

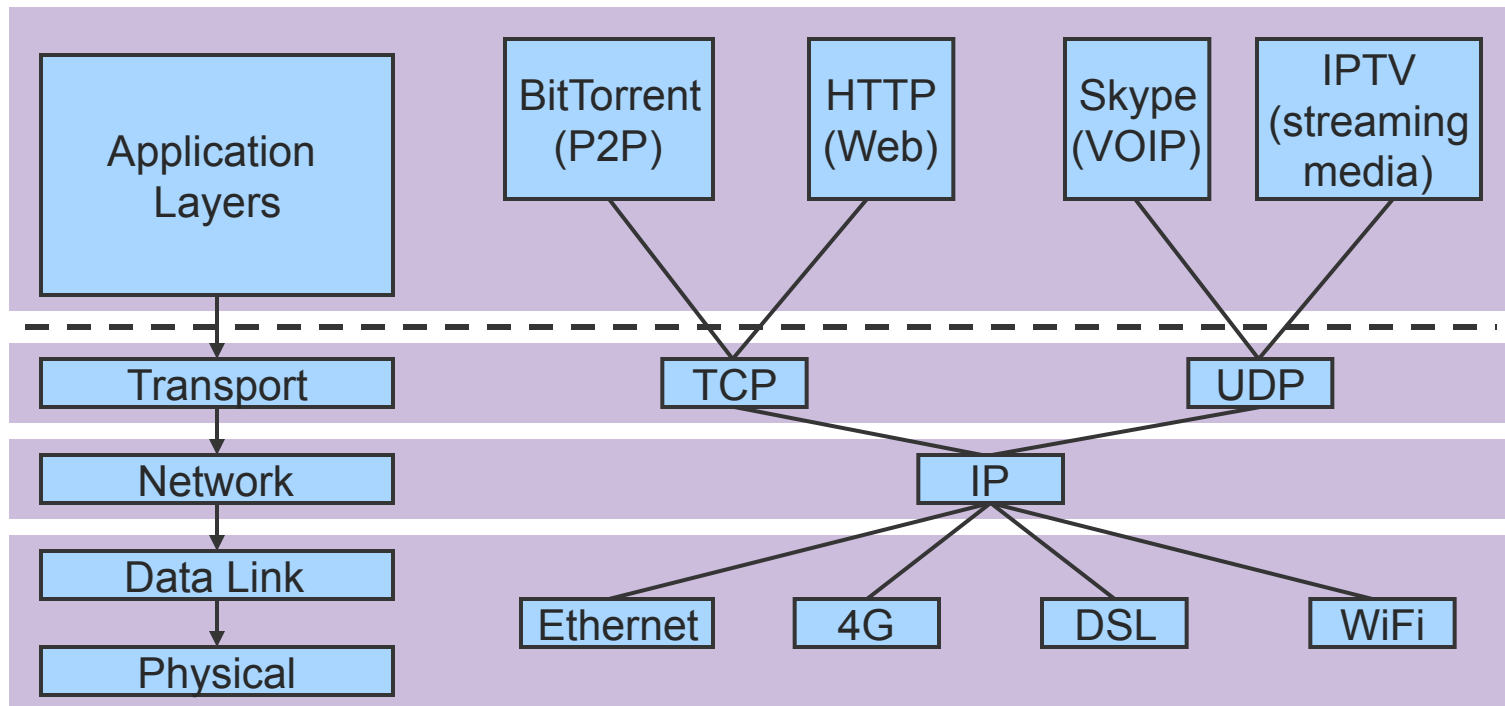


Direct Link Networks - Encoding

Reading: Peterson and Davie,
Chapter 2

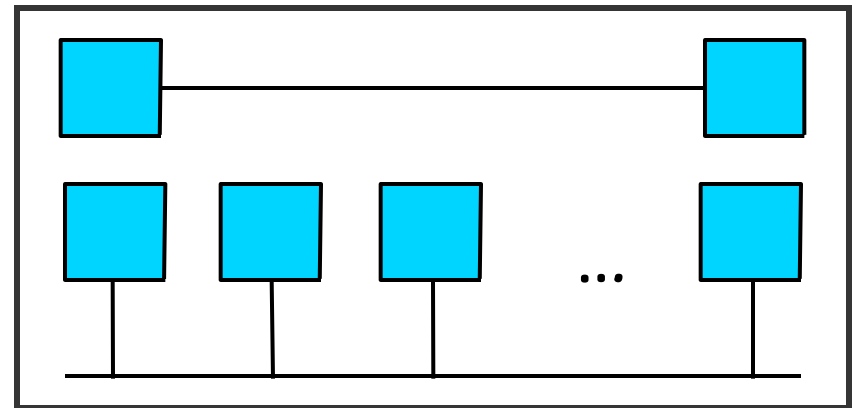
[Where are we?]

Today



[Direct Link Networks]

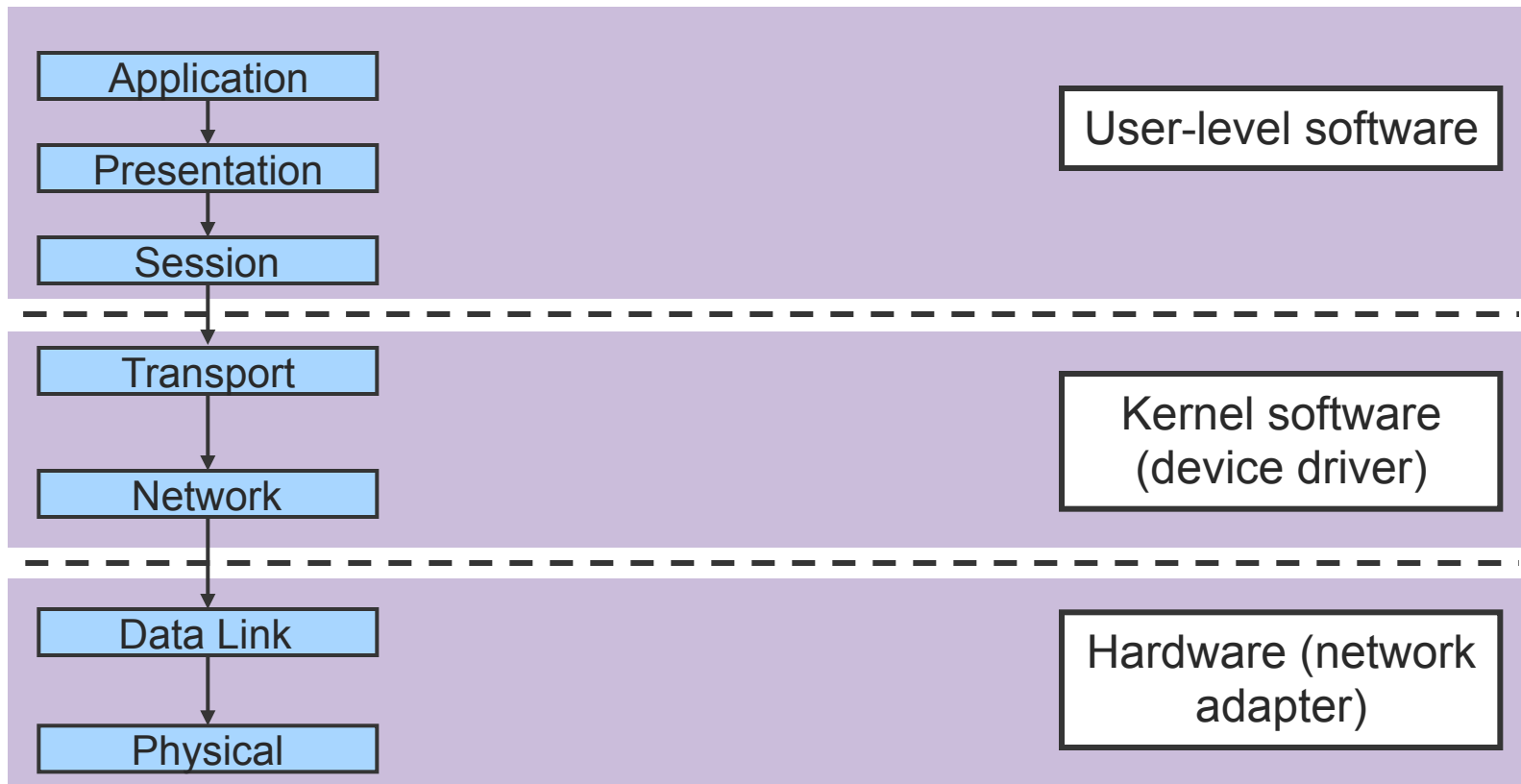
- All hosts are directly connected by a physical medium
- Key points
 - Encoding and Modulation
 - Framing
 - Error Detection
 - Medium Access Control



Internet Protocols

Encoding

Framing, error detection,
medium access control



[Direct Link Networks - Outline]

- Hardware building blocks
- Encoding
- Framing
- Error detection
- Multiple access media (MAC examples)
- Network adapters



[Hardware Building Blocks]

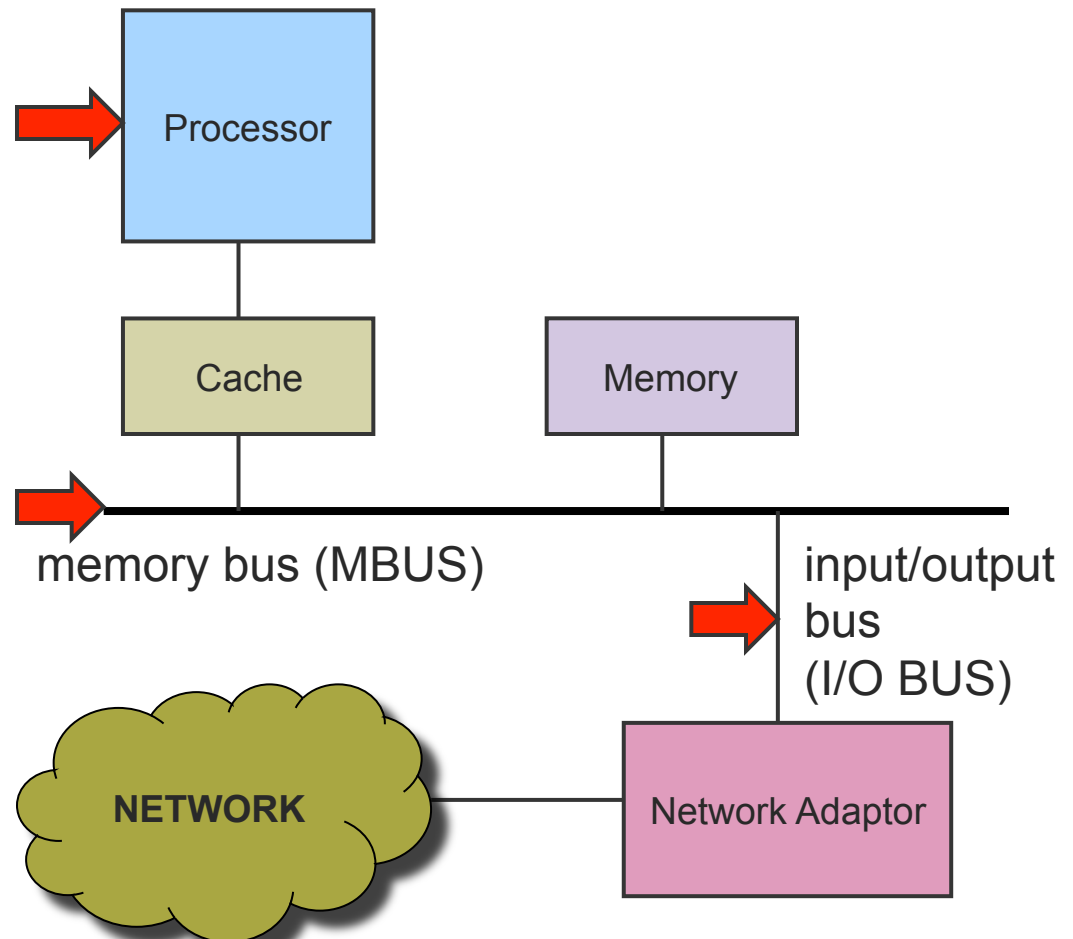
- Nodes

- Hosts: general purpose computers
- Switches: typically special purpose hardware
- Routers: varied



Nodes: Workstation Architecture

- Finite memory
 - Scarce resource
- Runs at memory speeds, NOT processor speeds



[Hardware Building Blocks]

- Links

- Physical medium

- Copper wire with electronic signaling
 - Glass fiber with optical signaling
 - Wireless with electromagnetic (radio, infrared, microwave) signaling
 - Two cups and a string



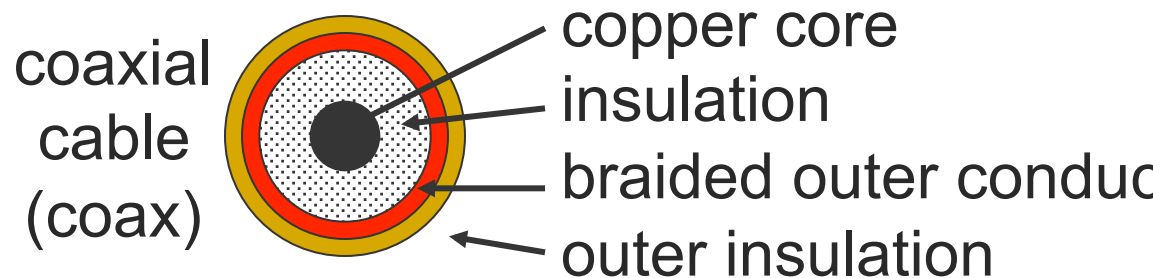
[Links - Copper]

