signal element belonging to a four-level signal.
- 2B1Q is used in DSL (Digital Subscriber Line).

	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

Multilevel: 8B6T

- Eight binary, six ternary (8B6T).
- To encode 1 pattern of 8-bit as a pattern of six signal elements, where the signal has three levels (ternary).
- $2^8 = 256$ and $3^6 = 729$, there are 729-256=473 redundant signal elements that provide synchronization and error detection.

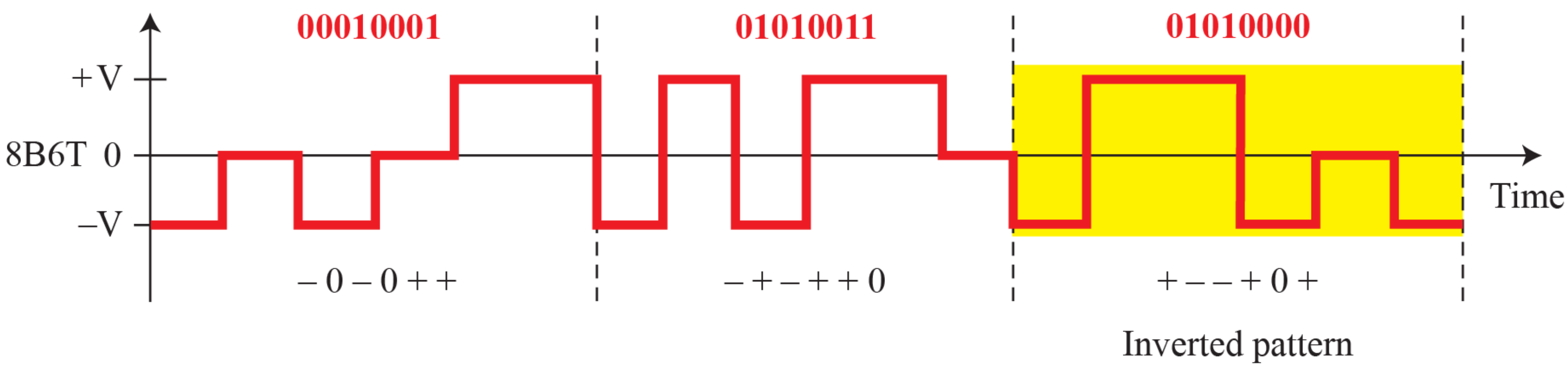


Table F.1 *8B/6T code*

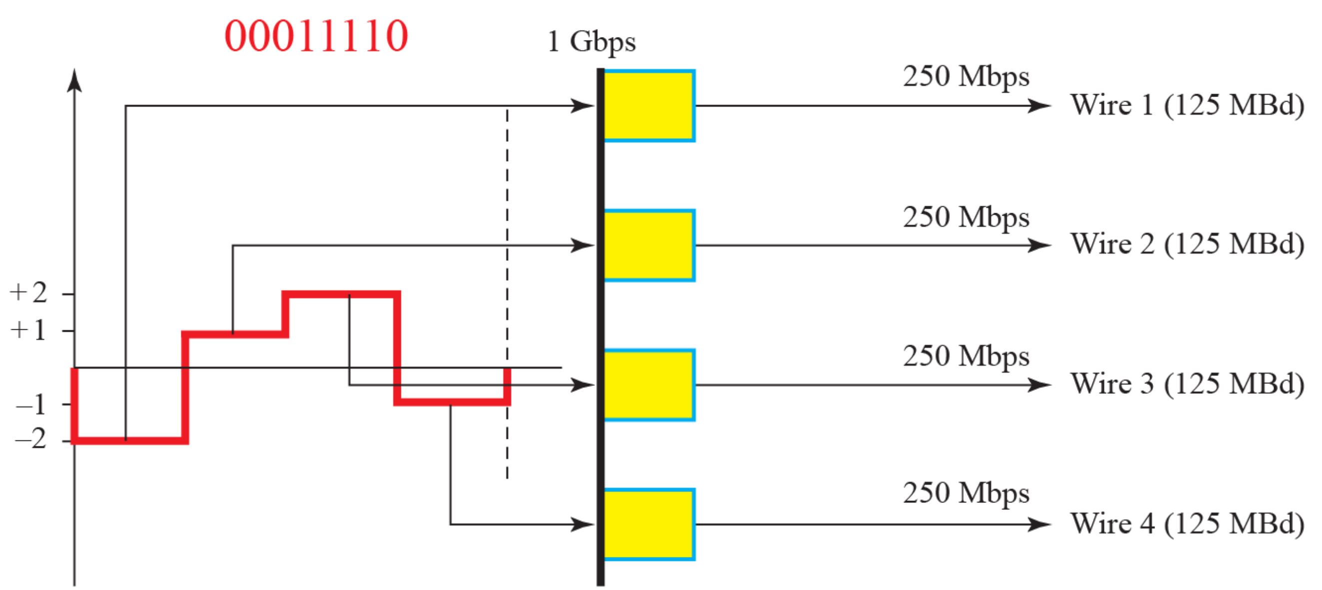
Data	Code	Data	Code	Data	Code	Data	Code
00	−+00−+	20	−++−00	40	−00+0+	60	0++0−0
01	0−+−+0	21	+00+−−	41	0−00++	61	+0+−00
02	0−+0−+	22	−+0−++	42	0−0+0+	62	+0+0−0
03	0−++0−	23	+−0−++	43	0−0++0	63	+0+00−
04	−+0+0−	24	+−0+00	44	−00++0	64	0++00−
