TRANSMISSION PRINCIPLES

September 17, 2020

Outline

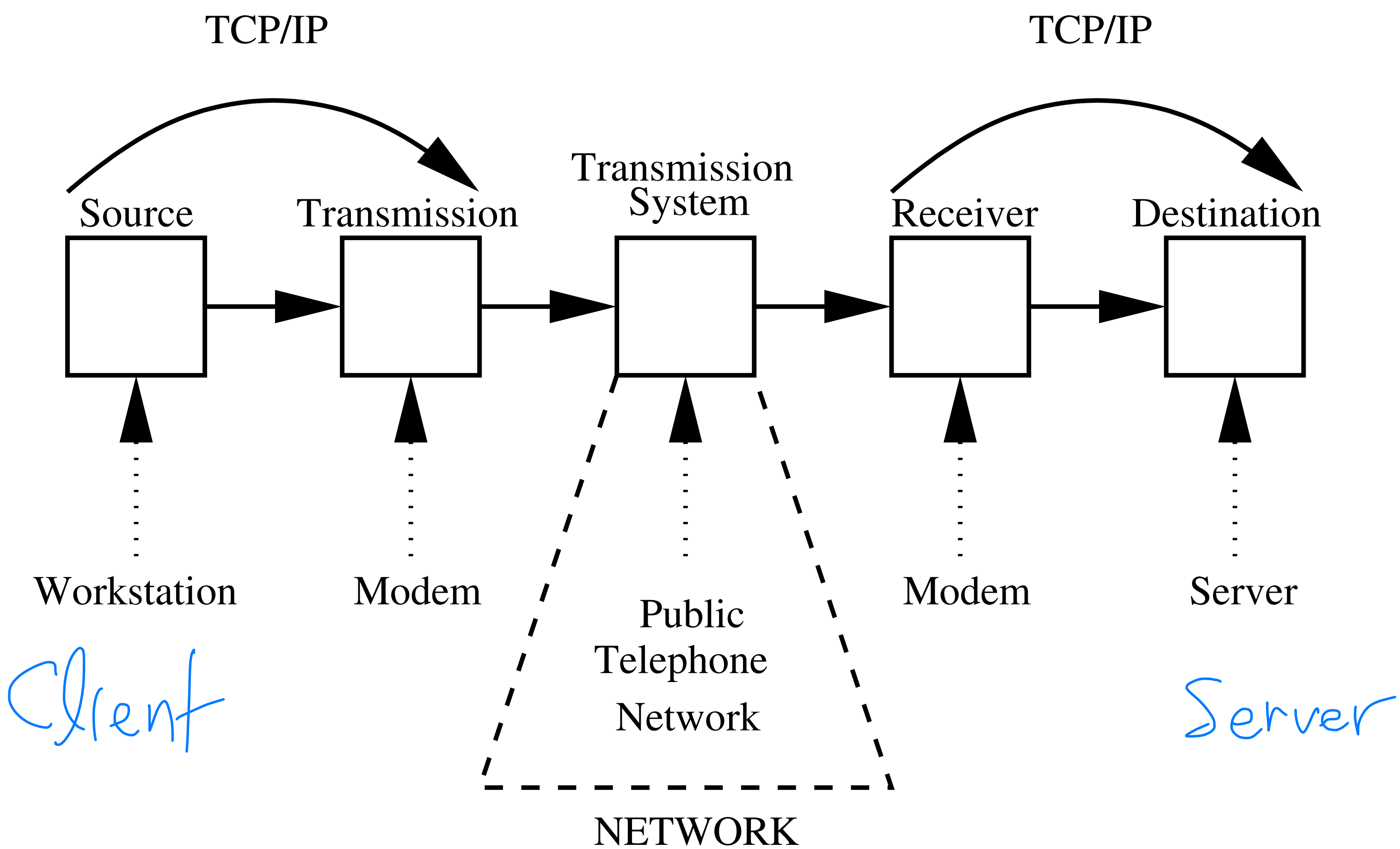
- Transmission
- Conversions
  - Digital-to-Digital
  - Analog-to-Digital
  - Digital-to-Analog
  - Analog-to-Analog
- Media
- Appendix (Not Required)

Computer-to-Computer

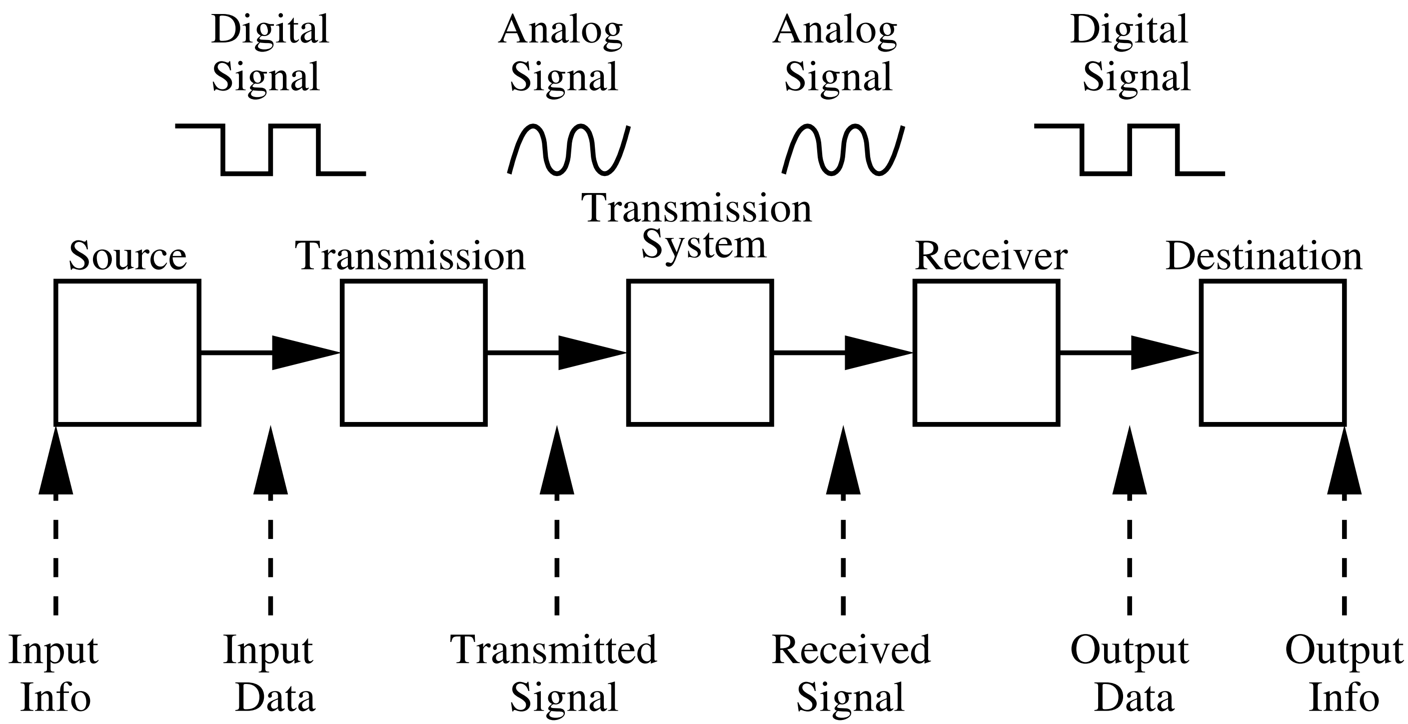
Digital-to-Digital

.

The Network Transmission Process



Transitions: Analog $\leftrightarrow$ Digital



The network infrastructure
not only physical
but also protocols
enables quality of service QoS

Encoding and Modulation

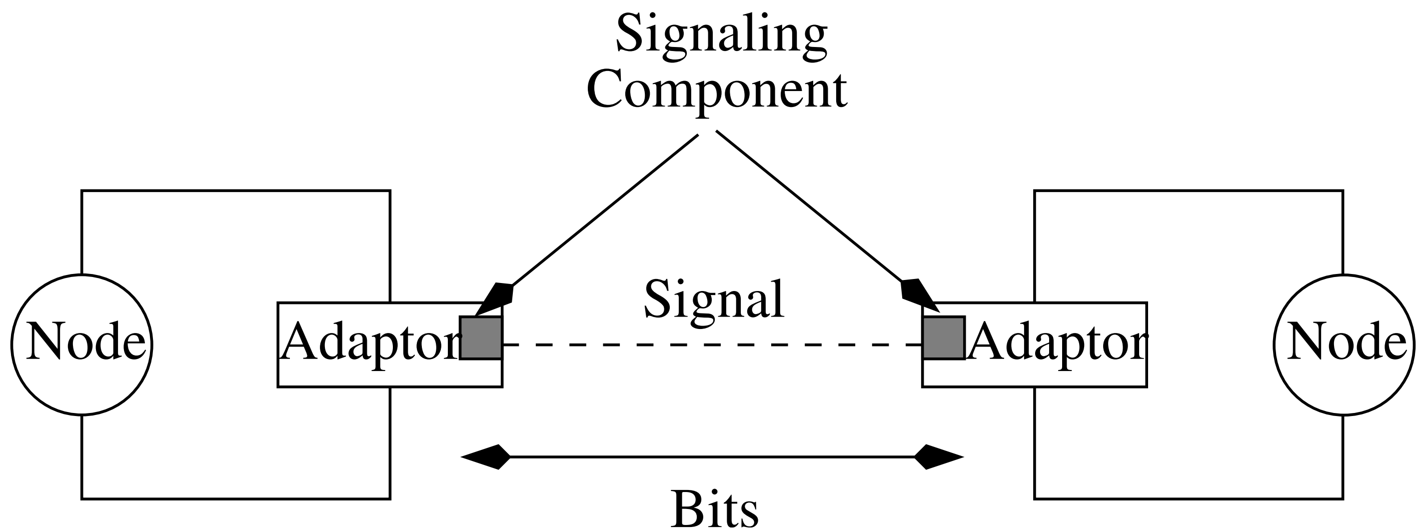
- **Digital-to-Digital Conversion:** Computer data are stored as 0s and 1s. To be carried from one place to the other (inside or outside the computer) they must be transformed from one representation to another (e.g. Binary Data to Gray Data).
- **Analog-to-Digital Conversion:** An analog signal (like voice) must converted to digital (to decrease noise effects).
- **Digital-to-Analog Conversion:** A digital signal must be often converted to analog to carry it over a medium.
- **Analog-to-Analog Conversion:** This is required for multiplexing purposes, for carrying a signal over long distances, etc.