■ Copper-based Media

- Category 5/6 Twisted Pair
- ThinNet Coaxial Cable
- ThickNet Coaxial Cable

more twists, less crosstalk, better signal over longer distances

10-1Gbps	100m
10-100Mbps	200m
10-100Mbps	500m

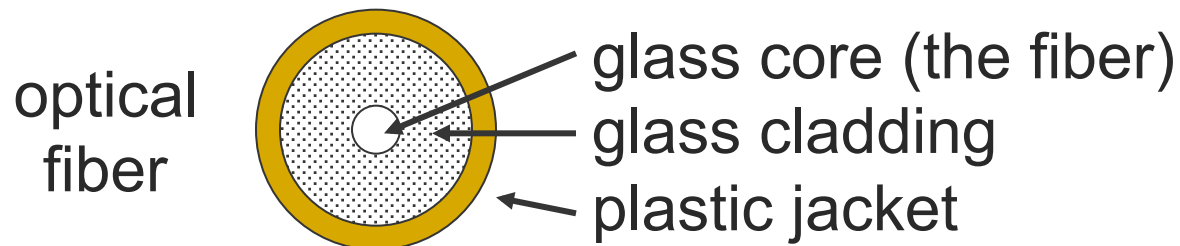


More expensive than twisted pair
High bandwidth and excellent noise immunity

[Links - Optical]

■ Optical Media

- | | | |
|---------------------|--------------|------|
| ○ Multimode Fiber | 100Gbps | 2km |
| ○ Single Mode Fiber | 100-2400Mbps | 40km |



[Links - Optical]

■ Single mode fiber

- Expensive to drive (Lasers)
- Lower attenuation (longer distances) ≤ 0.5 dB/km
- Lower dispersion (higher data rates)

■ Multimode fiber

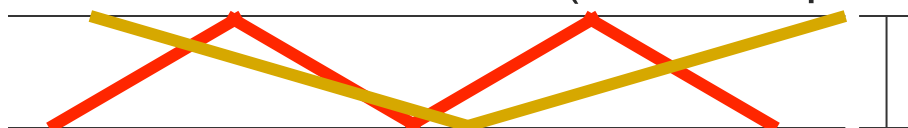
- Cheap to drive (LED's)
- Higher attenuation
- Easier to terminate

core of single mode fiber



~1 wavelength thick =
~1 micron

core of multimode fiber (same frequency; colors for clarity)



O(100 microns) thick



[Links - Optical]

- Advantages of optical communication
 - Higher bandwidths
 - Superior (lower) attenuation properties
 - Immune from electromagnetic interference
 - No crosstalk between fibers
 - Thin, lightweight, and cheap (the fiber, not the optical-electrical interfaces)



[Links - Wireless]

- Path loss
 - Signal attenuation as a function of distance
 - Signal-to-noise ratio (SNR—Signal Power/Noise Power) decreases, make signal unrecoverable
- Multipath propagation
 - Signal reflects off surfaces, effectively causing self-interference
- Internal interference (from other users)
 - Hosts within range of each other collide with one another's transmission
- External interference
 - Microwave is turned on and blocks your signal

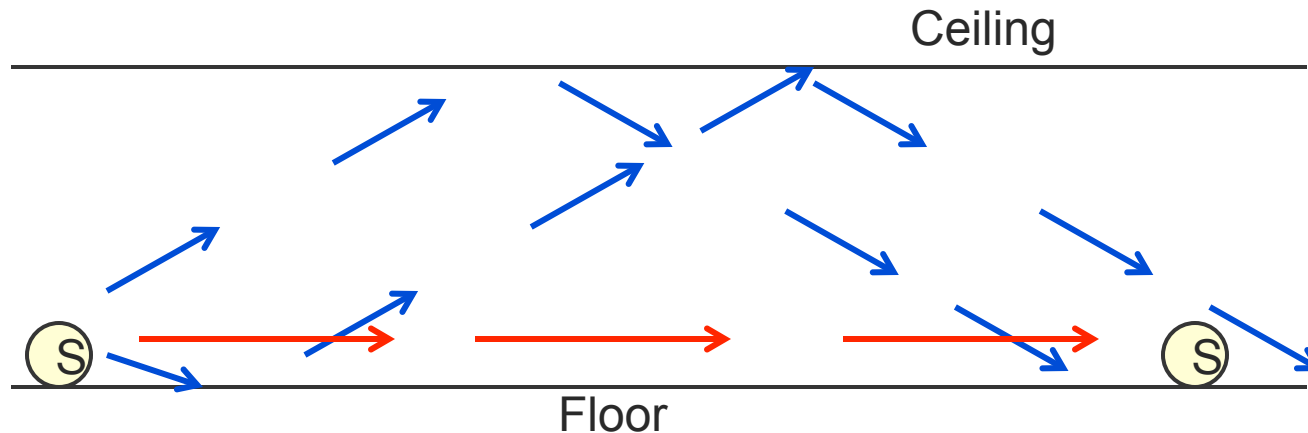


Wireless Path Loss

- Signal power attenuates by about $\sim r^2$ factor for omni-directional antennas in free space
 - r is the distance between the sender and the receiver
- The exponent in the factor is different depending on placement of antennas
 - Less than 2 for directional antennas
 - Faster attenuation
 - Exponent > 2 when antennas are placed on the ground
 - Signal bounces off the ground and reduces the power of the signal



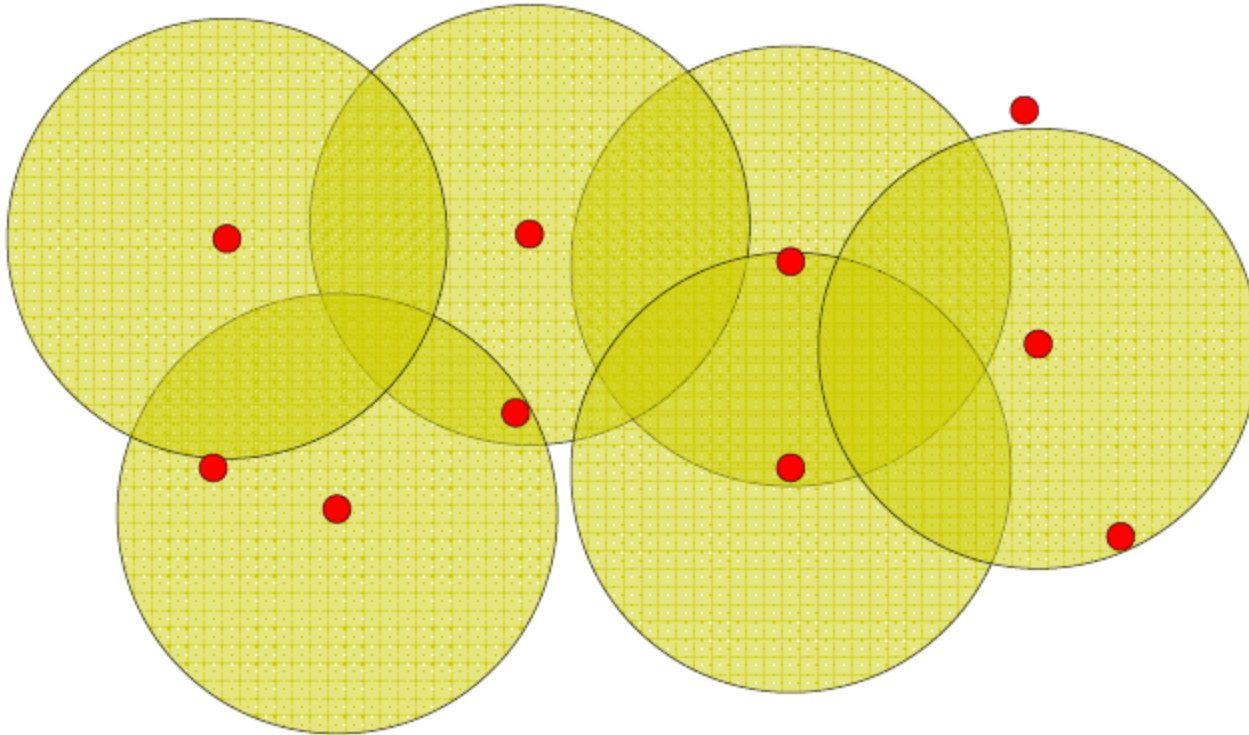
Wireless Multipath Effects



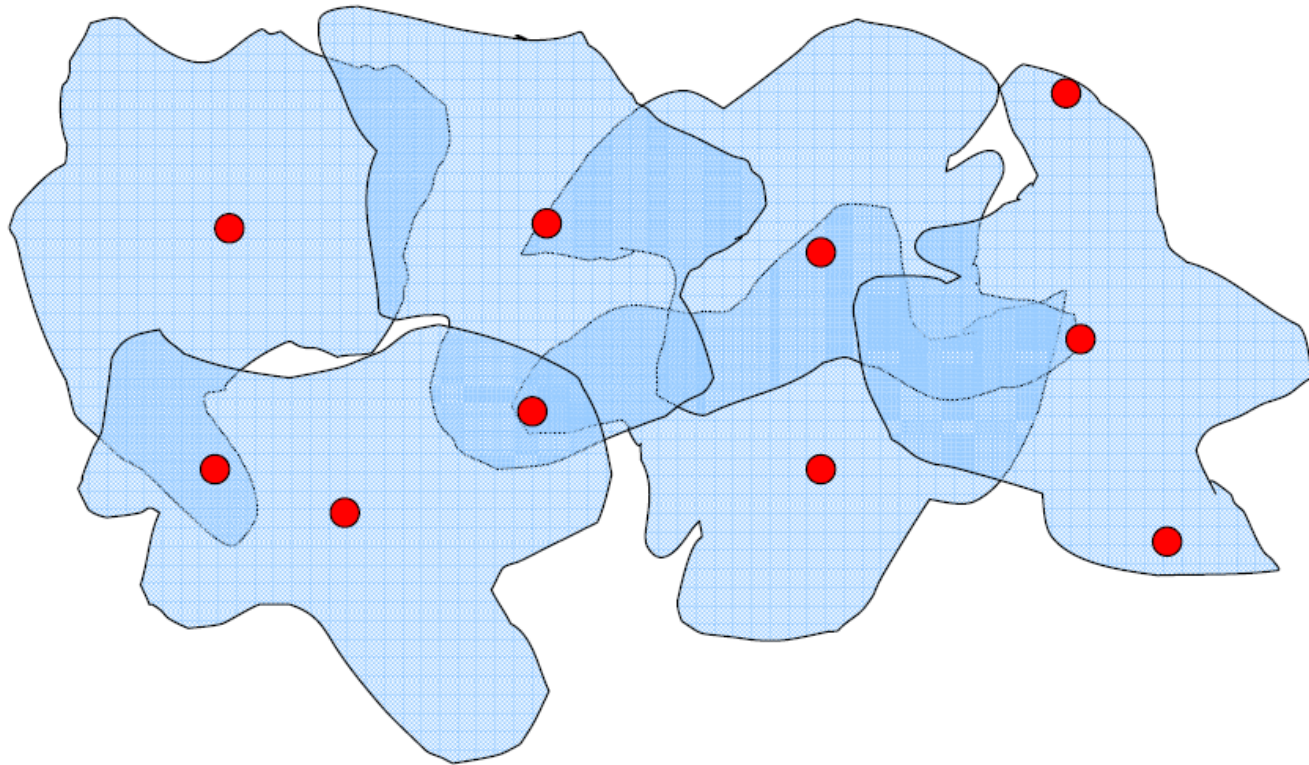
- Signals bounce off surfaces and interfere with one another
- What if signals are out of phase?
 - Orthogonal signals cancel each other and nothing is received!



[What is a Wireless “Link”?]



[What is a Wireless “Link”?]