05	+0−−+0	25	−+0+00	45	00−0++	65	++0−00
06	+0−0−+	26	+00−00	46	00−+0+	66	++00−0
07	+0−+0−	27	−+++−−	47	00−++0	67	++000−
08	−+00+−	28	0++−0−	48	00+000	68	0++−+−
09	0−++−0	29	+0+0−−	49	++−000	69	+0++−−
0A	0−+0+−	2A	+0+−0−	4A	+−+000	6A	+0+−+−
0B	0−+−0+	2B	+0+−−0	4B	−++000	6B	+0+−−+
0C	−+0−0+	2C	0++−−0	4C	0+−000	6C	0++−−+
0D	+0−+−0	2D	++00−−	4D	+0−000	6D	++0+−−
0E	+0−0+−	2E	++0−0−	4E	0−+000	6E	++0−+−
0F	+0−−0+	2F	++0−−−0	4F	−0+000	6F	++0−−+
10	0−−+0+	30	+−00−+	50	+−−+0+	70	000++−
11	−0−0++	31	0+−−+0	51	−+−0++	71	000+−+
12	−0−+0+	32	0+−0−+	52	−+−+0+	72	000−++
13	−0−++0	33	0+−+0−	53	−+−++0	73	000+00
14	0−−++0	34	+−0+0−	54	+−−++0	74	000+0−
15	−−00++	35	−0+−+0	55	−−+0++	75	000+−0
16	−−0+0+	36	−0+0−+	56	−−++0+	76	000−0+
17	−−0++0	37	−0++0−	57	−−++0	77	000−+0
18	−+0−+0	38	+−00+−	58	−+−0++	78	+++−−0

