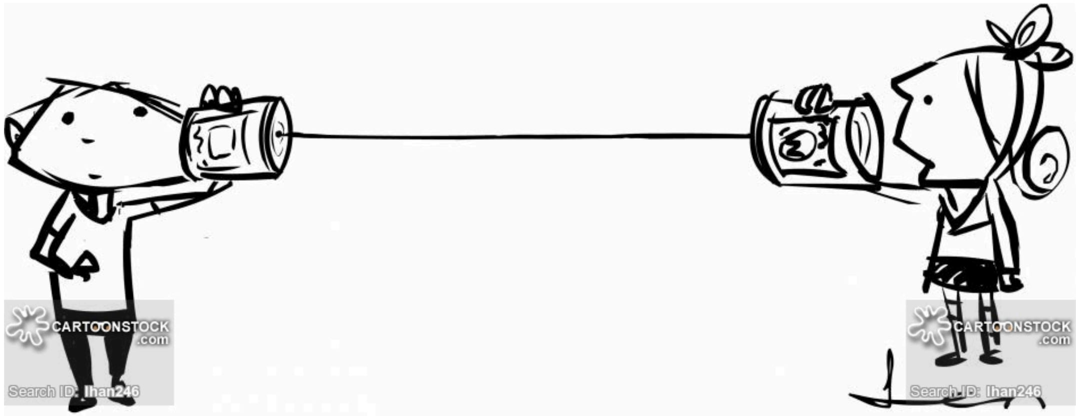
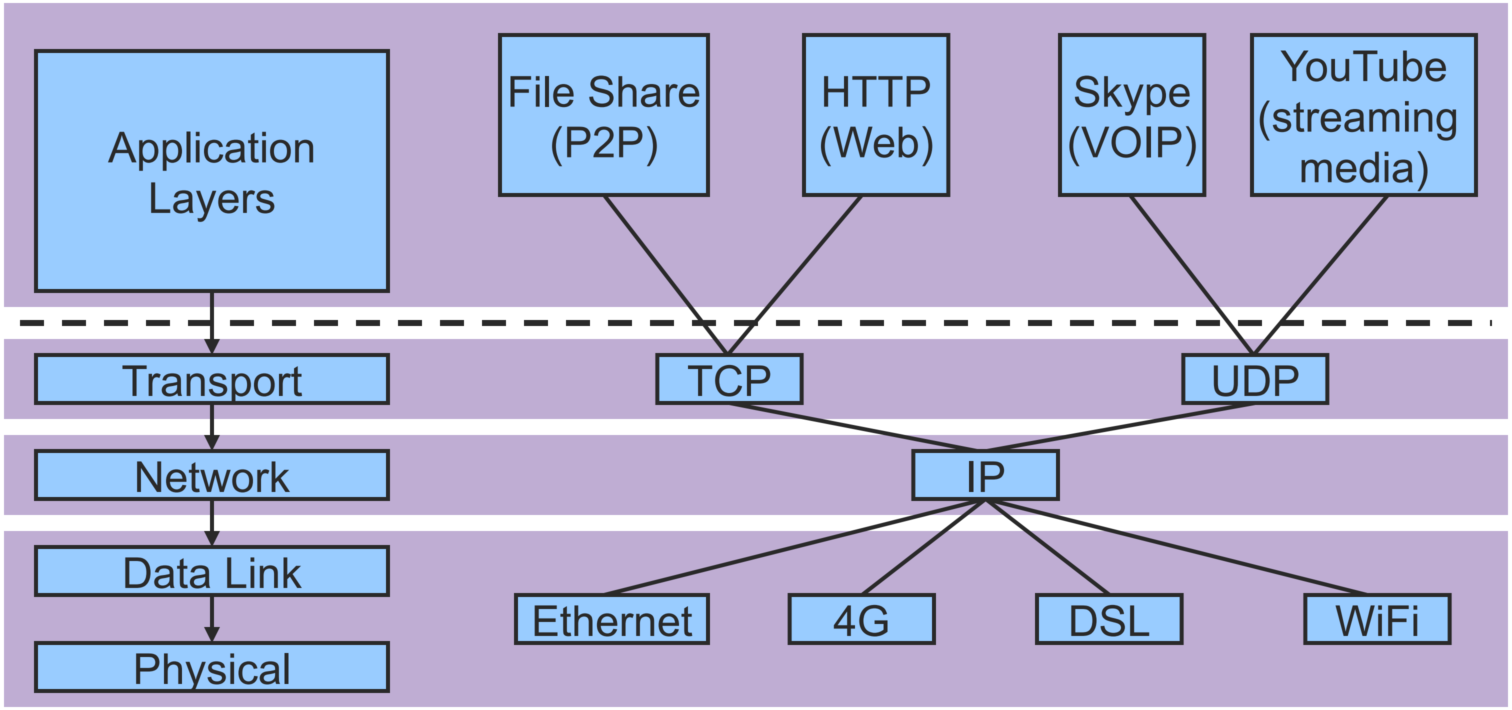
Direct Link Networks - Encoding

Reading: Peterson and Davie, Chapter 2



"I said, how do you send a text with this thing?"