NB: Each of these "Conversions" has different signal representations, which we look at in the sequel.

Digital $\rightarrow$ Digital

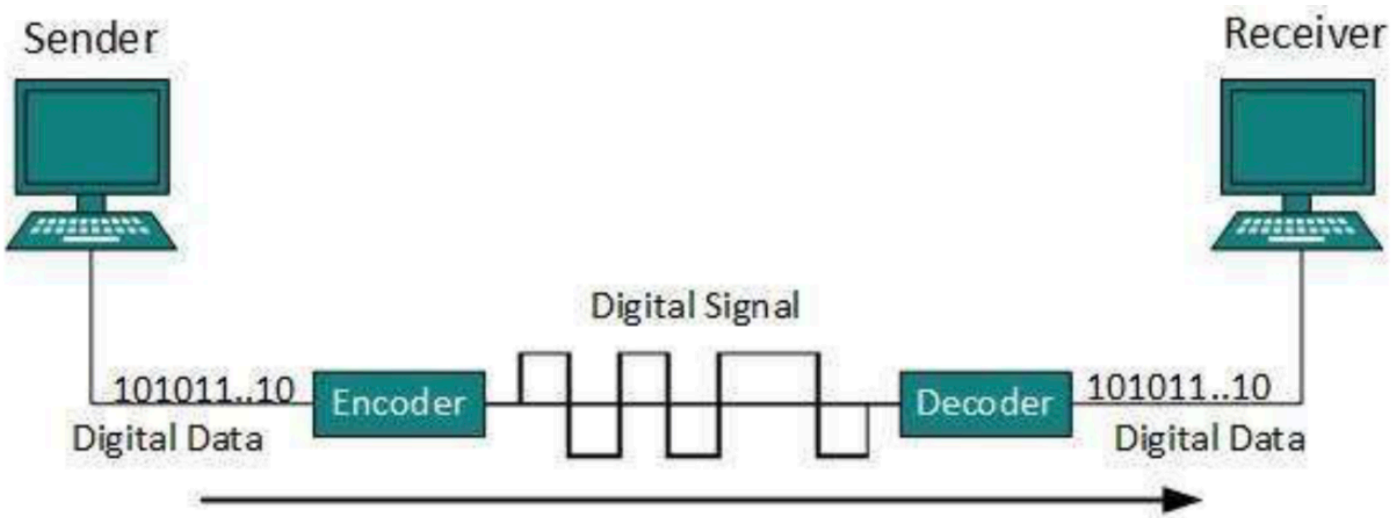
Sender and Receiver

- A signaling component is required to translate digital sequences betweem sender and receiver within a computer.



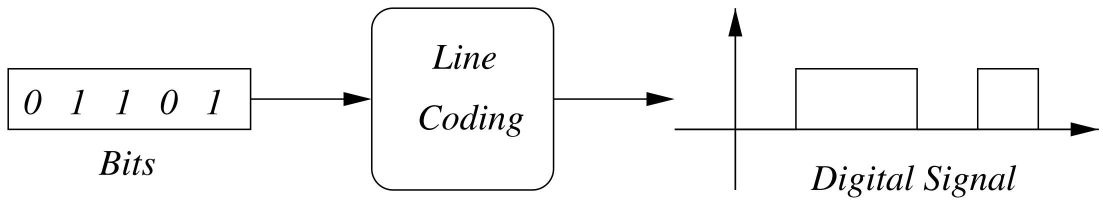
Line Coding

- Digital-to-digital encoding is the representation of digital information by a digital signal. When binary 1s and 0s generated by the computer are translated into a sequence of voltage pulses that can be propagated over a wire, this process is known as digital-to-digital encoding
- Line coding is the process of converting binary data (i.e., a sequence of bits) to a digital signal.

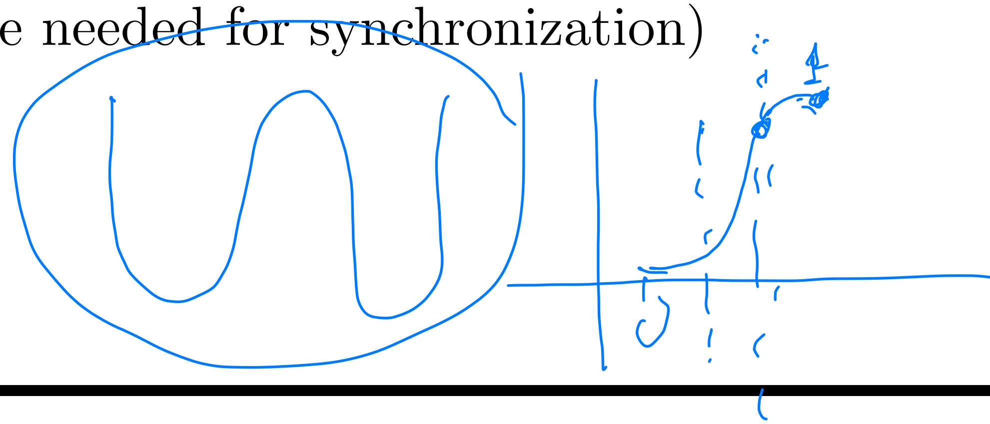


Line Coding

- Signals transmitted at various “levels” and “pulse rates” depending on the quality of the line to help differentiate.

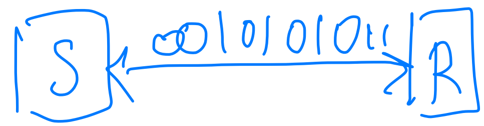


- Important issues taken into account include:
  - What should the signal level be? (Transmission Amplitude)
  - What should the pulse rate be? (How often you transmit)
  - How about (self-)synchronization between sender and receiver? (Change needed for synchronization)



On the Need for Encodings

- **Baseline wander:**
  - The receiver takes the average of what it has seen so far to distinguish between high and low!
  - Thus a long sequence of consecutive 1s (or 0s) changes this average and is hard to distinguish 0 and 1



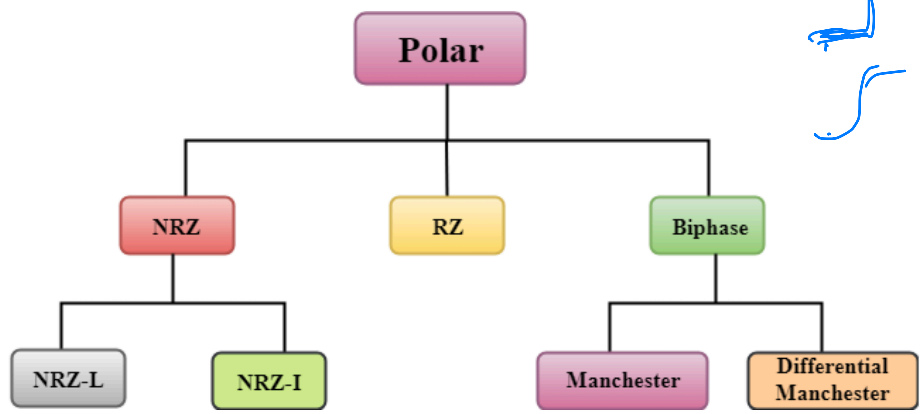
- **Clock Recovery:**
  - Coding and decoding processes are driven by (separate) clocks which must be synchronized.
  - Frequent transitions from 0 to 1 and vice versa are necessary in order to enable sender and receiver to synchronize.
- This indicates a "need for change" while transmitting!

Parameters to Consider

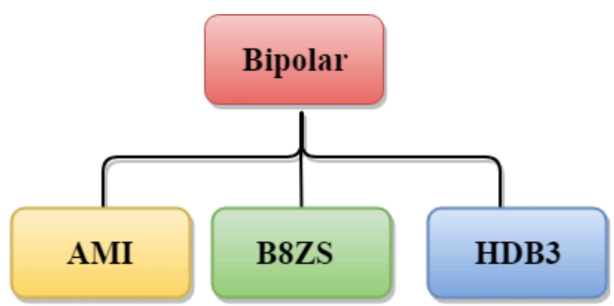
- Signals represented by voltages.
- What voltage is “high” and what voltage is “low”?
- How do you represent “high $\rightarrow$ low” and “low” $\rightarrow$ “high”?
- How often do you make transitions?