Table F.1 *8B/6T code (continued)*

Data	Code	Data	Code	Data	Code	Data	Code
19	+−0−+0	39	0+−+−0	59	−0−+++	79	+++−0−
1A	−++−+0	3A	0+−0+−	5A	0−−+++	7A	+++0−−
1B	+00−+0	3B	0+−−0+	5B	0−−0++	7B	0++0−−
1C	+00+−0	3C	+−0−0+	5C	+−−0++	7C	−00−++
1D	−+++−0	3D	−0++−0	5D	−000++	7D	−00+00
1E	+−0+−0	3E	−0+0+−	5E	0+++−−	7E	+−−−++
1F	−+0+−0	3F	−0+−0+	5F	0++−00	7F	+−−+00
80	−00+−+	A0	−++0−0	C0	−+0+−+	E0	−++0−+
81	0−0−++	A1	+−+−00	C1	0−+−++	E1	+−−++0
82	0−0+−+	A2	+−+0−0	C2	0−++−+	E2	+−+0−+
83	0−0++−	A3	+−+00−	C3	0−+++−	E3	+−++0−
84	−00++−	A4	−++00−	C4	−+0++−	E4	−+++0−
85	00−−++	A5	++−−00	C5	+0−−++	E5	++−−+0
86	00−+−+	A6	++−0−0	C6	+0−+−+	E6	++−0−+
87	00−++−	A7	++−00−	C7	+0−++−	E7	++−+0−
88	−000+0	A8	−++−+−	C8	−+00+0	E8	−++0+−
89	0−0+00	A9	+−++−−	C9	0−++00	E9	+−++−0
8A	0−00+0	AA	+−+−+−	CA	0−+0+0	EA	+−+0+−
8B	0−000+	AB	+−+−−+	CB	0−+00+	EB	+−+−0+
8C	−0000+	AC	−++−−+	CC	−+000+	EC	−++−0+
8D	00−+00	AD	++−+−−	CD	+0−+00	ED	++−+−0
8E	00−0+0	AE	++−−+−	CE	+0−0+0	EE	++−0+−
8F	00−00+	AF	++−−−+	CF	+0−00+	EF	++−−0+
90	+−−+−+	B0	+000−0	D0	+−0+−+	F0	+000−+
91	−+−−++	B1	0+0−00	D1	0+−−++	F1	0+0−+0
92	−+−+−+	B2	0+00−0	D2	0+−+−+	F2	0+00−+
93	−+−++−	B3	0+000−	D3	0+−++−	F3	0+0+0−
94	+−−++−	B4	−0000−	D4	+−0++−	F4	+00+0−
95	−−+−++	B5	00+−00	D5	−0+−++	F5	00+−+0
96	−−++−+	B6	00+0−0	D6	−0++−+	F6	00+0−+
97	−−+++−	B7	00+00−	D7	−0+++−	F7	00++0−
98	+−−0+0	B8	+00−+−	D8	+−00+0	F8	+000+−
99	−+−+00	B9	0+0+−−	D9	0+−+00	F9	0+0+−0
9A	−+−0+0	BA	0+0−+−	DA	0+−0+0	FA	0+00+−
9B	−+−00+	BB	0+0−−+	DB	0+−00+	FB	0+0−0+
9C	+−−00+	BC	+00−−+	DC	+−000+	FC	+00−0+
9D	−−++00	BD	00++−−	DD	−0++00	FD	00++−0
9E	−−+0+0	BE	00+−+−	DE	−0+0+0	FE	00+0+−
9F	−−+00+	BF	00+−−+	DF	−0+00+	FF	00+−0+