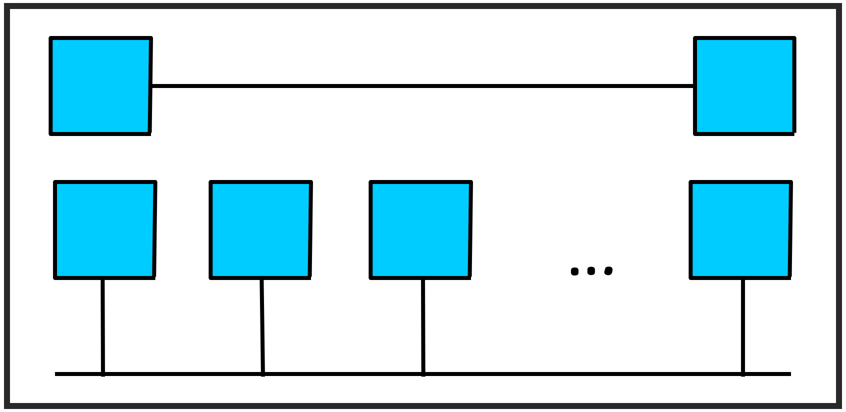
Where are we?



Today

Direct Link Networks

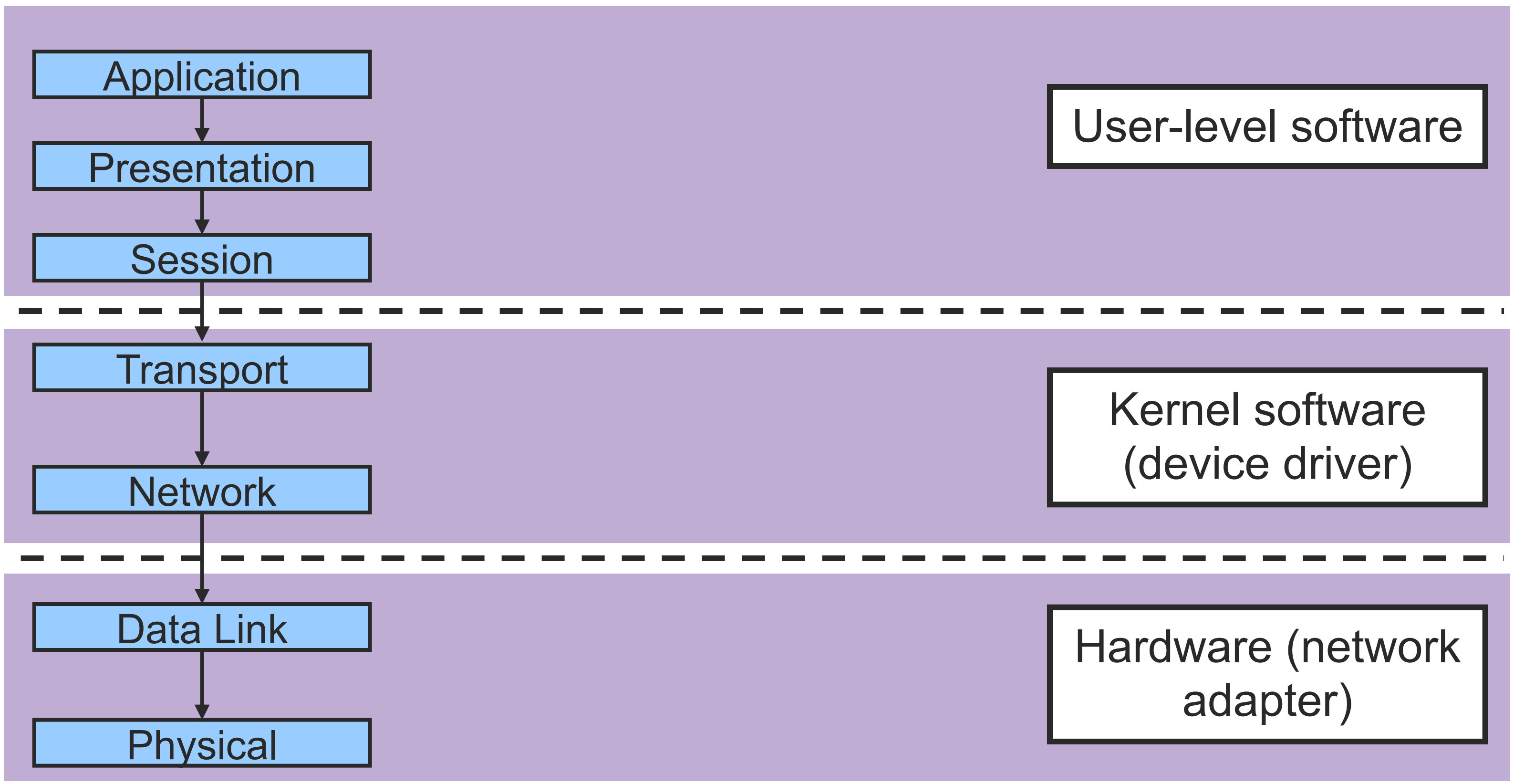
- All hosts are directly connected by a physical medium
- Key points
  - Encoding and Modulation
  - Framing
  - Error Detection
  - Medium Access Control