Polar and Bipolar Encodings

- Polar encodings use two voltage levels: one is positive, and another is negative.



- Bipolar encodings use three voltage levels: positive, negative, and zero



Two Additional Solutions

- 4B/5B
- Bit-Stuffing

4B/5B

- For every 4 bits of data a 5th bit is inserted (and transmitted) so that the resulting 5 bit sequence has no more than one leading 0 and no more than two trailing 0s.
- Thus, two such consecutive 5 bit sequences have no sequence of three consecutive 0s. The result is then transmitted with NRZ-I.
- **Example:** Arrange bits in groups of four and use the table

$$\begin{array}{ccc} 0011 & 1010 & 1111 \\ \downarrow & \downarrow & \downarrow \\ 10101 & 10110 & 11101 \end{array}$$

Now you can apply a polar or bipolar encoding technique (e.e., NRZ-I) to the result.

Table: 4B/5B

4-Bit Data	5-Bit Code
0000	11110
0001	01001
0010	10100
0011	10101
0100	01010
0101	01011
0110	01110
0111	01111

4-Bit Data	5-Bit Code
1000	10010
1001	10011
1010	10110
1011	10111
1100	11010
1101	11011
1110	11100
1111	11101

Bit-Stuffing

- **Bit Stuffing**
  1. Fix a value of k (usually $k = 6$).
  2. Scan string left-to-right.
  3. Insert 1 (respectively, 0) after an occurrence of k consecutive 0s (respectively, 1s).
- **Example:** For $k = 4$, in the string

$$001110101111$$

  we need only to insert a bit 0 at the end.
- **Mathematical Question:** For n random bits, what is the expected number of stuffed bits?

Bit stuffing $k=8$

100110000000010110011111111

1

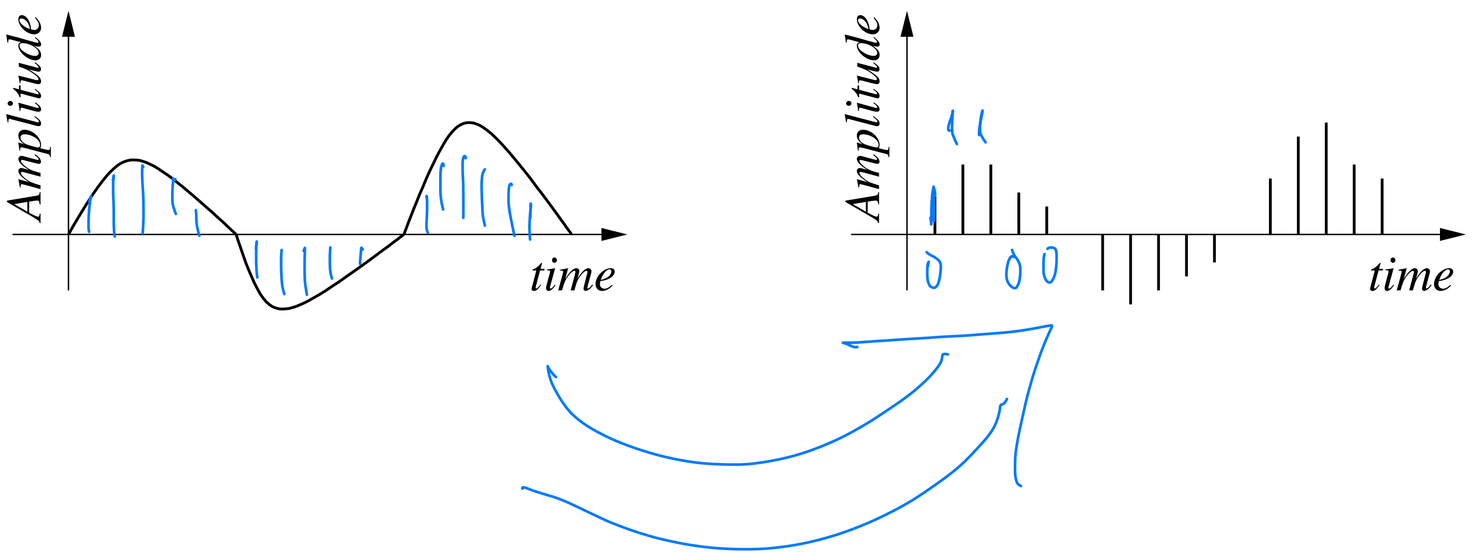
n bits

$$n + n \cdot 2^{-k}$$

Analog → Digital

Analog-to-Digital: From Waveforms to Bits

- This requires reduction of an "infinite number" of values in an analog message to a digital stream with min loss of information.
- Analog signal converted to digital by sampling.
- In **Pulse Amplitude Modulation (PAM)** you sample the amplitude.



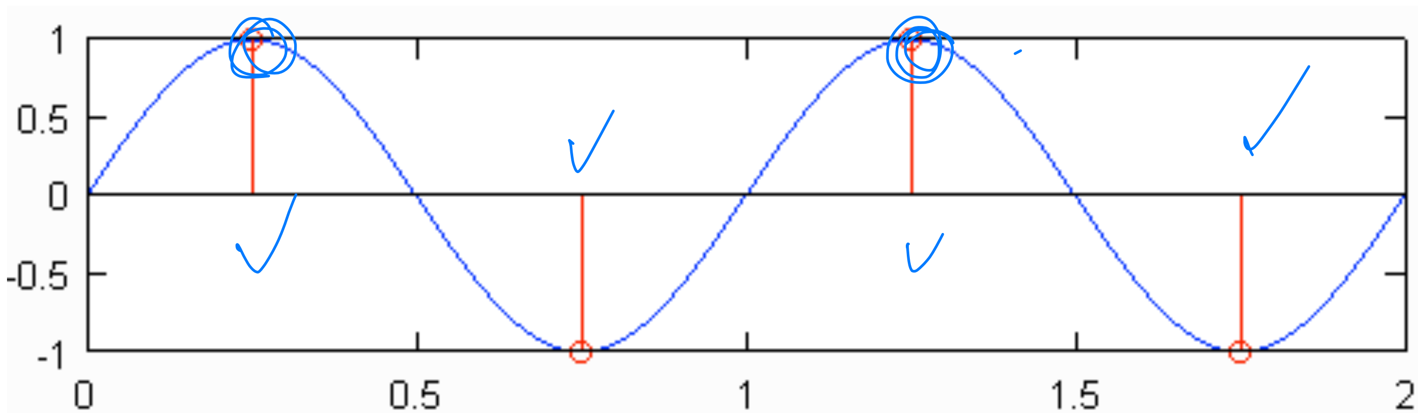
Sampling Rate

- **Sampling rate** plays an important role in the quality of the output.
- The more frequent the samples the more accurate the signal.
- **Main Question:**

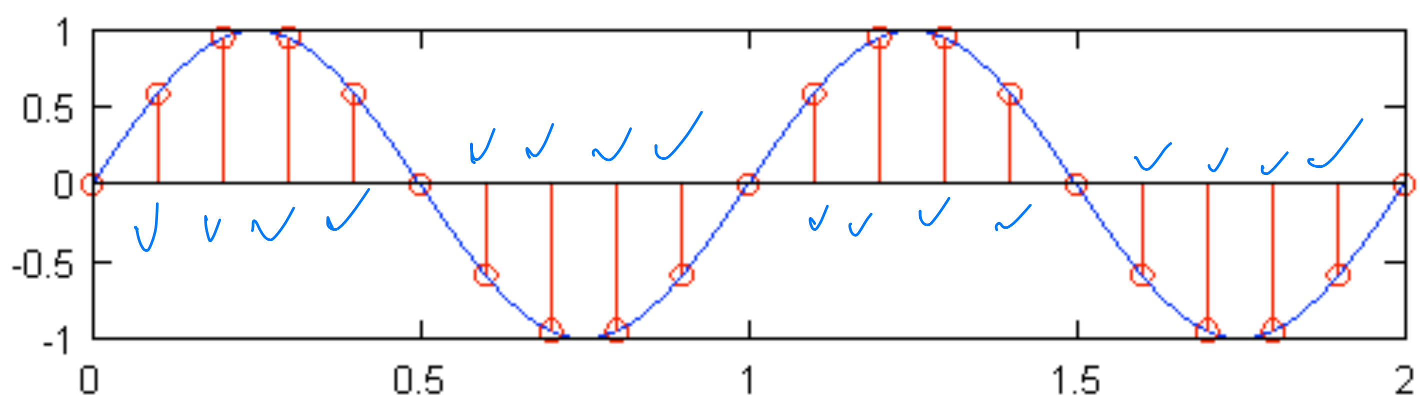
  What is the tradeoff between "sampling frequency" and "output accuracy"?
- Consider a noise-free channel.
- In this setting, the limitation on data rate is the bandwidth of the signal.