Multilevel: 4D-PAM5

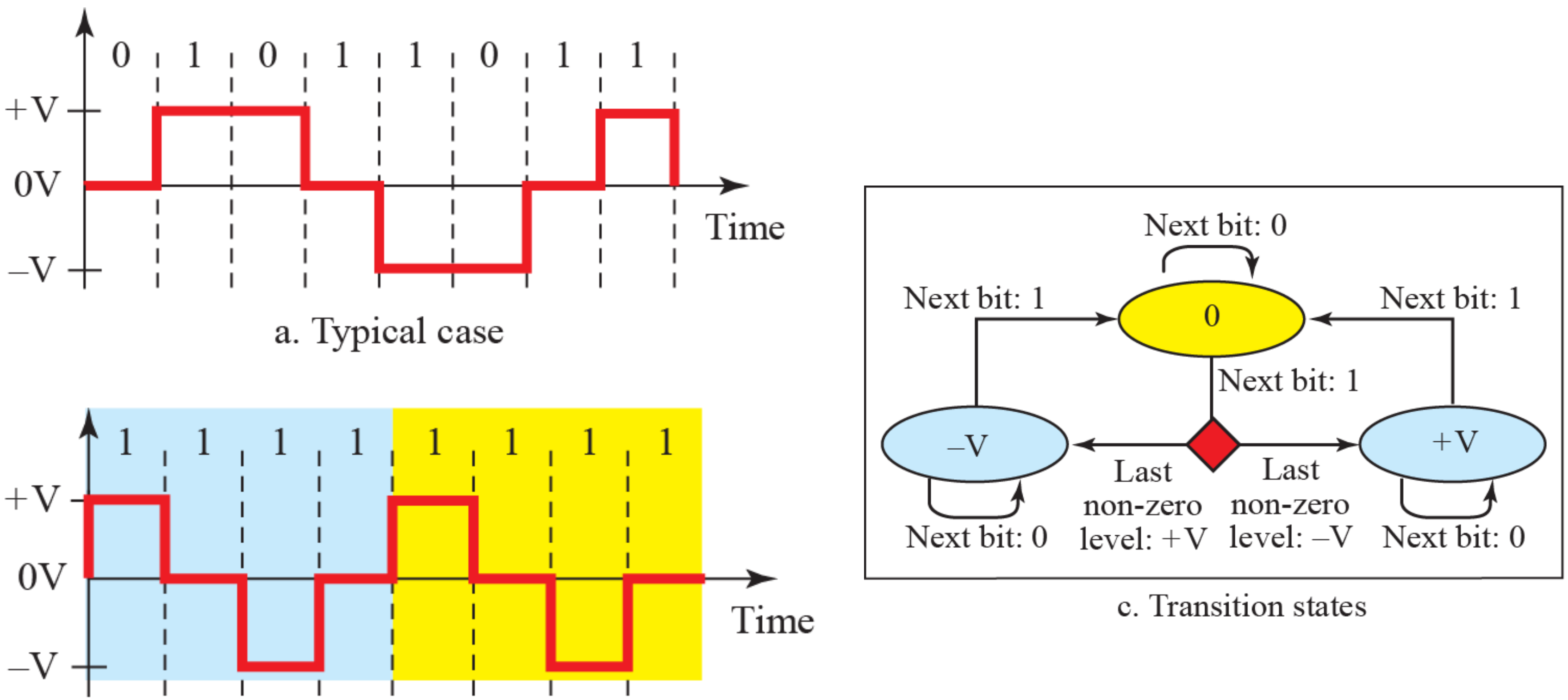
- Four-dimensional five-level pulse amplitude modulation.
- The 4D means that data is sent over four wires at the same time.
- It uses 5 voltage levels: -2, -1, 0, +1, +2. Level 0 is used only for forward error detection.
- Used in Gigabit LANs.



Multitransition: MLT-3

- Multiline transmission, three-level (MLT-3).
- It uses three 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 the last non-zero level.

Multitransition: MLT-3



a. Typical case

b. Worst case

c. Transition states

Scrambling

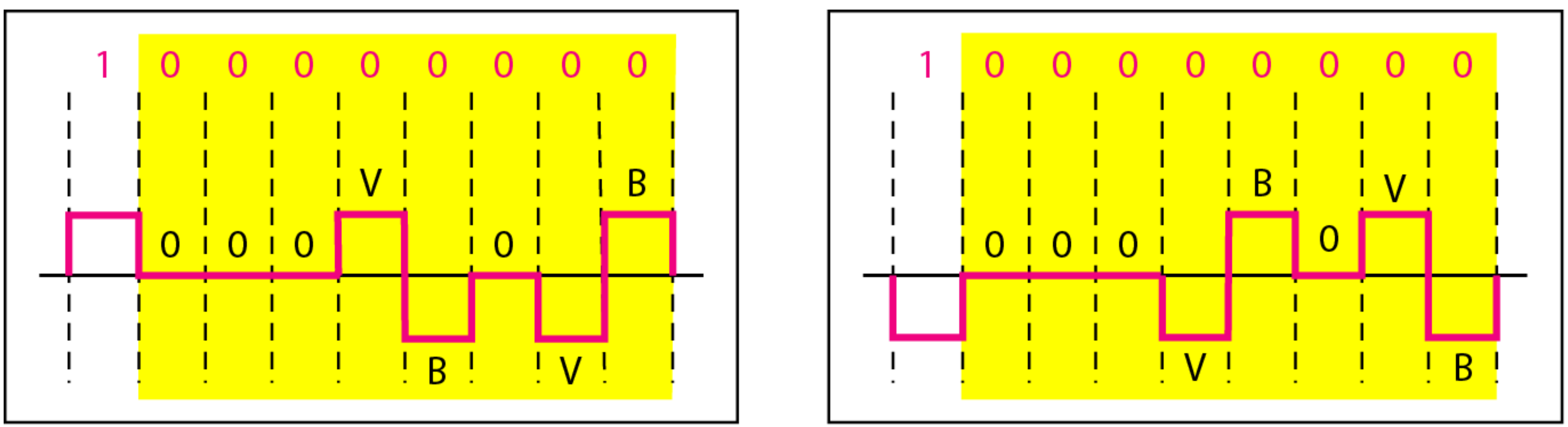
- Scrambling
  - Use scrambling to replace sequences that would produce constant voltage
  - These filling sequences must
    - Produce enough transitions to sync
    - Be recognized by receiver & replaced with original
    - Be same length as original