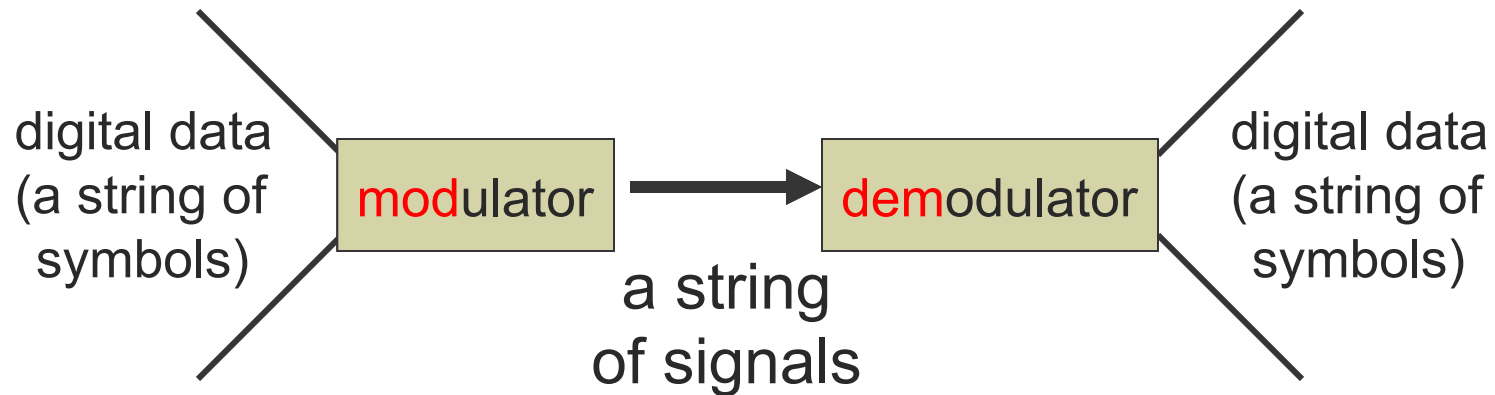


[Wireless Bit Errors]

- The lower the SNR (Signal/Noise) the higher the Bit Error Rate (BER)
- How can we deal with this?
 - Make the signal stronger
- Why is this not always a good idea?
 - Increased signal strength requires more power
 - Increases the interference range of the sender, so you interfere with more nodes around you
- Error correction can correct **some** problems



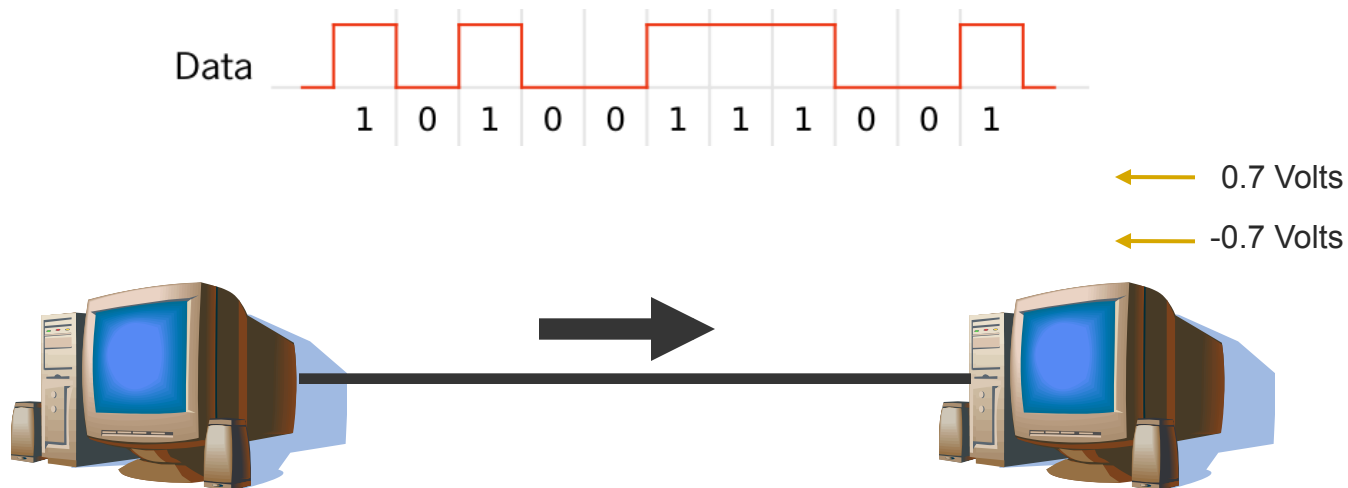
[Encoding]



- Problems with signal transmission
 - Attenuation: Signal power absorbed by medium
 - Dispersion: A discrete signal spreads in space
 - Noise: Random background “signals”



How can two hosts communicate?



- Encode information on modulated “Carrier signal”
 - Phase, frequency, and/or amplitude modulation
 - Ethernet: self-clocking Manchester coding
 - Technologies: copper, optical, wireless

[Encoding]

■ Goal

- Understand how to connect nodes in such a way that bits can be transmitted from one node to another

■ Idea

- The physical medium is used to propagate signals
 - Modulate electromagnetic waves
 - Vary voltage, frequency, wavelength
- Data is encoded in the signal



[Bauds and Bits]

- Baud rate

- Number of **physical symbols** transmitted per second

- Bit rate

- Actual number of **data bits** transmitted per second

- Relationship

- Depends on the number of **bits** encoded in each **symbol**



[Analog vs. Digital Transmission]

- **Analog** and **digital** correspond roughly to **continuous** and **discrete**
- Data: entities that convey meaning
 - **Analog**: continuously varying patterns of intensity (e.g., voice and video)
 - **Digital**: discrete values (e.g., integers, ASCII text)
- Signals: electric or electromagnetic encoding of data
 - **Analog**: continuously varying electromagnetic wave
 - May be propagated over a variety of media
 - **Digital**: sequence of voltage pulses
 - May be transmitted over a wire medium



[Analog vs. Digital Transmission]

- Advantages of digital transmission over analog
 - Cheaper
 - Simpler for multiplexing distinct data types (audio, video, e-mail, etc.)
 - Easier to encrypt
- Two examples based on modulator-demodulators (modems)
 - Electronic Industries Association (EIA) standard: RS-232
 - International Telecommunications Union (ITU) V.32 9600 bps modem standard



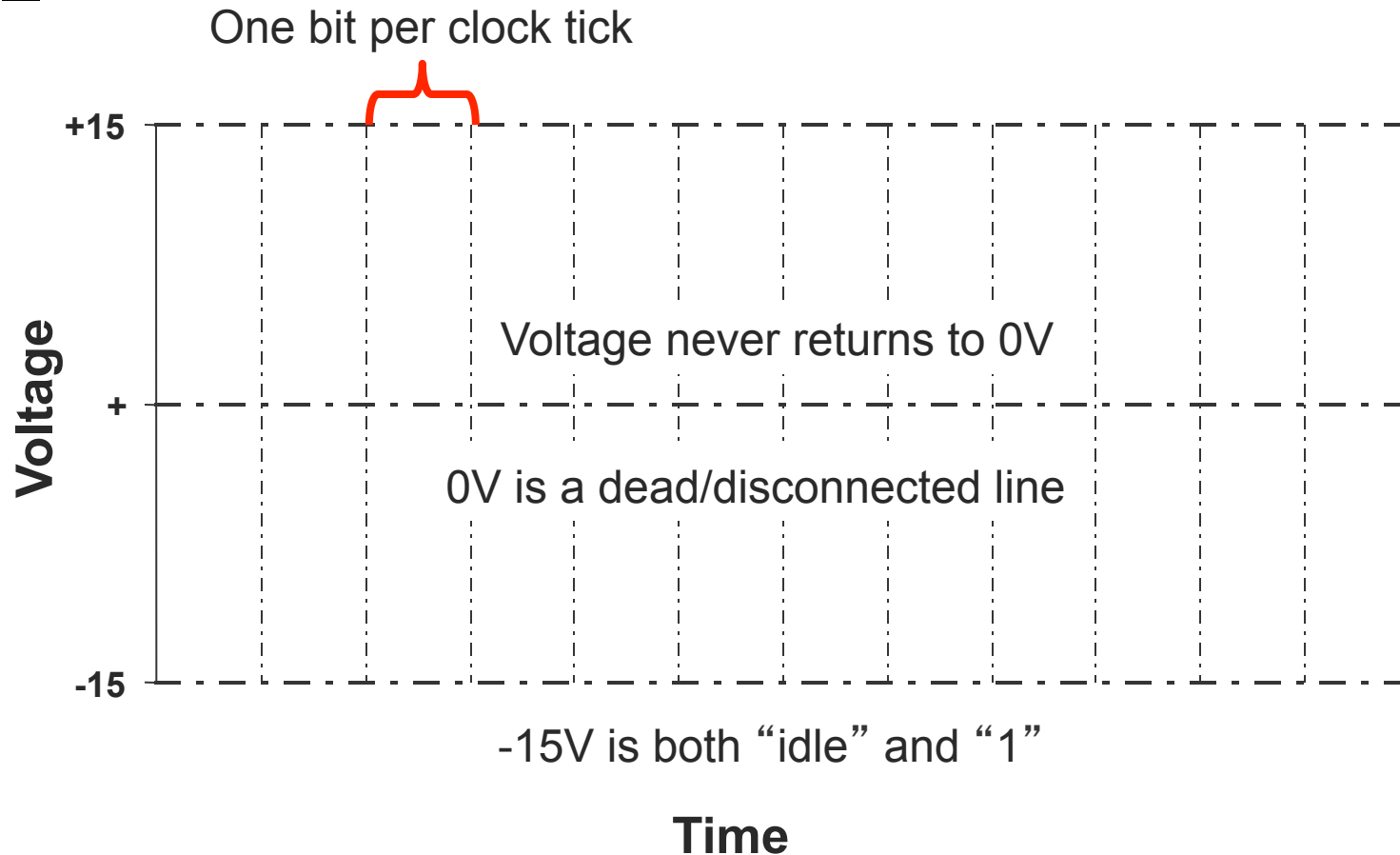
[RS-232]

- Communication between computer and modem
- Uses two voltage levels (+15V, -15V), a binary voltage encoding
- Data rate limited to 19.2 kbps (RS-232-C); raised to 115,200 kbps in later standards
- Characteristics
 - Serial
 - One signaling wire, one bit at a time
 - Asynchronous
 - Line can be idle, clock generated from data
 - Character-based
 - Send data in 7- or 8-bit characters





[RS-232 Timing Diagram]



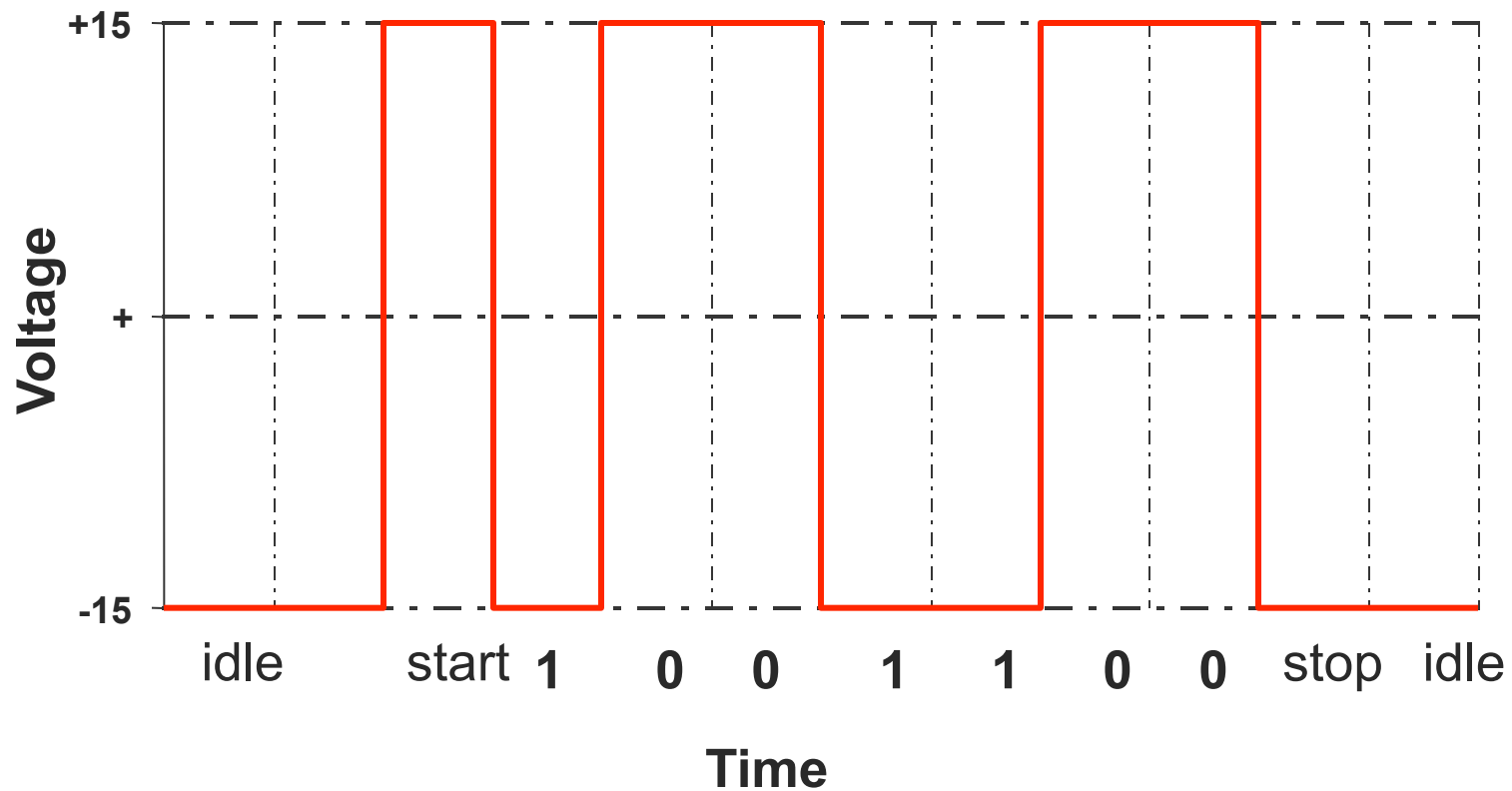
[RS-232]