Nyquist Limits (1/2)

- Sampling at the limit (2 times the max frequency of the signal)

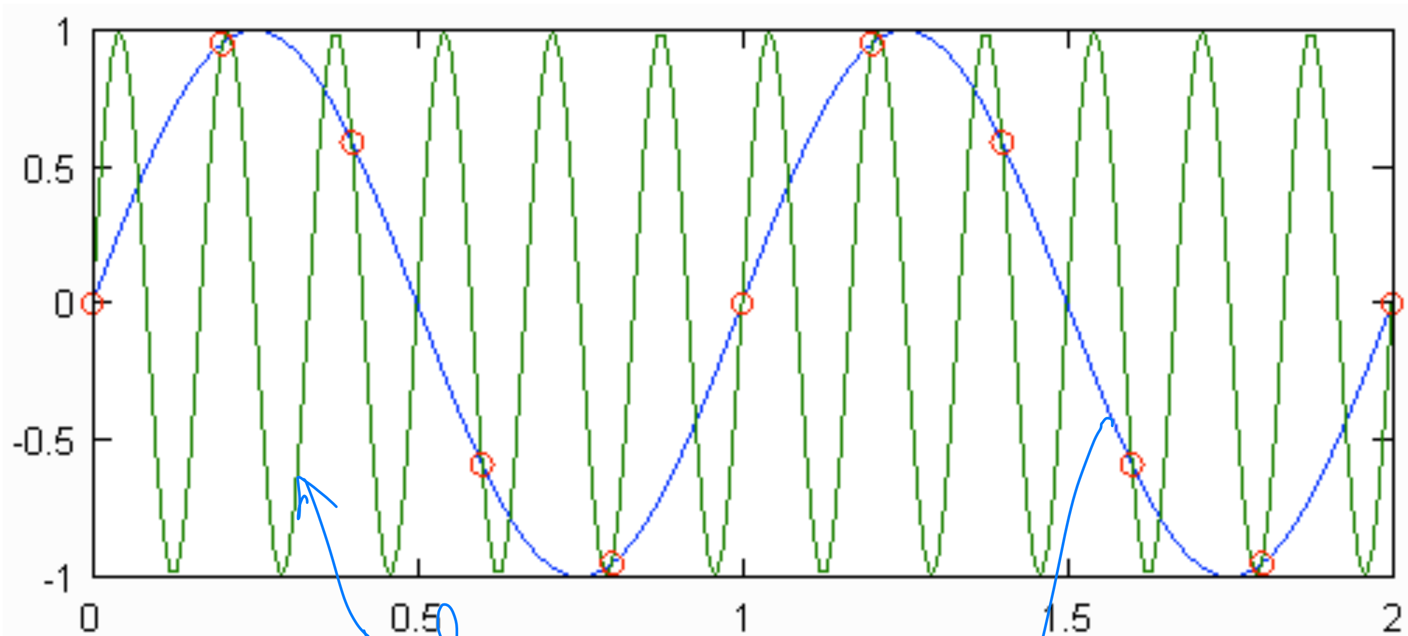


- Sampling above the limit (oversampling)



Nyquist Limits (2/2)

- Sampling below the limit (under sampling)



real

- Sampling is inadequate!

blue sampling

Nyquist Limits (or Nyquist Frequencies)

- **Nyquist Theorem:**
  If the rate of signal transmission is $2B$, then a signal with frequencies no greater than B is sufficient to carry the signal rate.
  - Also conversely: Given bandwidth B, the highest signal rate that can be carried is $2B$.
- This limitation is due to the effect of inter-symbol interference, such as is produced by delay distortion.

Nyquist Limits (or Nyquist Frequencies): Example

- To sample telephone voice with max frequency $4,000\ Hz$ we must sample at the rate $8,000$ per sec.
- If transmitted signals are binary (two voltage levels), then the data rate that can be supported by B Hz is $2B$ bps.
- However, we can also use signals with more than two levels: each signal element can represent more than one bit.

Nyquist Limits: Limitations

- For example,
  - if four possible voltage levels are used as signals, then each signal element can represent two bits.
  - With multilevel signaling, the Nyquist formulation becomes

$$C = 2B \log_2 M,$$

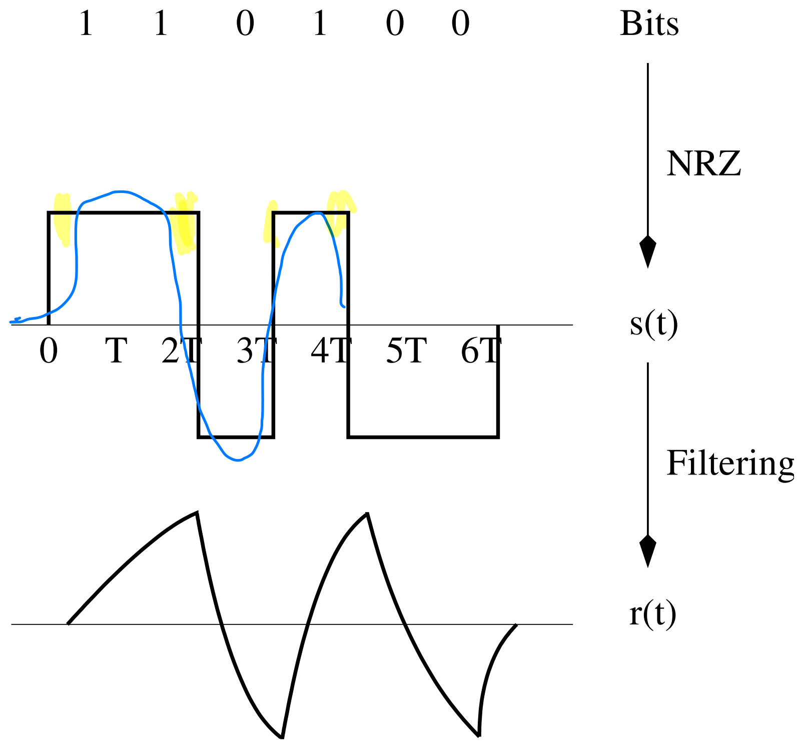
    where M is the number of discrete signal or voltage levels.

- For a given bandwidth, the data rate can be increased by increasing the number of different signal elements.
- This increases burden of the receiver: Instead of distinguishing one of two possible signal elements during each signal time, it must distinguish one of M possible signal elements.
- Noise and other impairments on the transmission line will limit the practical value of M.

Digital $\rightarrow$ Analog

Digital-to-Analog: From Bits to Waveforms

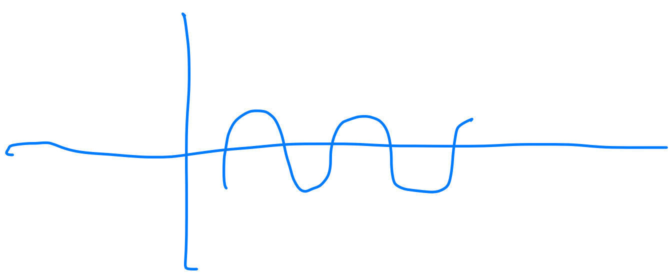
- Converts bits to signals and then filtering takes place.



- Usually: 1 goes to high voltage and 0 to low voltage.

Digital-to-Analog Methods

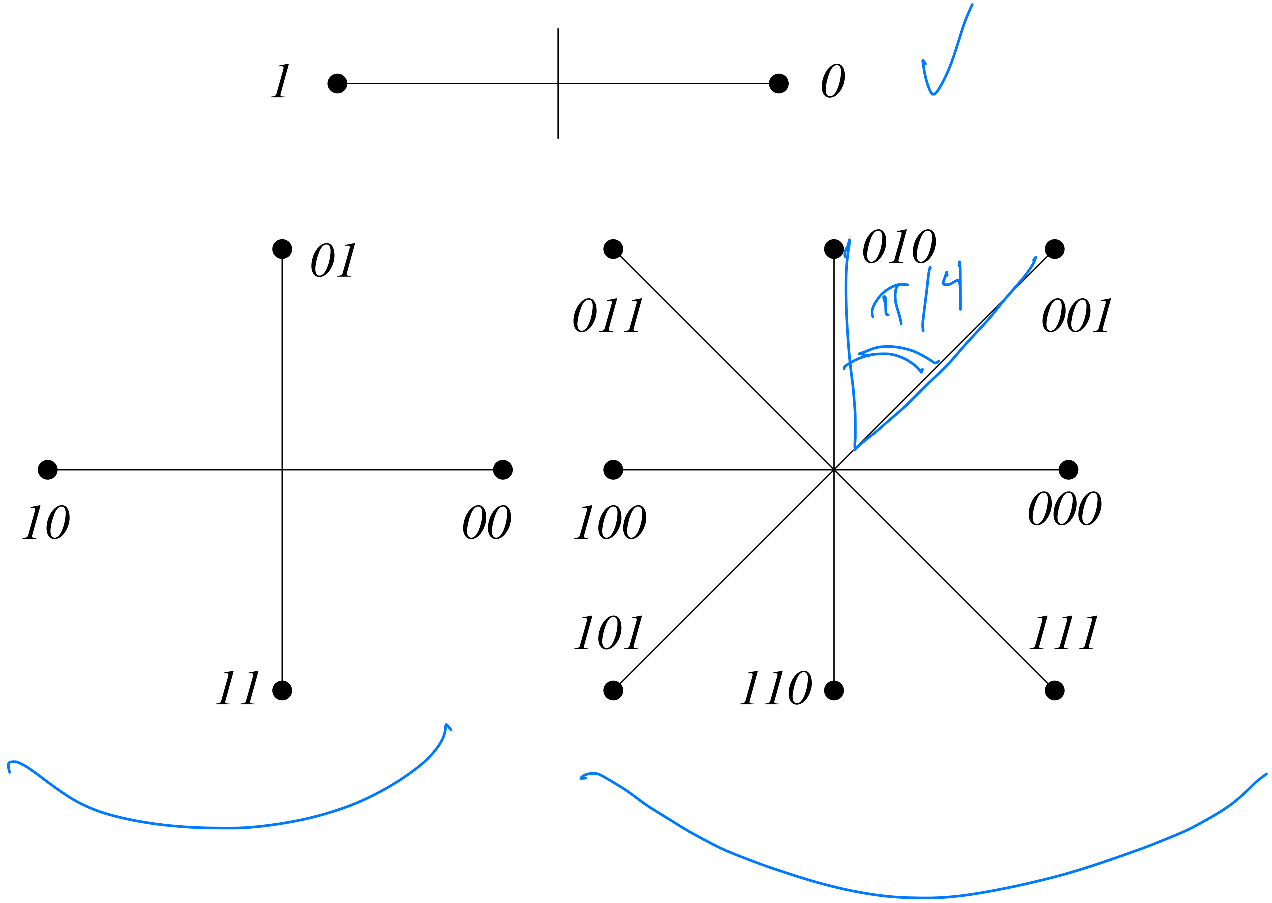
- Waves are represented as combinations of sin, cos functions and as such are characterized by amplitude, frequency, and phase.
  - **Amplitude Shift Keying (ASK):** You vary the strength of the signal to represent binary 0s and 1s.
  - **Frequency Shift Keying (FSK):** You vary the frequency of the signal to represent binary 0s and 1s.
  - **Phase Shift Keying (PSK):** You vary the phase of the signal to represent binary 0s and 1s.
  - **Quadratic Amplitude Modulation (QAM):** Combines ASK and PSK in order to maximize contrast between bits.