Scrambling

- Design goals
  - Have no dc component
  - Have no long sequences of zero level line signal
  - Have no reduction in data rate
  - Give error detection capability

Bipolar with 8-zeros Substitution (B8ZS)

- B8ZS substitutes eight consecutive zeros with 000VB0VB
  - If an octet of all zeros occurs and the last voltage pulse preceding this octet was positive, then the eight zeros of the octets are encoded as 000+–0–+
  - If an octet of all zeros occurs and the last voltage pulse preceding this octet was negative, then the eight zeros of the octets are encoded as 000-+0+–



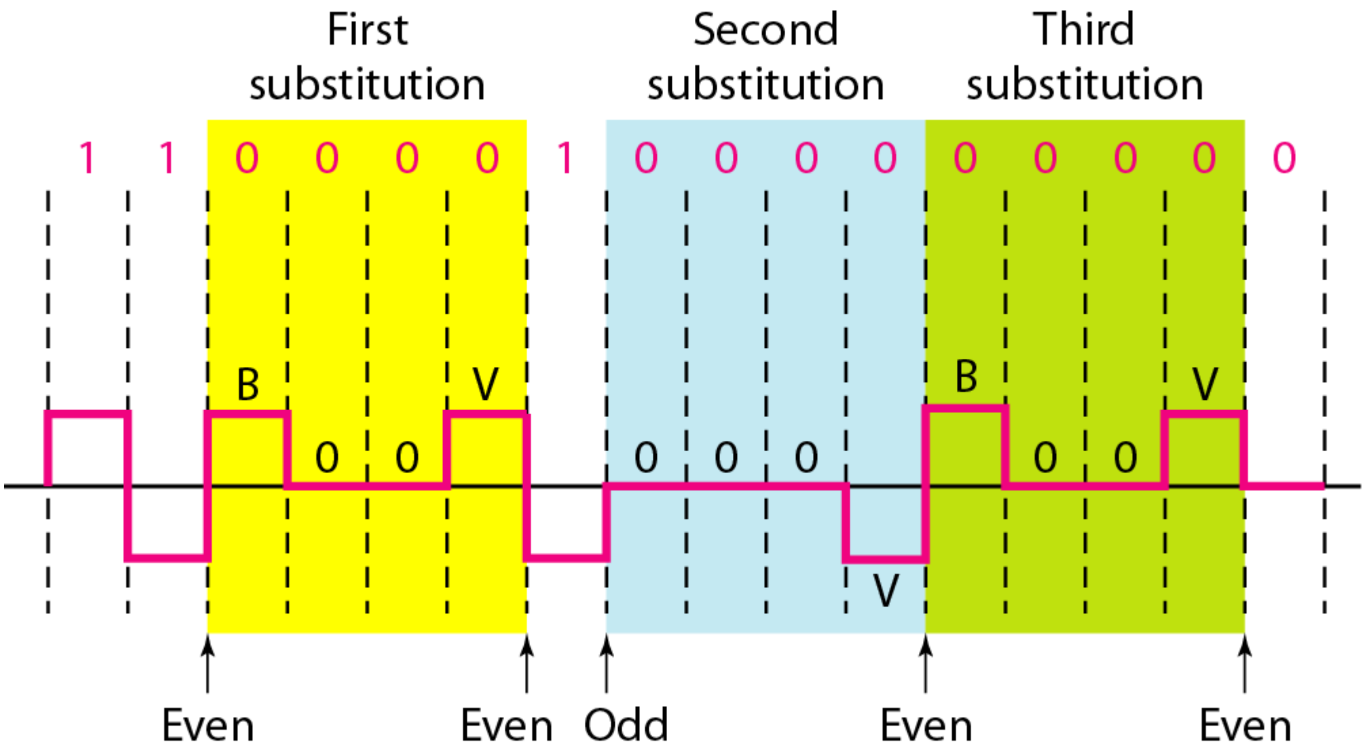
a. Previous level is positive.

b. Previous level is negative.