- Initiate send by
 - Push to 15V for one clock (start bit)
- Minimum delay between character transmissions
 - Idle for one clock at -15V (stop bit)
- One character
 - 0, 1 or 2 voltage transitions
- Total Bits
 - 9 bits for 7 bits of data (78% efficient)
- Start and stop bits also provide framing





[RS-232 Timing Diagram



[Voltage Encoding]

- Binary voltage encoding
 - Done with RS-232 example
 - Generalize before continuing with V.32 (not a binary voltage encoding)
- Common binary voltage encodings
 - Non-return to zero (NRZ)
 - NRZ inverted (NRZI)
 - Manchester (used by IEEE 802.3—10 Mbps Ethernet)
 - 4B/5B



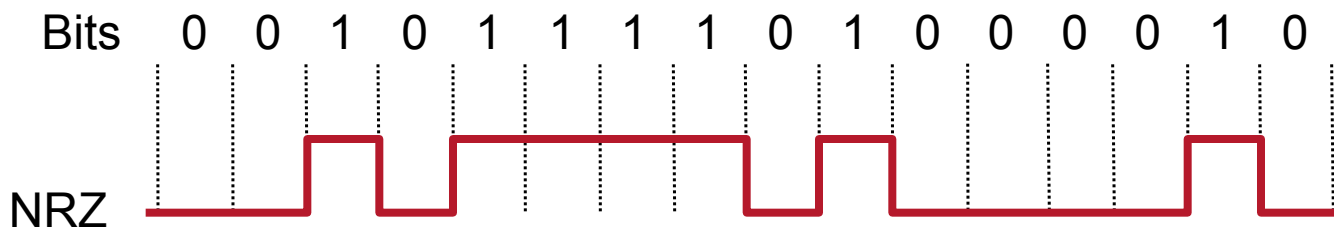
[Non-Return to Zero (NRZ)]

■ Signal to Data

- High \Rightarrow 1
- Low \Rightarrow 0

■ Comments

- Transitions maintain clock synchronization
- Long strings of 0s confused with no signal
- Long strings of 1s causes baseline wander
- Both inhibit clock recovery



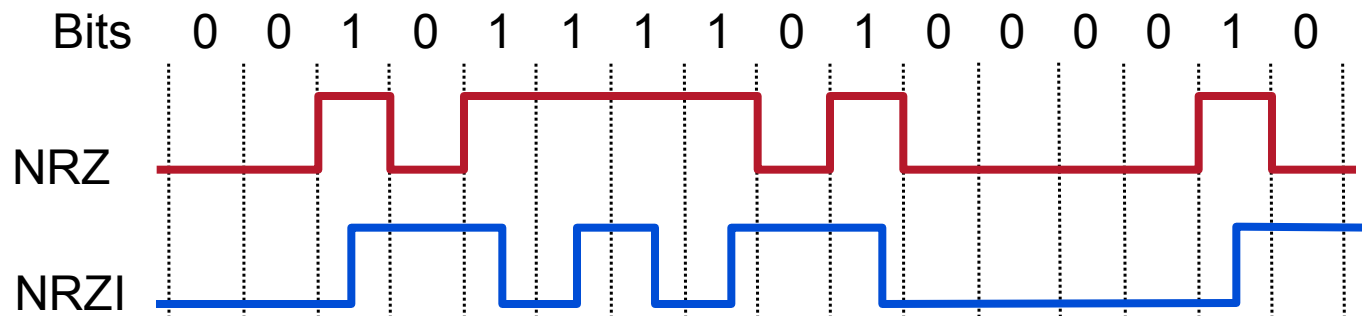
Non-Return to Zero Inverted (NRZI)

■ Signal to Data

- Transition \Rightarrow 1
- Maintain \Rightarrow 0

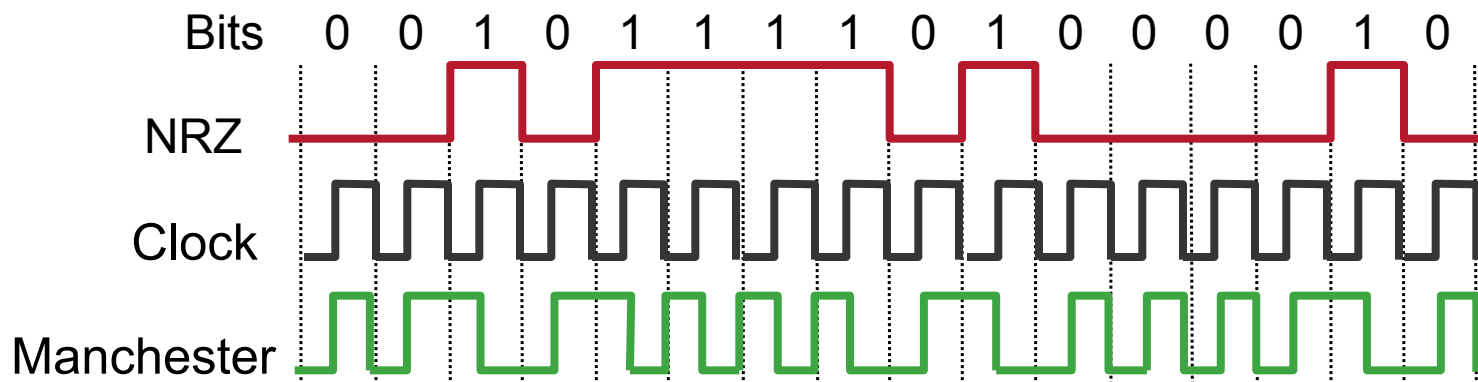
■ Comments

- Solves series of 1s, but not 0s



Manchester Encoding

- Signal to Data
 - XOR NRZ data with clock
 - High to low transition \Rightarrow 1
 - Low to high transition \Rightarrow 0
- Comments
 - (used by IEEE 802.3—10 Mbps Ethernet)
 - Solves clock recovery problem
 - Only 50% efficient ($\frac{1}{2}$ bit per transition)



[4B/5B]

- Signal to Data
 - Encode every 4 consecutive bits as a 5 bit symbol
- Symbols
 - At most 1 leading 0
 - At most 2 trailing 0s
 - Never more than 3 consecutive 0s
 - Transmit with NRZI
- Comments
 - 16 of 32 possible codes used for data
 - At least two transitions for each code
 - 80% efficient



[4B/5B – Data Symbols]

At most 1 leading 0

At most 2 trailing 0s

■	0000	⇒	11110
■	0001	⇒	01001
■	0010	⇒	10100
■	0011	⇒	10101
■	0100	⇒	01010
■	0101	⇒	01011
■	0110	⇒	01110
■	0111	⇒	01111

■	1000	⇒	10010
■	1001	⇒	10011
■	1010	⇒	10110
■	1011	⇒	10111
■	1100	⇒	11010
■	1101	⇒	11011
■	1110	⇒	11100
■	1111	⇒	11101



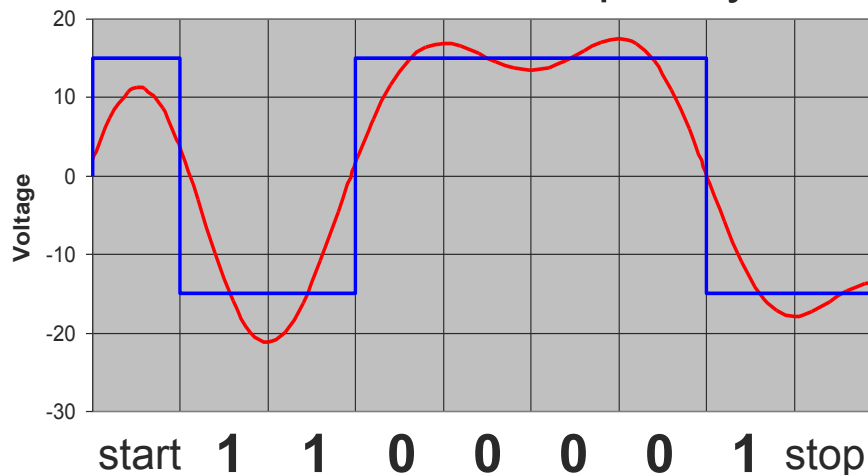
[4B/5B – Control Symbols]

- 11111 \Rightarrow idle
- 11000 \Rightarrow start of stream 1
- 10001 \Rightarrow start of stream 2
- 01101 \Rightarrow end of stream 1
- 00111 \Rightarrow end of stream 2
- 00100 \Rightarrow transmit error
- Other \Rightarrow invalid



Binary Voltage Encodings

- Problem with binary voltage (square wave) encodings
 - Very wide (Infinite) frequency range required, implying
 - Significant dispersion
 - Uneven attenuation
 - Prefer to use a narrower frequency band



[Binary Voltage Encodings]

- Problem with binary voltage (square wave) encodings
 - Very wide (Infinite) frequency range required, implying
 - Significant dispersion
 - Uneven attenuation
 - Prefer to use a narrower frequency band
- Types of modulation
 - Amplitude (AM)
 - Frequency (FM)
 - Phase/phase shift
 - Combinations of these