Fourier Analysis

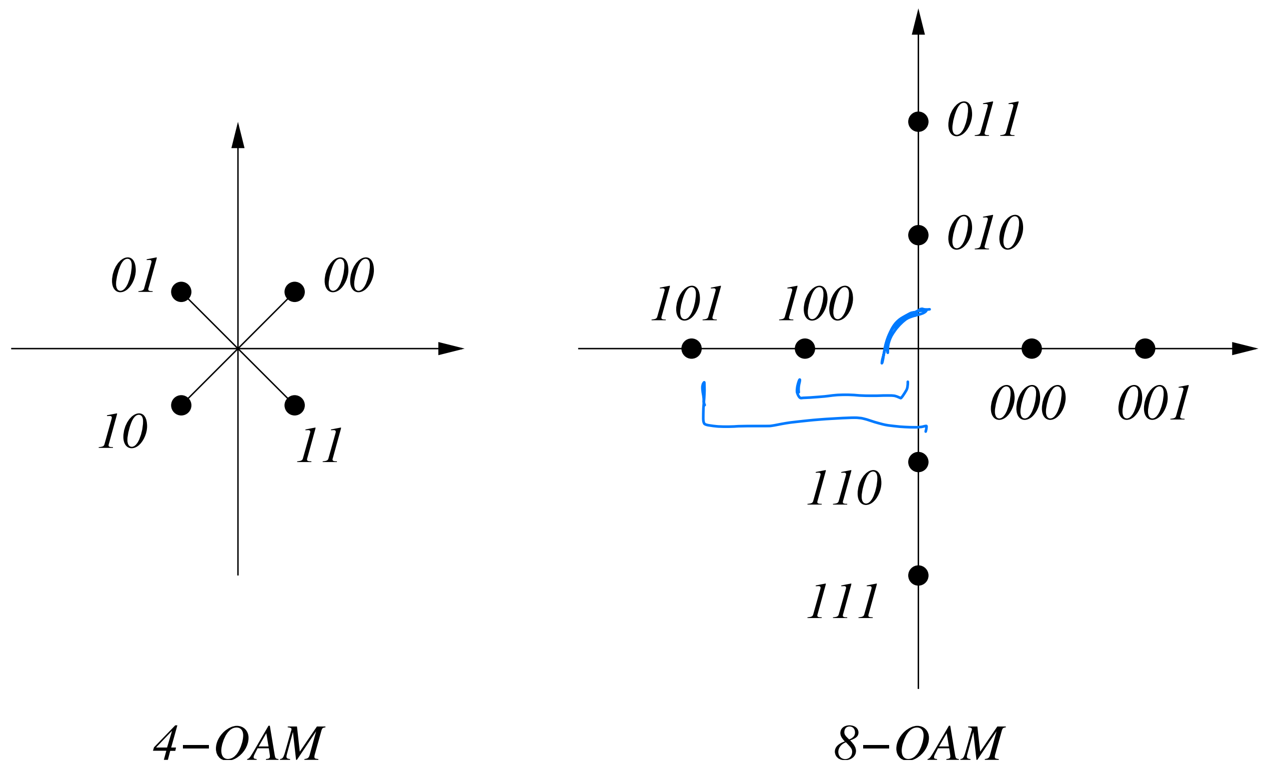
PSK: Examples

- Examples of PSK with (1) $0, 180$, (2) $0, 90, 180, 270$, and (3) $0, 45, 90, 135, 180, 225, 270, 315$ degrees, respectively.



QAM: Examples

- QAM has numerous variants: (1) 4-QAM uses 1 amplitude and 4 phases, (2) 8-QAM uses 2 amplitudes and 4 phases.



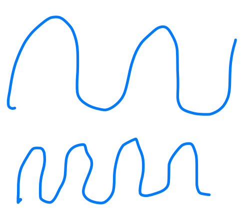
Analog $\rightarrow$ Analog

Analog-to-Analog: From Waveforms to Waveforms

Very useful for transfering from medium to medium, multiplexing, etc.

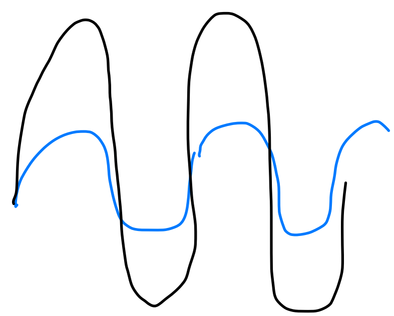
- **Amplitude Modulation (AM):** You modulate the amplitude.
- **Frequency Modulation (FM):** You modulate the frequency.
- **Phase Modulation (PM):** You modulate the phase.

Very Important!



like accordeon

AM



Media

Bit Pipes

There are several kinds of bit pipes.

- **Synchronous:** The data is supplied synchronously.
  - If there is no data it must send dummy data.
- **Intermittent Synchronous:** It is the same as above except that if there is no data available, the modem sends no signal.
- **Asynchronous:** Data flows with no synchronicity whatsover.
  - Bits within a character are sent at a fixed rate, but successive characters may be separated by a variable delay.
- **Total Asynchronous:** No restrictions on delay.

Transmission Lines and Signals

- Transmission lines are:
  - either simplex (only in one direction)
  - or half-duplex (either direction but only one direction at a time) or
  - or (full-)duplex (either direction, both directions simultaneously) or multiplex
- Signals are:
  - either discrete or continuous
  - either periodic or aperiodic
  - represented either as functions either of time or frequency
- sin and cos are two fundamental periodic signals which are also "orthogonal".

Propagation Media

- **Guided** (e.g., Twisted Pair, Coaxial Cable, Optical Fiber) and **Unguided** (Radio, Microwave, Satellite).

Medium	Data Rate
Twisted Pair	1 Mbps
Coaxial Cable	$10 - 1,000$ Mbps
Optical Fiber	$> 1,000$ Mbps
Radio	$< 1,000$ MHz
Microwave	$> 1,000$ MHz
Satellite	$> 1,000$ MHz

modulation

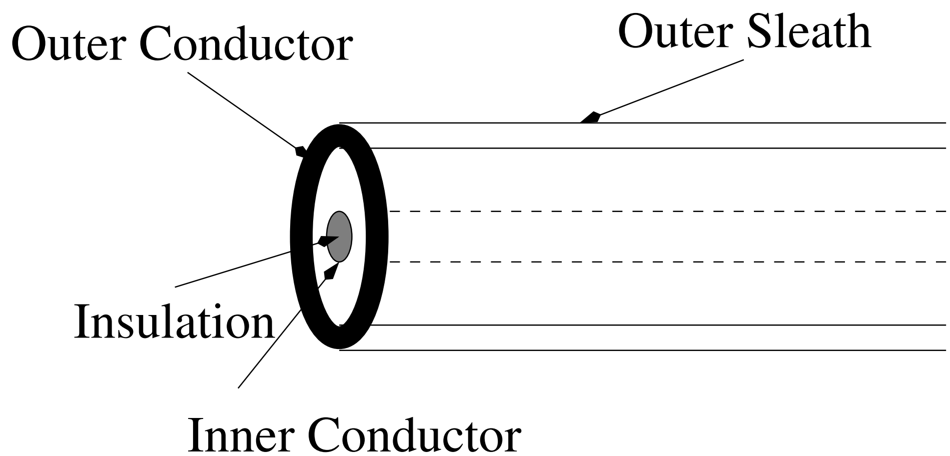
- They are unreliable bit pipes (with various degrees of unreliability) which makes important the study of **error-correction** and **error-detection**

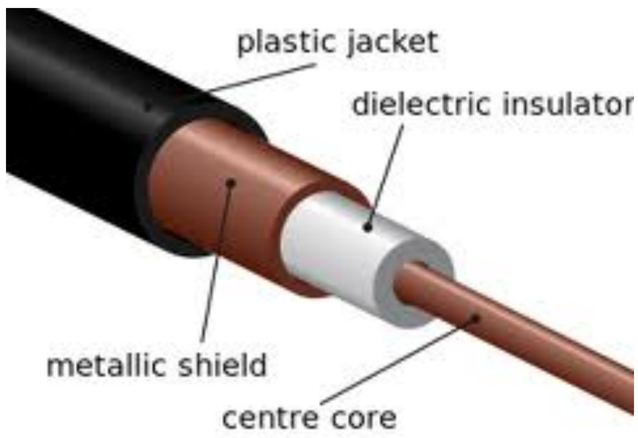
Propagation Media (Twisted Pair)

- Telephony for Subscribers
- Local Stations.
- ADSL (Assymetric Digital Subscriber Line).