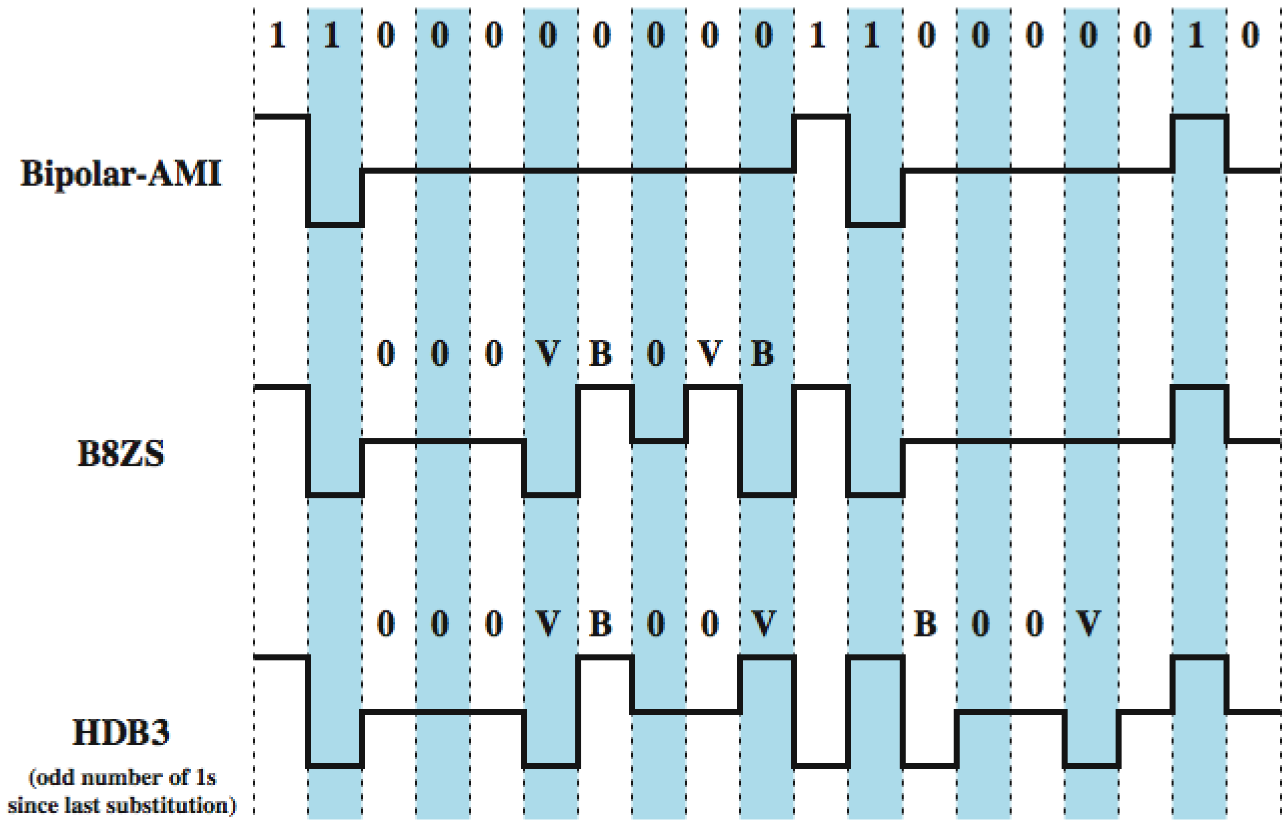
High-density bipolar-3 zeros (HDB3)

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

High-density bipolar-3 zeros (HDB3)



B8ZS and HDB3



B = Valid bipolar signal
V = Bipolar violation

Reading

- B. A. Forouzan, "Data Communications and Networking," 5th Edition, McGraw-Hill 2013 (Chapters 3, 4 and 7)
- William Stallings, "Data and Computer Communications," 10th Edition, Pearson 2015 (Chapters 3, 4 and 5)