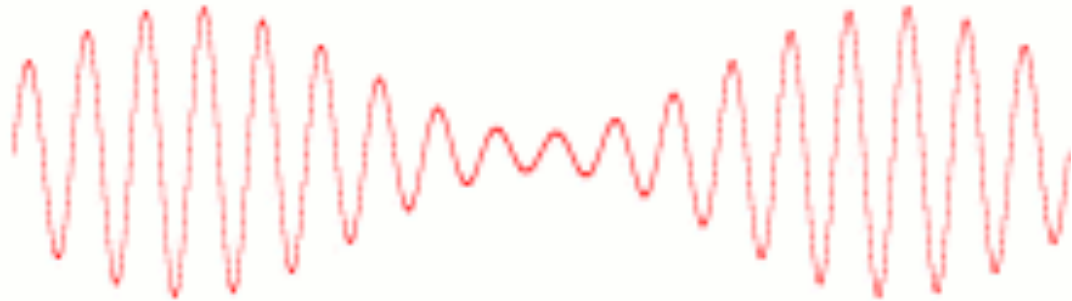


Example: AM/FM for continuous signal

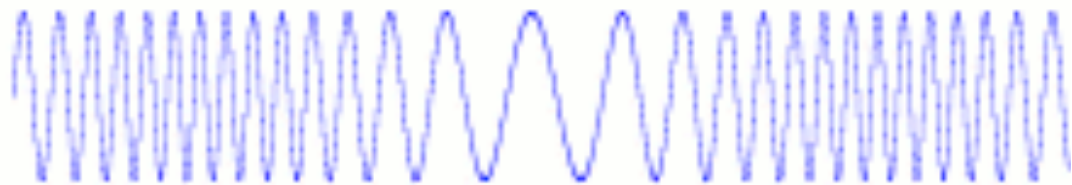
- Original signal



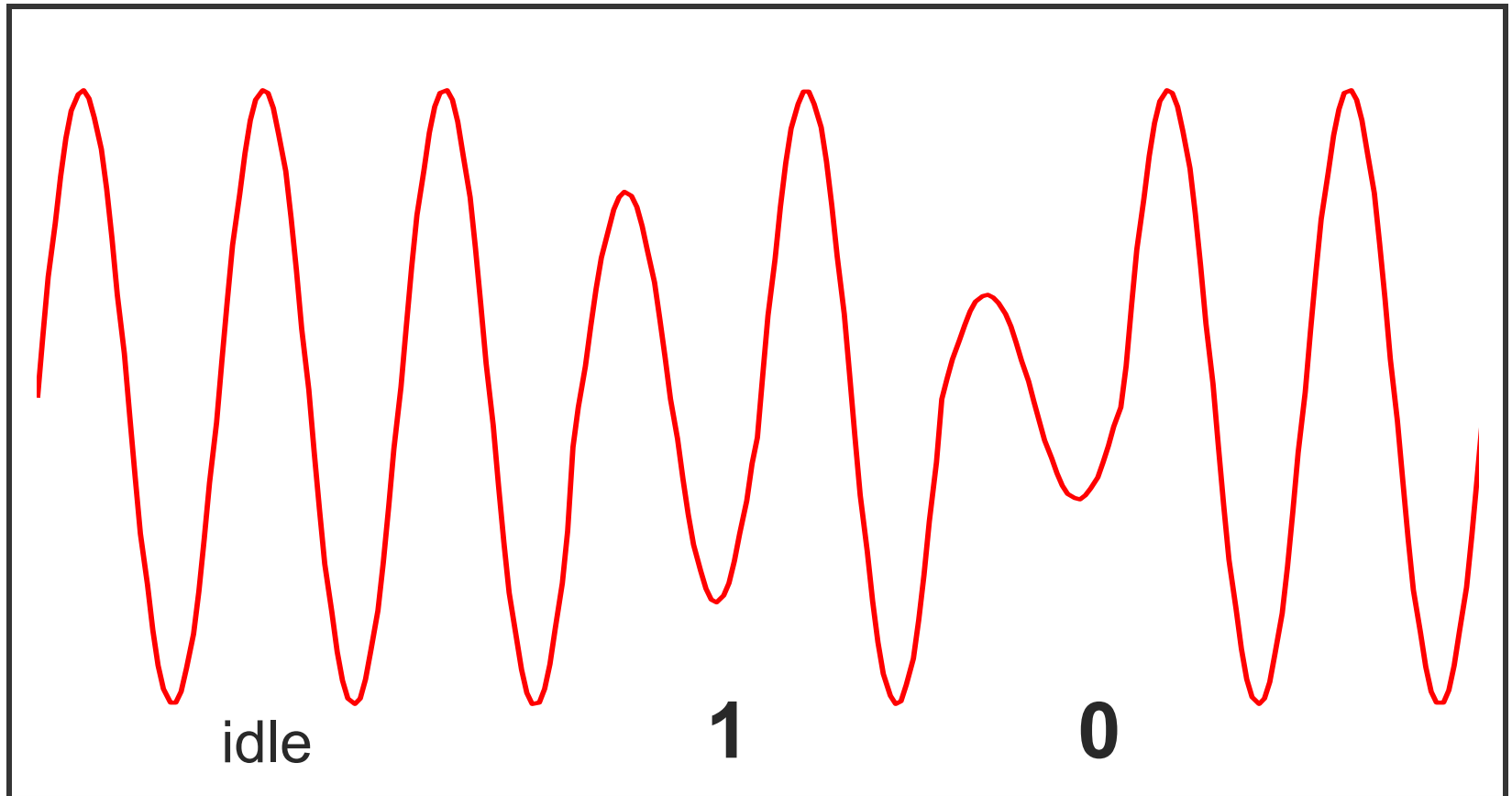
- Amplitude modulation



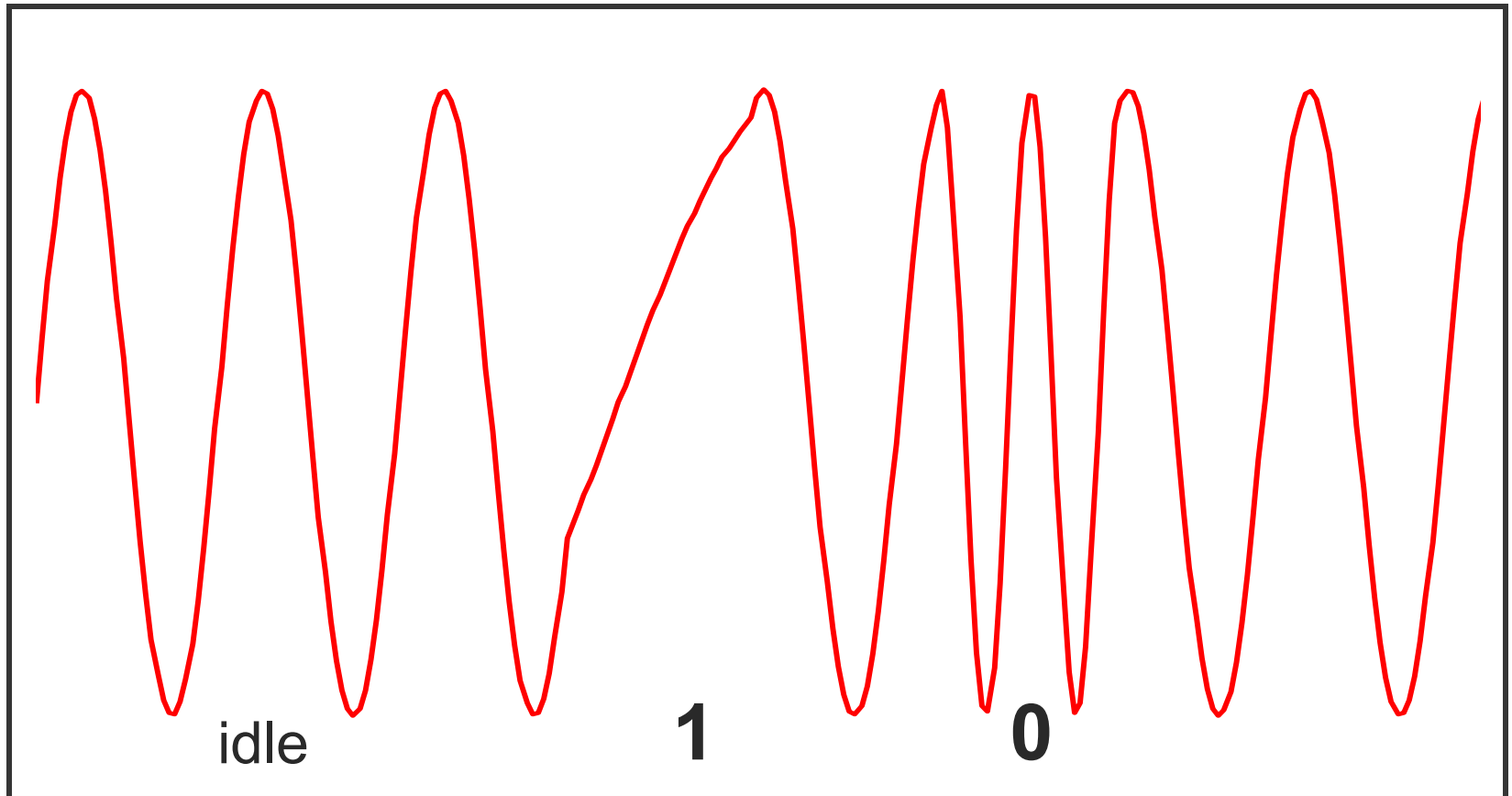
- Frequency modulation



[Amplitude Modulation]

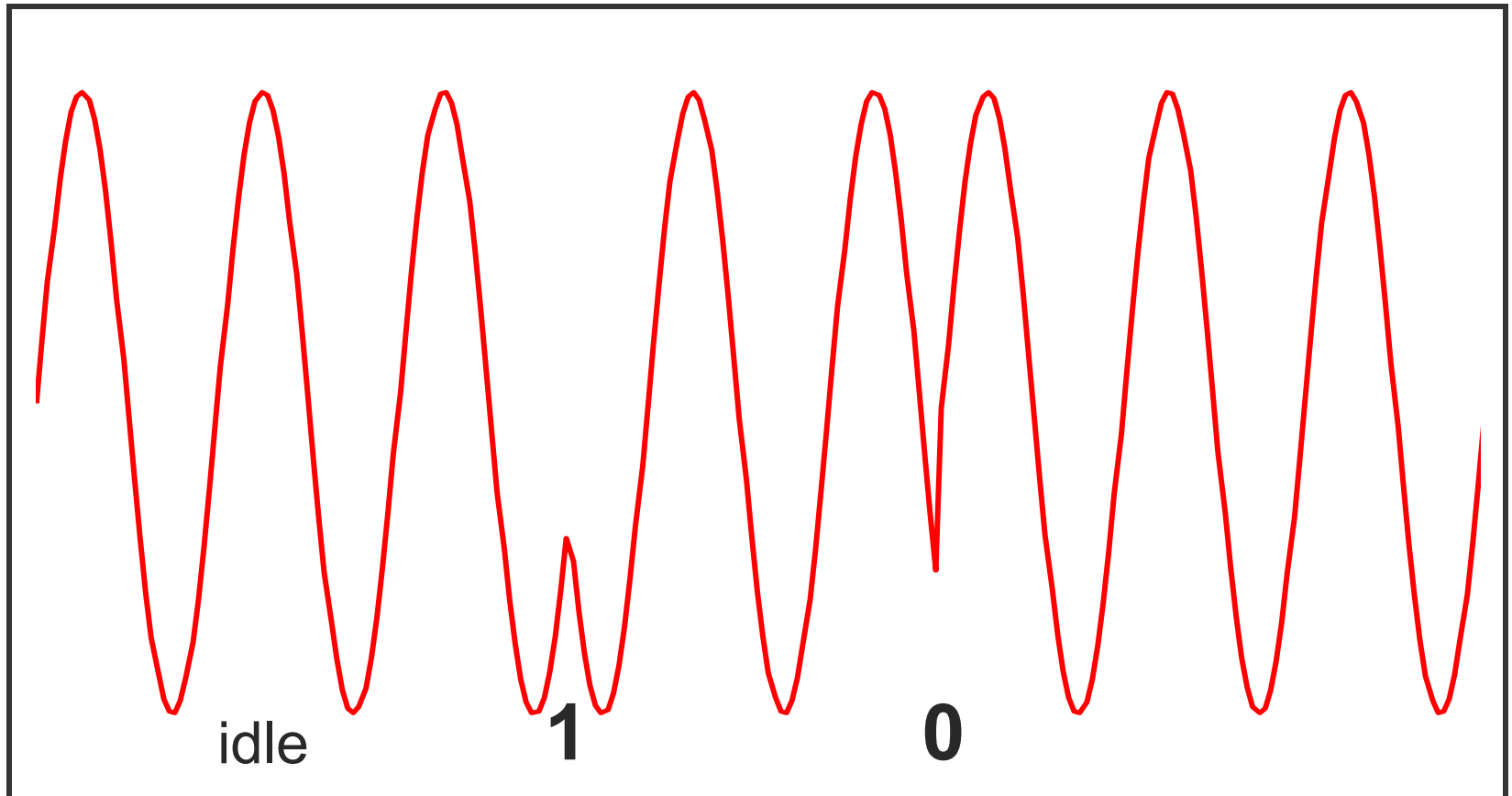


[Frequency Modulation]



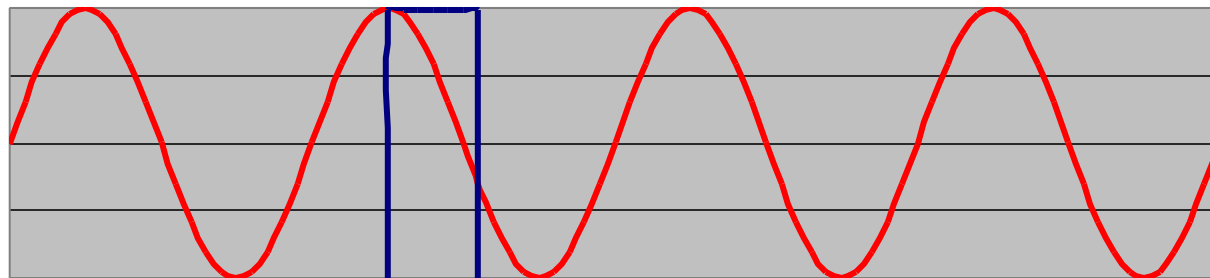


[Phase Modulation





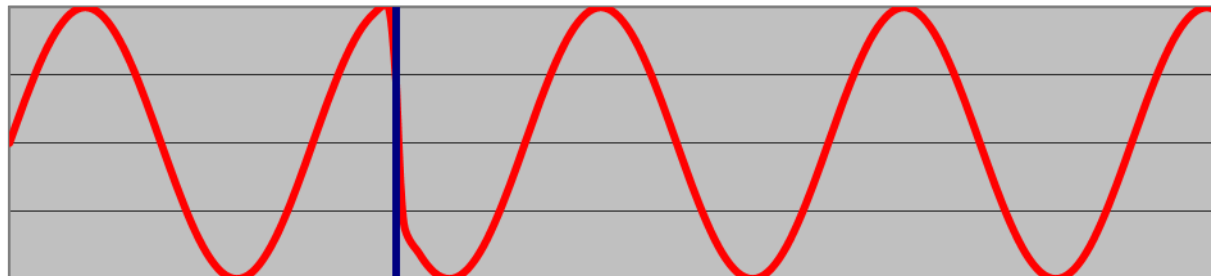
[Phase Modulation]



phase shift
in carrier
frequency

→ | ← 108° difference in phase

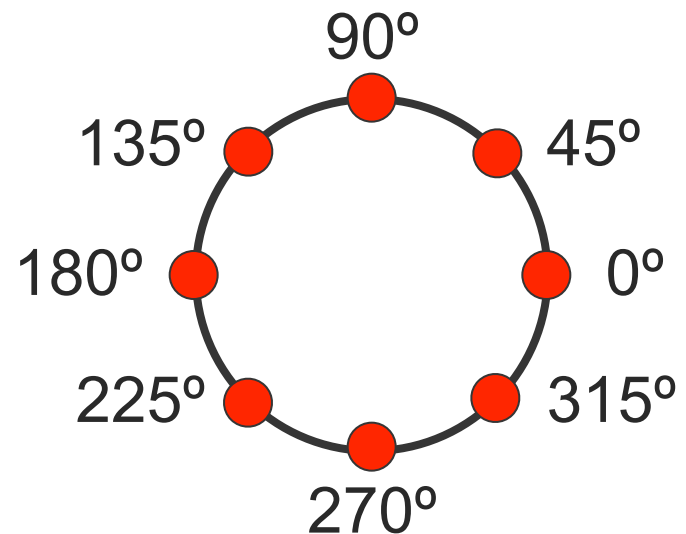
→ | ← collapse for 108° shift



[Phase Modulation Algorithm]

- Send carrier frequency for one period
 - Perform phase shift
 - Shift value encodes symbol
 - Value in range $[0, 360^\circ)$
 - Multiple values for multiple symbols
 - Represent as circle