Propagation Media (Coaxial Cable)

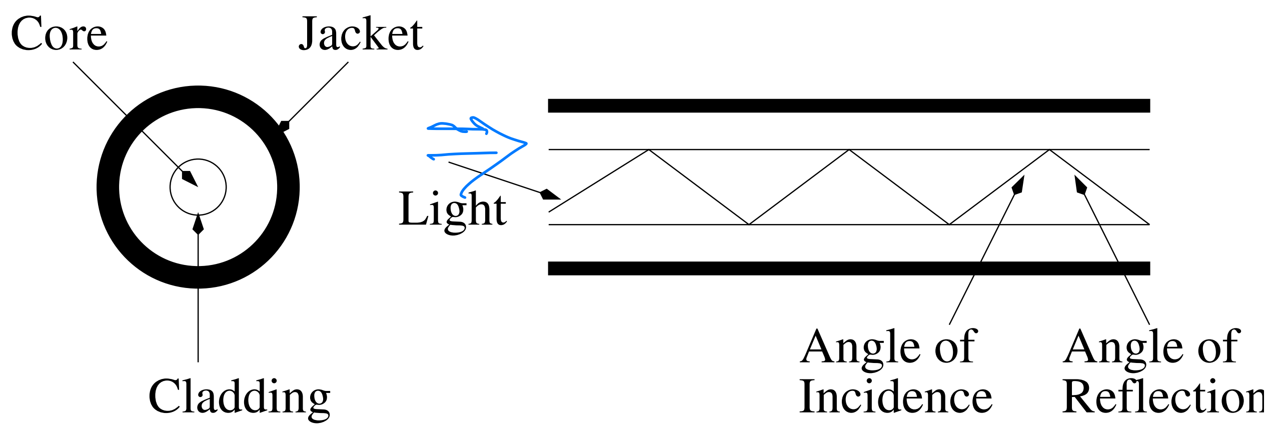
- LANs, Cable TV, High-Speed point-to-point.

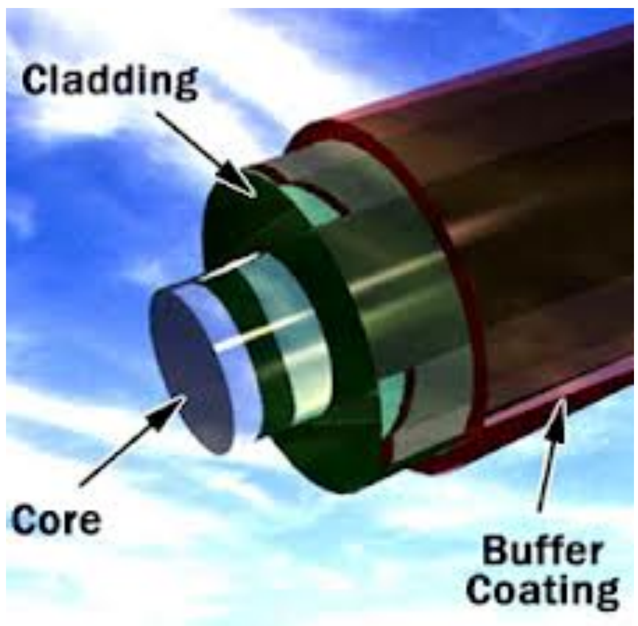




Propagation Media (Optical Fiber)

- Growing in importance for High-end applications.





Need for Repeaters

- For all these three types of media, propagated signal decays exponentially with distance and (many) repeaters are needed.
- In general, the rate of attentuation depends on the frequency.

Propagation Media (Radio: frequency $< 1,000$)

- < 30 **MHz:** Electromagnetic waves reflected by ionosphere.
  - Long distance of propagation is possible by reflection to the ionosphere.
  - The 3 to 30 MHz range is called HF band and is used by ham radio. This band is very noisy and achieves data rates of $\leq 2,400$ bps.
- > 30 **MHz:** Ionosphere transparent to these electromagnetic waves.
  - Propagation is on **line-of-sight** paths.
  - Antennas placed on towers, hills, etc. in order to increase length of line-of-sight paths.
  - Used for UHF and VHF TV broadcast, FM broadcast, and Packet Radio Networks.

Propagation Media (Microwave, Satellite: frequency $> 1,000$)

- **Microwave: frequency** $> 1,000$
  - Uses line-of-sight paths
  - Antennas used are highly directional
  - Typical lengths achieved are $10 - 200$ km
  - Larger paths need repeaters
  - Can carry $1,000$ Mbps
- **Satellites: frequency** $> 1,000$
  - Rates similar to Microwave
  - Satellites used as repeaters
  - Used for broadcast and multicast

Allocation Techniques (1/2)

- Allocation techniques depend on network type (wireline or wireless) and technology used.
- ALOHA (a dynamic allocation technique) is used in Ethernet.
- Several types of DMA (Division Multiple Access) techniques have been used in Wireless network design.
- The table below

Features	1G	2G	3G	4G	5G
Start/Devlopment	1970/1984	1980/1999	1990/2002	2000/2010	2010/2015
Technology	AMPS, NMT, TACS	GSM	WCDMA	LTE, WiMax	MIMO, mm Waves
Frequency	30 KHz	1.8 Ghz	1.6 - 2 GHz	2 - 8 GHz	3 - 30 Ghz
Bandwidth	2 kbps	14.4 - 64 kbps	2 Mbps	2000 Mbps to 1 Gbps	1 Gbps and higher
AccessSystem	FDMA	TDMA/CDMA	CDMA	CDMA	OFDM/BDMA
Core Network	PSTN	PSTN	Packet Network	Internet	Internet

depicts the evolution of DMA techniques.

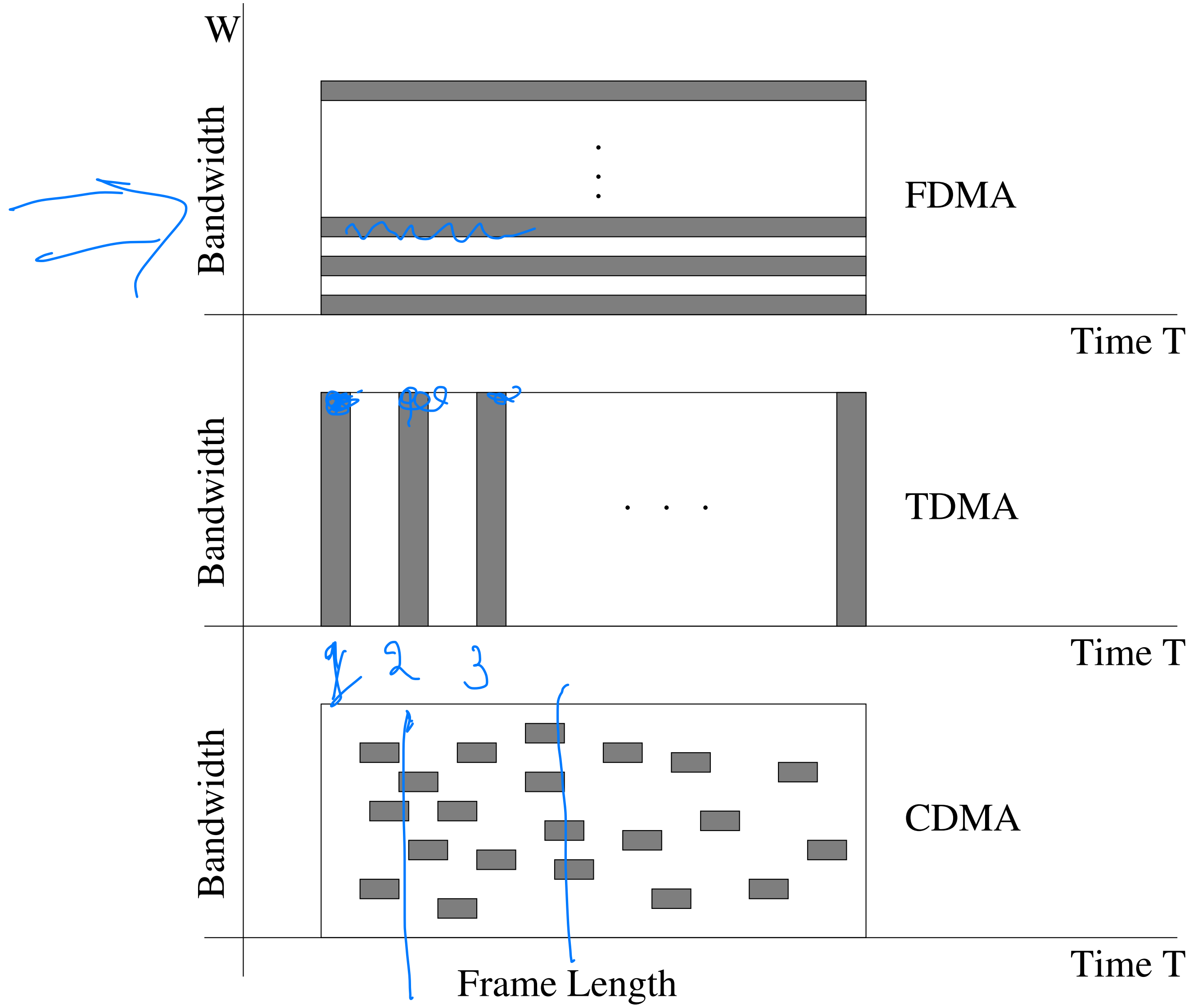
Allocation Techniques (2/2)