8-symbol
example

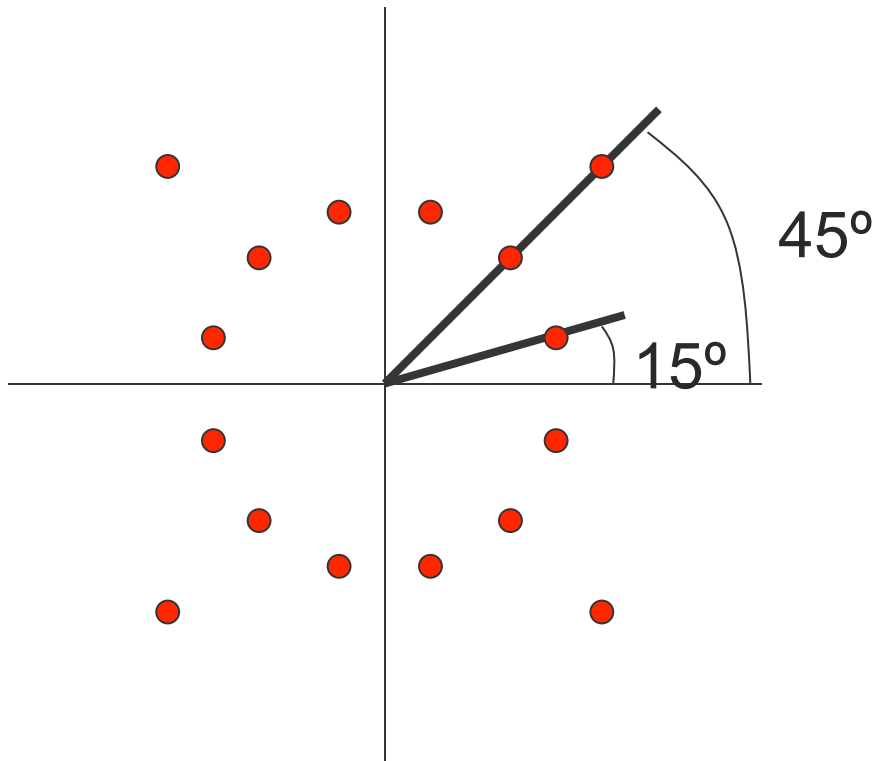


[V.32 9600 bps]

- Communication between modems
- Analog phone line
- Uses a combination of amplitude and phase modulation
 - Known as Quadrature Amplitude Modulation (QAM)
- Sends one of 16 signals each clock cycle



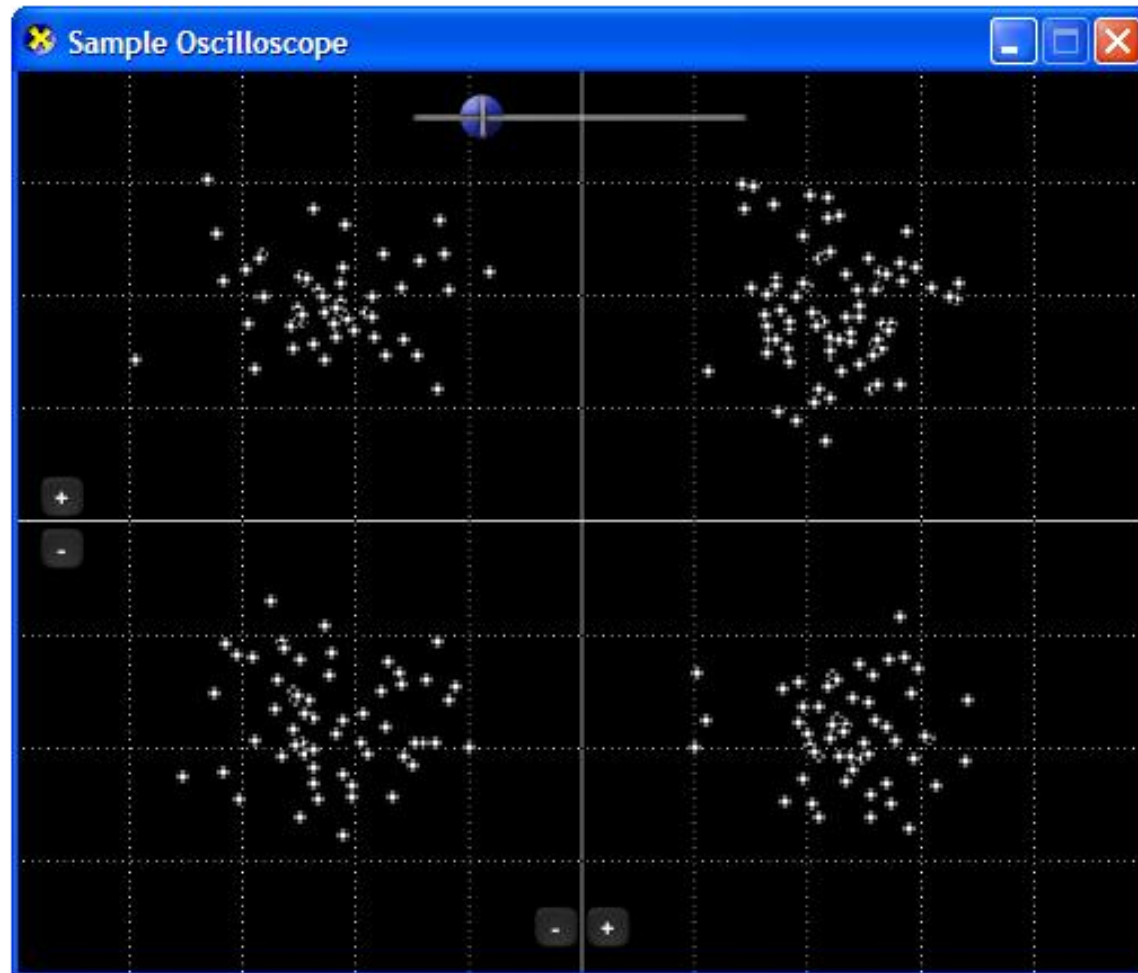
Constellation Pattern for V.32 QAM



16-symbol example

- Same algorithm as phase modulation
- Can also change signal amplitude
- 2-dimensional representation
 - Angle is phase shift
 - Radial distance is new amplitude

[Example constellation]



[Comments on V.32]

- V.32 transmits at 2400 baud
 - *i.e.*, 2,400 symbols per second
- Each symbol contains
 - $\log_2 16 = 4$ bits
- Data rate
 - $4 \times 2400 = 9600$ bps
- Points in constellation diagram
 - Chosen to maximize error detection
 - Process called trellis coding

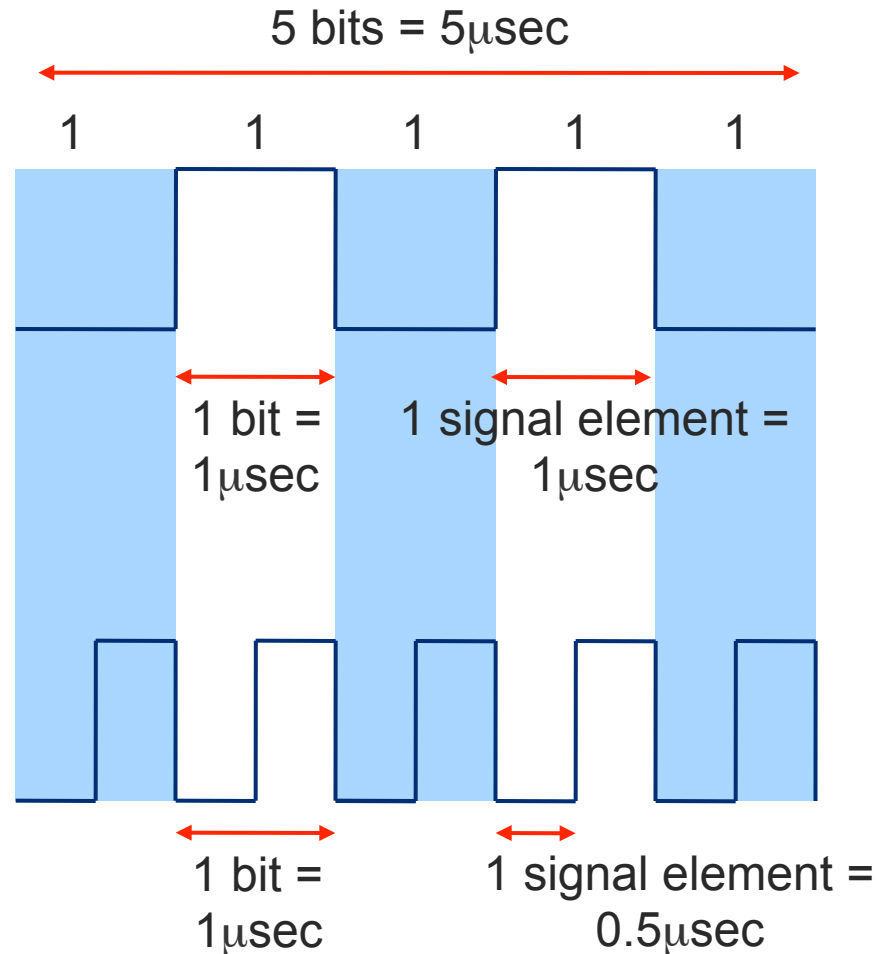


[Modulation (Baud) Rate]

A stream of binary 1s
at 1 Mbps

NRZI

Manchester



What is a
bit?

What is a
signal
element?

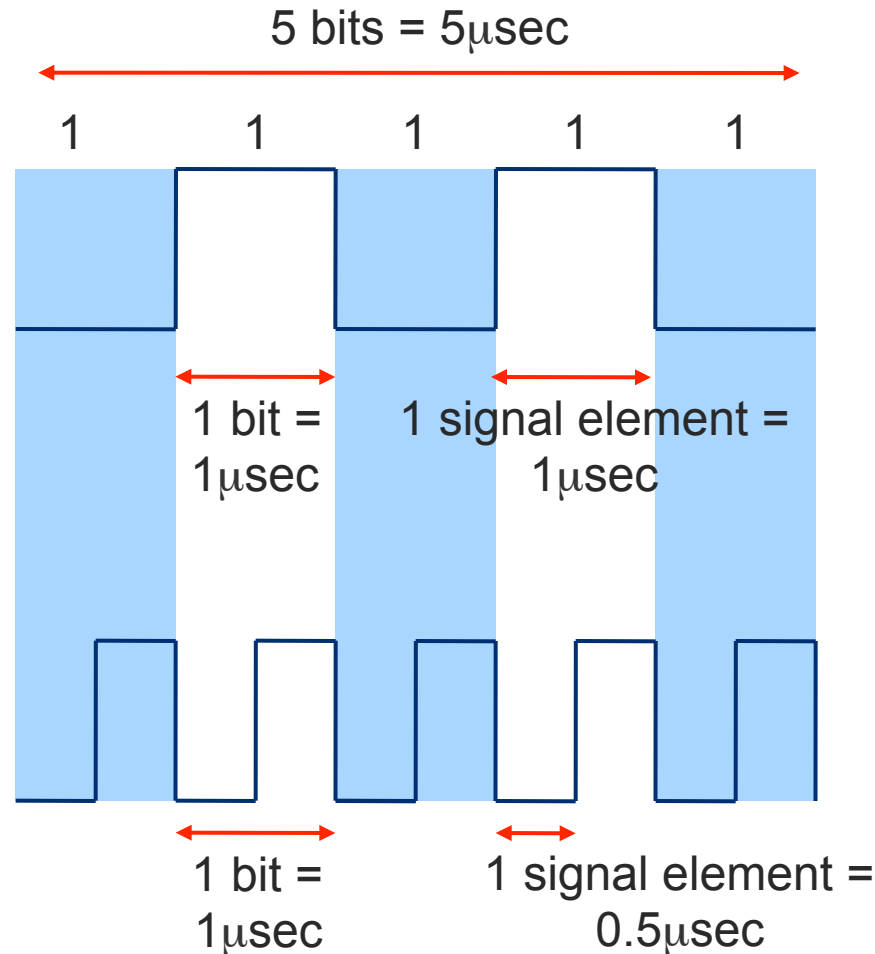


Modulation (Baud) Rate

A stream of binary 1s
at 1 Mbps

What is the
data rate?