$W = [f_L, f_H]$

- **F(requency)DMA:** Splits channel into many little channels. If physical channel has bandwidth W herz then we split it into m equal subchannels each of bandwidth W/m.
- **T(ime)DMA:** Same bandwidth is used, however data is sent in frames with each frame having m slots (e.g T1 carrier).
- **C(ode)DMA:** Encodes 64 channels into 1.25 MHz of spectrum. Each channel uses an orthogonal code with all channels transmitting across the same bandwidth.
- **S(tatistical)DMA:** Channels are allocated at random. This is the most efficient but has a lot of overhead.

DMA = Division Multiple Access

Conceptual Characterization of Allocation Techniques



Coctail Party Paradigm

- Imagine a coctail party with many participating people in a large room.
  - **FDMA:** is when people break up into small independent groups each group holding conversation independently of the other groups.
  - **TDMA:** is when all people are in a single group with people taking turns talking.
  - **CDMA:** is when they are all talking at once but each pair of people using a different language.
- In certain cases we may use mixed DMA techniques, e.g., GSM uses FDMA and TDMA).

Exercises[a]

1. Why do we need digital to digital encodings?
2. For n random bits, what is the expected number of stuffed bits?
3. What are advantages and disadvantages of using geostationary satellites in communication networks?
4. How Low Earth Orbit (LEO) satellites differ from geostationary satellites?
5. Why can't we simplify things and use exclusively wireless networks everywhere?
6. Why do we need physical to digital (and vice versa) conversions?
7. It is desired to send a sequence of computer screen images over an optical fiber. The screen is 480×640 pixels, each pixel

[a] Not to hand in!

being 24 bits. There are 60 screen images per second. How much bandwidth is needed?

8. There are several DMA (Division Multiple Access) access techniques in the scientific literature. Investigate how the following work:
   (a) Spatial Division Multiple Access (allocates space)
   (b) Beam Division Multiple Access (BDMA) (uses multiple radiators)
   (c) Orthogonal Frequency Division Multiple Access (OFDMA)
9. Sometimes combinations of the Division Multiple Access techniques discussed is also being used. Elaborate why this can create efficiencies. E.g., GSM uses a combination of both TDMA and FDMA techniques. The FDMA element divides the assigned frequency of 25 MHz bandwidth into 124 carrier frequencies, all spaced 200 kHz apart. The carriers are also

divided in time using TDMA. Different users of each RF channel are allocated different time slots (there are 8 time slots per channel).

10. The uplink band in GSM has a total of 25 MHz of bandwidth and each radio channel has an assigned bandwidth of 200 kHz. What is the number of radio channels (FDMA)?

11. In practice GSM uses 124 channels (not 125). Each channel is divided into 8 time slots, so 8 users are allowed per radio channel (TDMA). What is the max number of users?

12. GSM also has a corresponding downlink band for sending signals to the mobile phone. For GSM in Europe the uplink and downlink frequency bands are 890 to 915 MHz and 935 to 960 MHz, respectively. How does this affect the number of users?

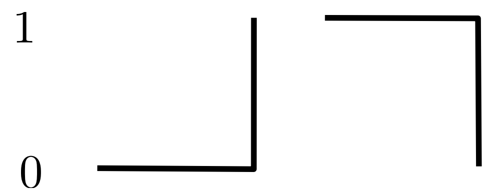
Appendix

(Digital $\rightarrow$ Digital)

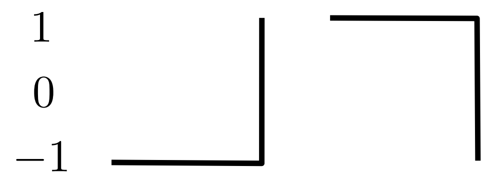
(Not Required)

Representing Transitions

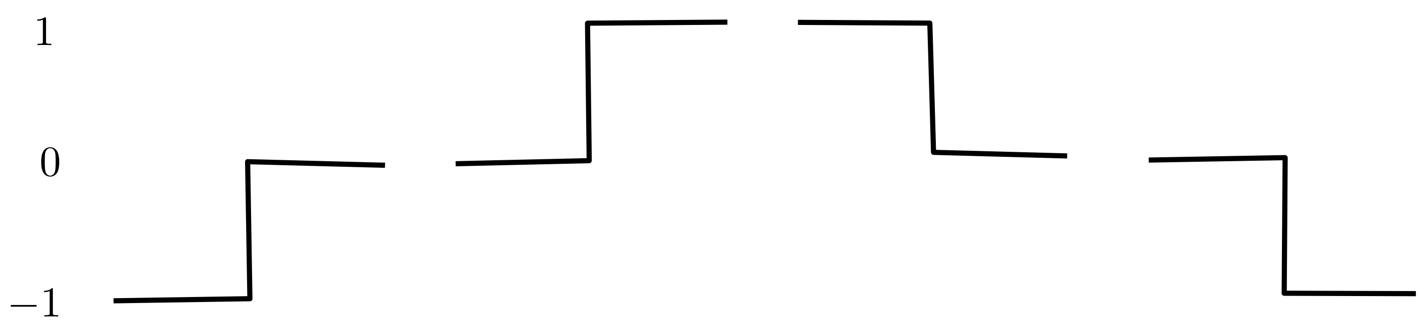
- Levels $0, 1$ (Returns to 0)



- Levels $-1, 0, 1$ (Does not return to 0)



- Levels $-1, 0, 1$



Amplitude Levels

1. **Unipolar:** Very primitive (and almost obsolete) and uses only one level of value
2. **Polar:** Two levels (one positive and one negative) of amplitude are being used.
   (a) NRZ (Non Return to Zero): Signal always either positive or negative (does not return to 0).
      i. NRZ-L (Non Return to Zero Level): the level of the signal is dependent upon the state of the bit it represents.
      ii. NRZ-I (Non Return to Zero Invert): voltage inversion represents the bit 1.
   (b) RZ (Return to Zero): uses positive, negative and zero.
3. **Bipolar:** uses three levels (positive, negative and zero) but unlike RZ zero is used to represent binary 0.

1: Unipolar

- Uses only one voltage level (other than 0).
- Very primitive (and almost obsolete) and uses only one level of value.
- This type of encoding is also known as **unipolar** encoding because it uses only one level of value.

Problems with Unipolar

- **Baseline wander:**
  - The receiver takes the average of what it has seen so far to distinguish between high and low!
  - Thus a long sequence of consecutive 1s (or 0s) changes this average and is hard to distinguish 0 and 1
- **Clock Recovery:**
  - Coding and decoding processes are driven by (separate) clocks which must be synchronized.
  - Frequent transitions from 0 to 1 and vice versa are necessary in order to enable sender and receiver to synchronize.
- This indicates a "need for change" while transmitting!

2: Polar Encodings RZ and NRZ

- **NRZ-L:**[a] Voltage is constant during the bit interval; the level of the signal depends on the state of the bit. Positive (resp., negative) voltage means bit is 0 (resp., 1).
- **NRZ-I (invert on ones):**[b] Voltage is constant during the bit interval; the signal is inverted when a 1 is encountered and is left unchanged otherwise, at the beginning of the bit time.
- **Bipolar RZ:**[c] Is a return to zero encoding (always returns to 0) so that three levels: negative, zero, and positive are used. .