Data Rate (R)
= bits/sec
= 1 Mbps for both
NRZI
Manchester

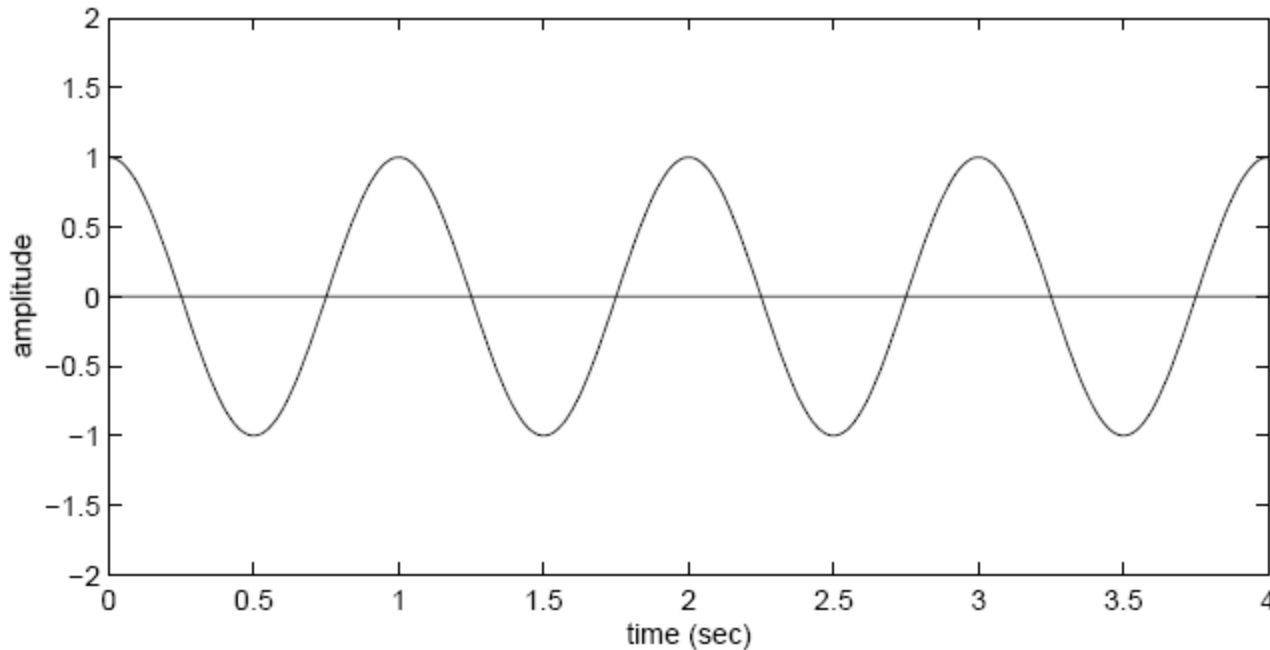


What is the
modulation
rate?

Modulation Rate
= Baud Rate
= Rate at which
signal elements
are generated
= R (NRZI)
= $2R$ (Manchester)



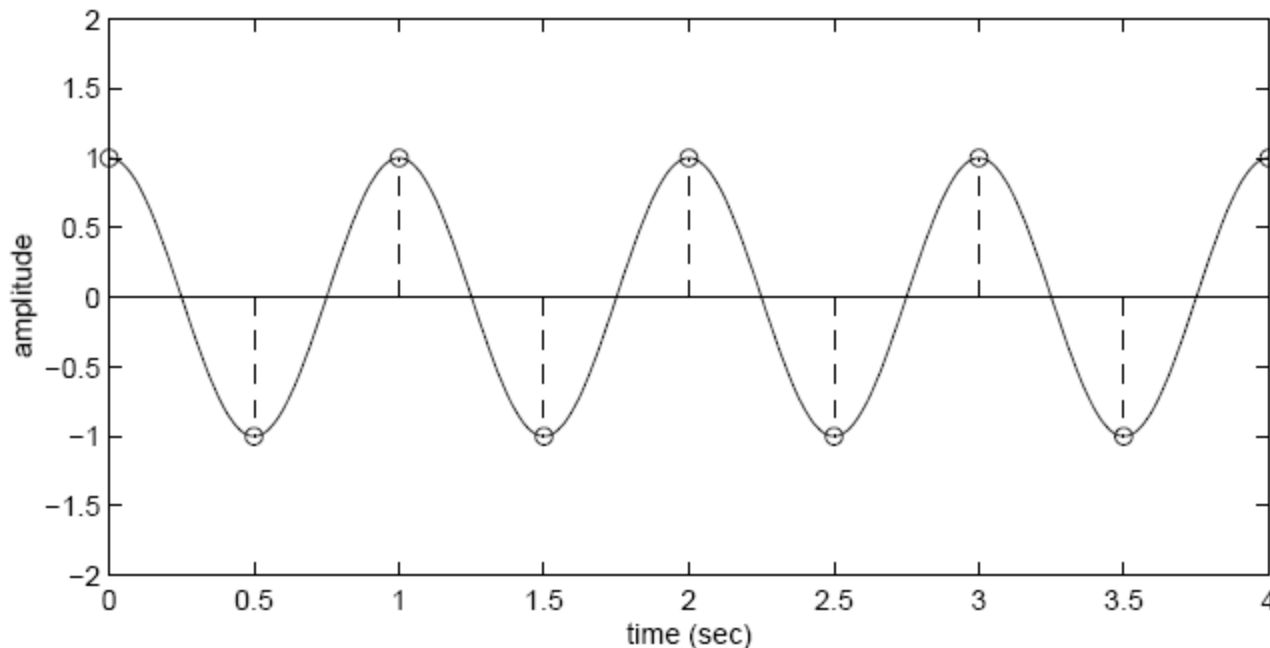
[Sampling]



- Suppose you have the following 1Hz signal being received
- How fast to sample, to capture the signal?



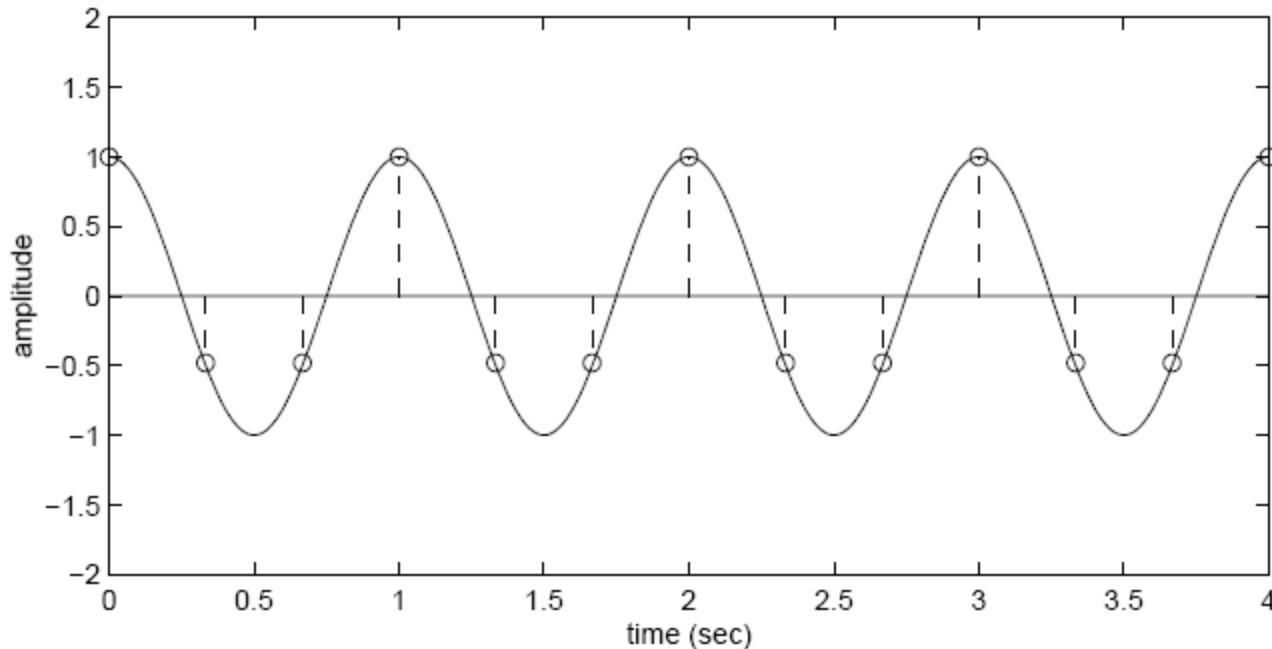
[Sampling]



- Sampling a 1 Hz signal at 2 Hz is enough
 - Captures every peak and trough



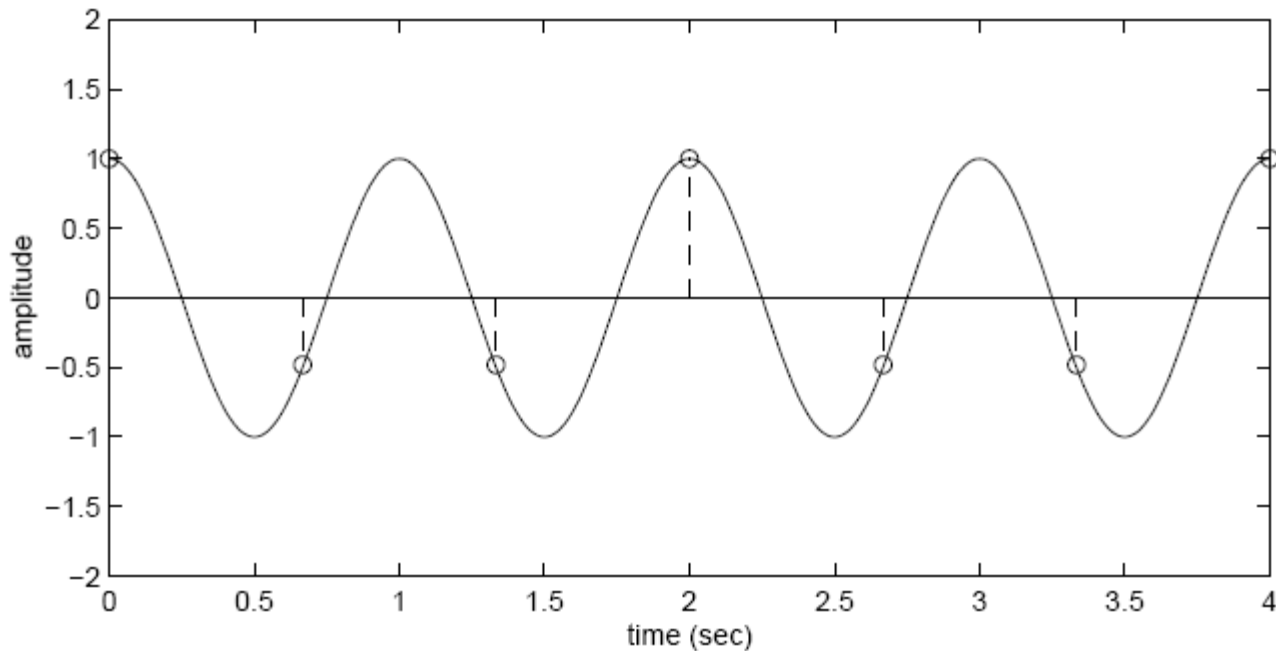
[Sampling]



- Sampling a 1 Hz signal at 3 Hz is also enough
 - In fact, more than enough samples to capture variation in signal



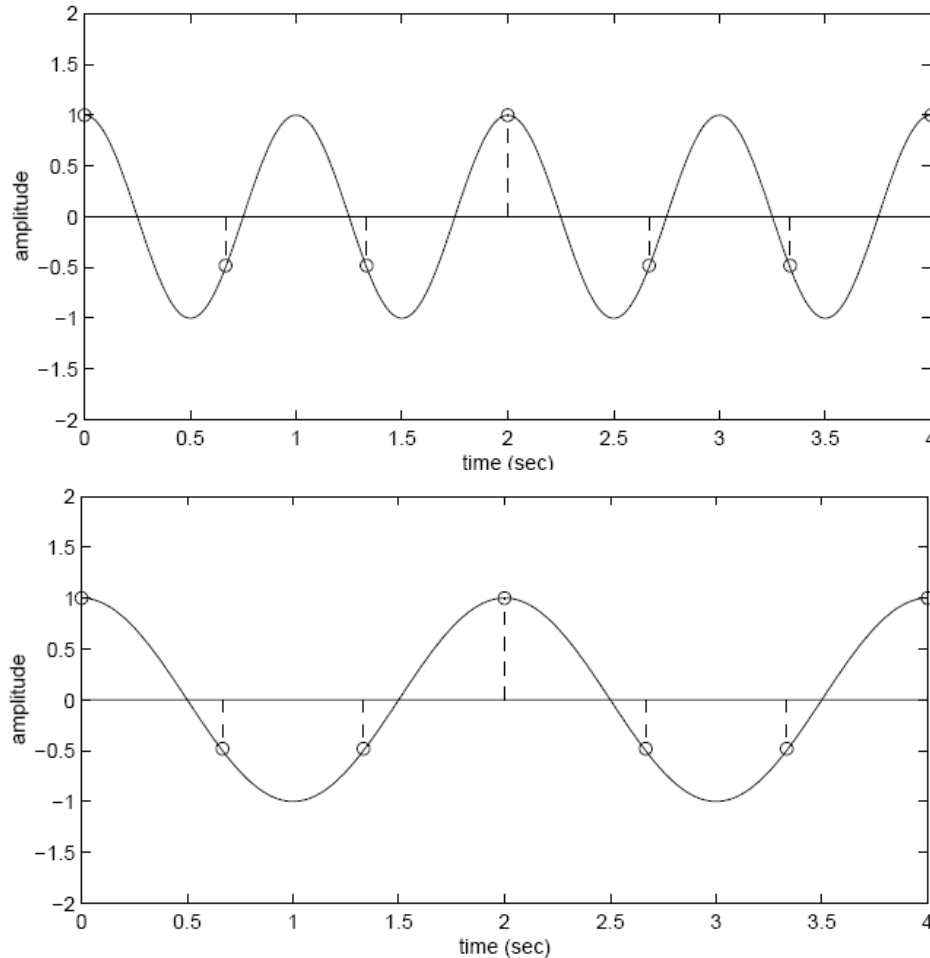
[Sampling]



- Sampling a 1 Hz signal at 1.5 Hz is not enough
 - Why?