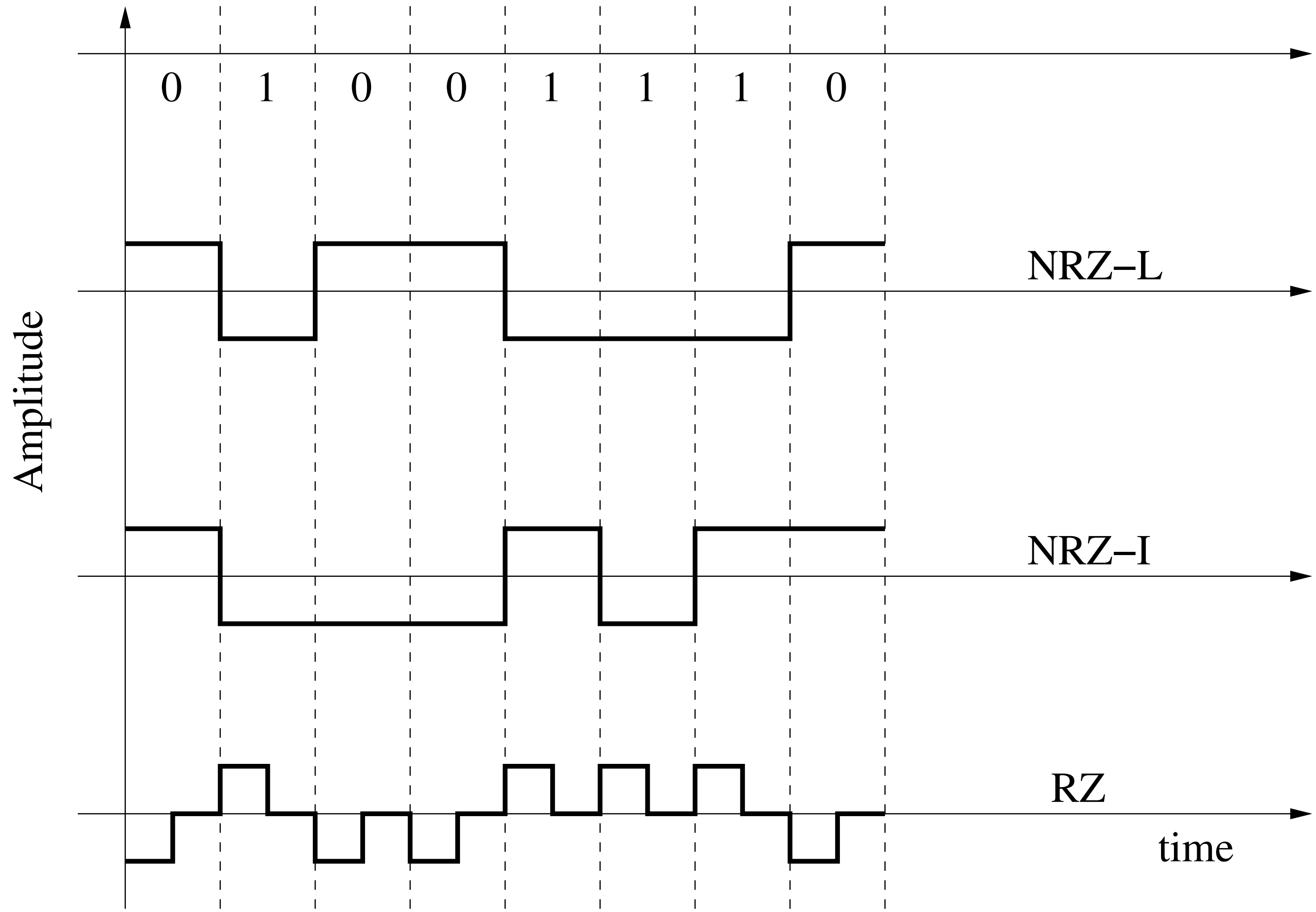
[a] NRZ-L used for short distances
[b] NRZ-I commonly used with serial ports.
[c] Bipolar RZ encodings are designed to be DC–Direct Current balanced.

Solution: NRZ-I

- **NRZ-I** (i.e., NRZ Inverted):
- The sender does the following:
  - To encode a 1: makes transition from current signal
  - To encode a 0 stays at the current signal.
- **Example:**

$$
\begin{array}{cccccccccc}
0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 \\
\downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\
0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0
\end{array}
$$

Bipolar RZ and NRZ Polar Encodings



Polar Biphase: Manchester (1/2)

- **Manchester:**
  Transmits $0 \to 01$ and $1 \to 10$.

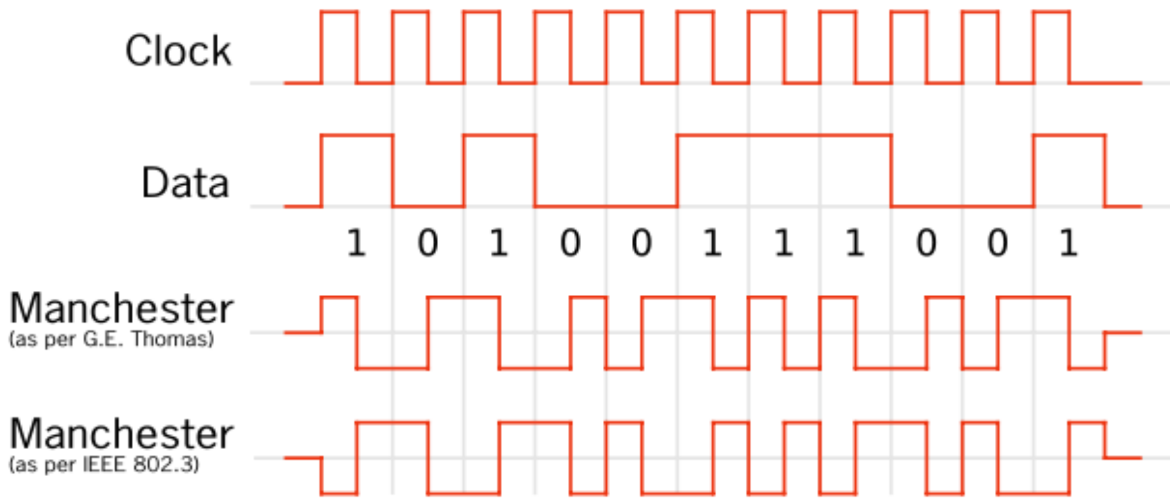
- **Example:**

$$\begin{array}{cccccccccc} 0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 \\ \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\ 01 & 01 & 10 & 10 & 10 & 01 & 10 & 01 & 10 & 10 \end{array}$$

- **Shortcomings:** Manchester code needs twice the bandwidth of asynchronous communications, and the signal spectrum is much wider. Most high-speed communication now uses encoding schemes with better coding performance.

Polar Biphase: Manchester (2/2)

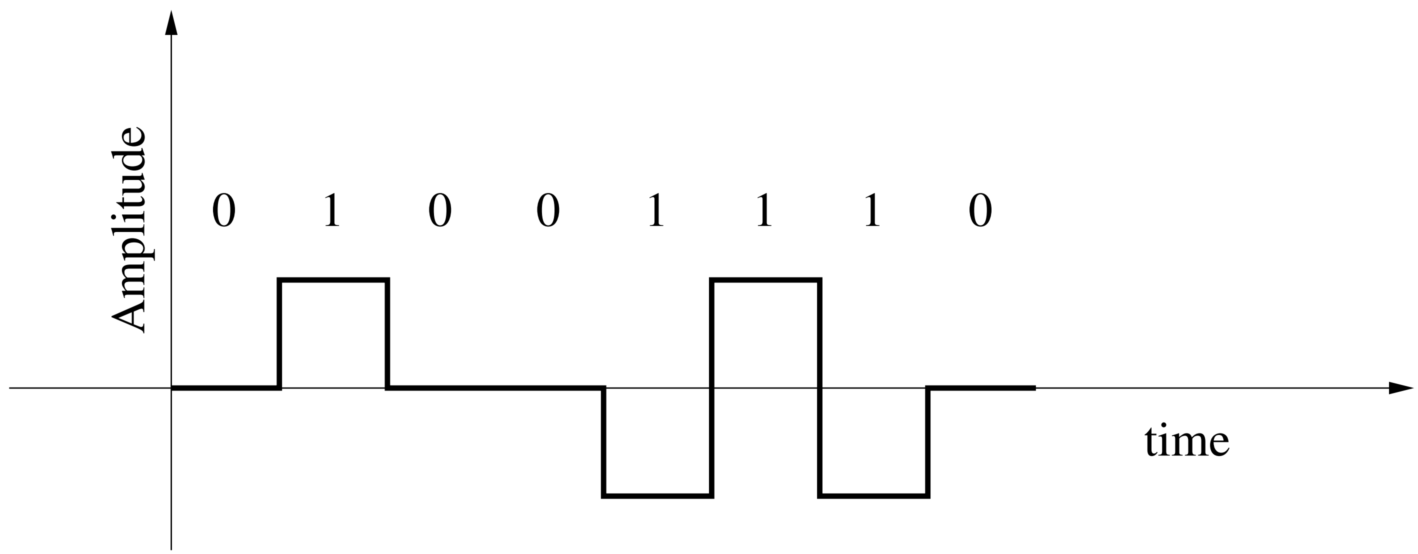
- **Manchester:** Transmits the XOR of NRZ with the clock.



- Important consideration is synchronization of the receiver to the transmitter. It might appear that a half bit period error would give an inverted output at the receiver, but for typical data this leads to code violations. The receiver can detect these violations and use this information to synchronise accurately.

Bipolar (Alternate "Mark" Inversion (AMI))

- Here the word "Mark" means "1".
- AMI means "Alternate 1 Inversion": i.e., invert 1s.



- Neutral voltage represented by 0 and 1s represented by alternating positive and negative voltages.

More Bipolar

- **Bipolar** 8 **Zero Substitution (B8ZS):**
  - Force artificial signal changes to AMI whenever eight conscutive 0s occur in the signal (similar to 4B/5B).
  - This system is used in North America.
- **Bipolar (High Density Bipolar 3 (HDB3)**
  - Force artificial signal changes to AMI whenever four conscutive 0s occur in the signal (similar to 4B/5B).
  - This system is used in Europe and Japan.