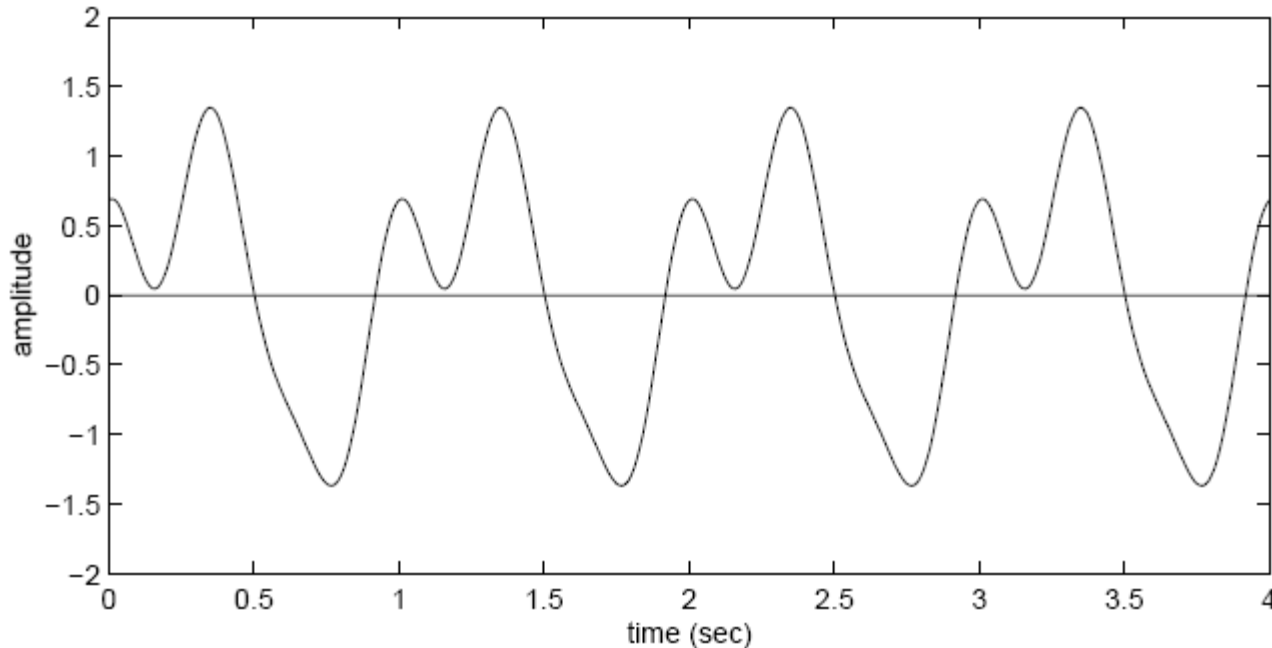
[Sampling]



- Sampling a 1 Hz signal at 1.5 Hz is not enough
 - Cant distinguish between multiple possible signals
 - Problem known as aliasing



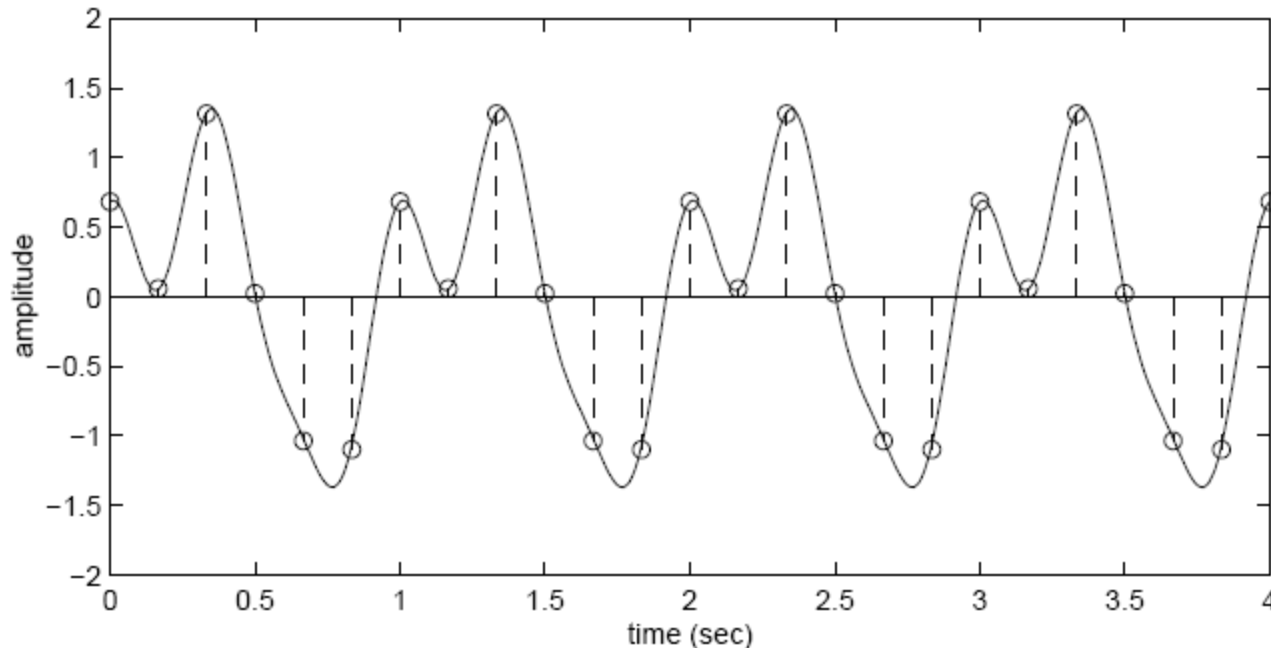
What about more complex signals?



- Fourier's theorem
 - Any continuous signal can be decomposed into a sum of sines and cosines at different frequencies
- Example: Sum of 1 Hz, 2 Hz, and 3 Hz sines
 - How fast to sample?



What about more complex signals?



- Fourier's theorem
 - Any continuous signal can be decomposed into a sum of sines and cosines at different frequencies
- Example: Sum of 1 Hz, 2 Hz, and 3 Hz sines
 - How fast to sample? --> **answer: 6 Hz**



[Generalizing the Examples]

- What limits baud rate?
- What data rate can a channel sustain?
- How is data rate related to bandwidth?
- How does noise affect these bounds?
- What else can limit maximum data rate?



[What Limits Baud Rate?]

- Baud rate
 - Typically limited by electrical signaling properties
- Changing voltages takes time
 - No matter how small the voltage or how short the wire
- Electronics
 - Slow compared to optics
- Baud rate
 - Can be as high as twice the bandwidth of communication



What Data Rate can a Channel Sustain? How is Data Rate Related to Bandwidth?

- Transmitting N distinct signals over a noiseless channel with bandwidth B , we can achieve at most a data rate of

Number of signals per second \longrightarrow $2B \log_2 N$ \longleftarrow Number of bits per signal

- Nyquist's Sampling Theorem (H. Nyquist, 1920's)



What Data Rate can a Channel Sustain?

How is Data Rate Related to Bandwidth?

- Transmitting **N** distinct signals over a noiseless channel with bandwidth **B**, we can achieve at most a data rate of

Number of symbols
per second

Baud rate

Number of **physical symbols**
transmitted per second

Number of bits per
signal

- Nyquist, 1920

Bit rate

Actual number of **data bits**
transmitted per second

Nyquist,

Relationship

Depends on the number of **bits**
encoded in each **symbol**



[Noiseless Capacity]

- Nyquist's theorem: $2B \log_2 N$
- Example 1: sampling rate of a phone line
 - $B = 4000$ Hz
 - $2B = 8000$ samples/sec.
 - sample every 125 microseconds



[Noiseless Capacity]

- Nyquist's theorem: $2B \log_2 N$
- Example 2: noiseless capacity
 - $B = 1200 \text{ Hz}$
 - $N = \text{each pulse encodes 16 symbols}$
 - $C =$



[Noiseless Capacity]

- Nyquist's theorem: $2B \log_2 N$
- Example 2: noiseless capacity
 - $B = 1200 \text{ Hz}$
 - $N = \text{each pulse encodes 16 symbols}$
 - $C = 2B \log_2 (N) = D \times \log_2 (N)$
 $= 2400 \times 4 = 9600 \text{ bps}$



How does Noise affect these Bounds?

- Noise

- Blurs the symbols, reducing the number of symbols that can be reliably distinguished

- Claude Shannon (1948)

- Extended Nyquist's work to channels with additive white Gaussian noise (a good model for thermal noise)

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

where

C is the maximum supportable bit rate

B is the channel bandwidth

S/N is the ratio between signal power
and in-band noise power

← This N is noise
not number of
symbols



How does Noise affect these Bounds?

■ Noise

- Blurs the symbols, reducing the number of symbols that can be reliably distinguished

■ Claude Shannon (1948)

- Extended Nyquist's work to channels with additive white Gaussian noise (a good model for thermal noise)

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

- Represents error free capacity
 - also used to calculate the noise that can be tolerated to achieve a certain rate through a channel
- Result is based on many assumptions
 - Formula assumes white noise (thermal noise)
 - Impulse noise is not accounted for
 - Various types of distortion are also not accounted for



[Noisy Capacity]

$$\text{SNR(dB)} = 10 \log_{10} \left(\frac{P_{\text{signal}}}{P_{\text{noise}}} \right)$$

- Telephone channel
 - 3400 Hz at 40 dB SNR

decibels (dB) is a **logarithmic** unit of measurement that expresses the magnitude of a physical quantity (usually power or intensity) relative to a specified or implied reference level



[Decibels]

- A ratio between signal powers is expressed in decibels

$$\text{decibels (db)} = 10\log_{10}(P_1 / P_2)$$

- Used in many contexts
 - The loss of a wireless channel
 - The gain of an amplifier
- Note that dB is a relative value
 - Can be made absolute by picking a reference point
 - Decibel-Watt – power relative to 1W
 - Decibel-milliwatt – power relative to 1 milliwatt



[Signal-to-Noise Ratio]

- Signal-to-noise ratio (SNR, or S/N)
 - Ratio of
 - the power in a signal
 - to
 - the power contained in the noise
 - Typically measured at a receiver
- A high SNR
 - High-quality signal
- Low SNR
 - May be hard to “extract” the signal from the noise
- SNR sets upper bound on achievable data rate

$$(SNR)_{dB} = 10 \log_{10} \frac{\text{signal power}}{\text{noise power}}$$



[Noisy Capacity]

$$\text{SNR(dB)} = 10 \log_{10} \left(\frac{P_{\text{signal}}}{P_{\text{noise}}} \right)$$

- Telephone channel

- 3400 Hz at 40 dB SNR
- $C = B \log_2 (1 + S/N)$ bits/s
- SNR = 40 dB

$$40 = 10 \log_{10} (S/N)$$

$$S/N = 10,000$$

- $C = 3400 \log_2 (10001) = 44.8 \text{ kbps}$



More examples of Nyquist and Shannon Formulas

- Spectrum of a channel between 3 MHz and 4 MHz ; $\text{SNR}_{\text{dB}} = 24 \text{ dB}$

$$B =$$

$$\text{SNR} =$$

- Using Shannon's formula

$$C = B \log_2 (1 + S/N)$$



More examples of Nyquist and Shannon Formulas

- Spectrum of a channel between 3 MHz and 4 MHz ; $\text{SNR}_{\text{dB}} = 24 \text{ dB}$

$$B = 4 \text{ MHz} - 3 \text{ MHz} = 1 \text{ MHz}$$

$$\text{SNR}_{\text{dB}} = 24 \text{ dB} = 10 \log_{10}(\text{SNR})$$

$$\text{SNR} = 251$$

- Using Shannon's formula

$$C = B \log_2 (1 + S/N)$$
$$C = 10^6 \times \log_2 (1 + 251) \approx 10^6 \times 8 = 8 \text{ Mbps}$$



More examples of Nyquist and Shannon Formulas

- How many signaling levels are required?

$$C = 2B \log_2 M$$



More examples of Nyquist and Shannon Formulas

- How many signaling levels are required?

$$C = 2B \log_2 M$$

$$8 \times 10^6 = 2 \times (10^6) \times \log_2 M$$

$$4 = \log_2 M$$

$$M = 16$$

- Look out for: dB versus linear values, \log_2 versus \log_{10}



[Summary of Encoding]

- Problems: attenuation, dispersion, noise
- Digital transmission allows periodic regeneration
- Variety of binary voltage encodings
 - High frequency components limit to short range
 - More voltage levels provide higher data rate
- Modulation schemes
 - Amplitude, frequency, phase, and combinations
 - Quadrature amplitude modulation: amplitude and phase, many signals
- Nyquist (noiseless) and Shannon (noisy) limits on data rates