Internet Protocols

Encoding

Framing, error detection, medium access control



Direct Link Networks - Outline

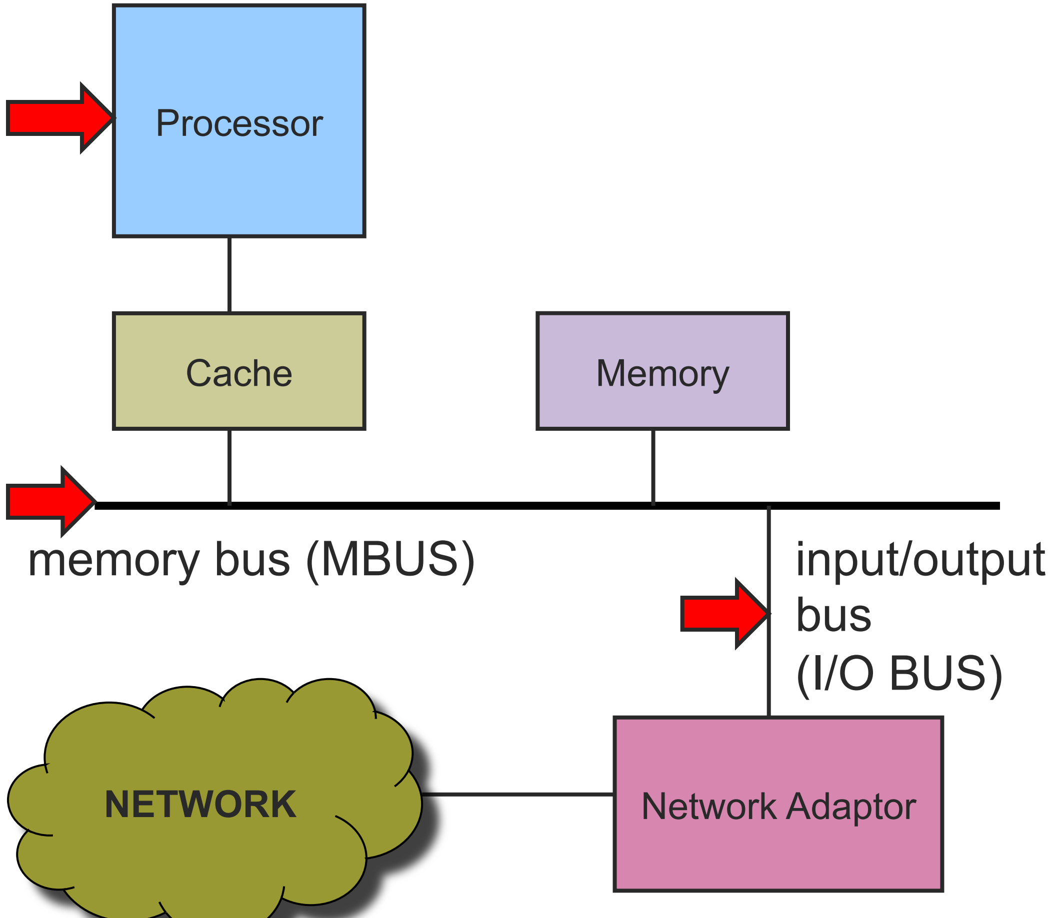
- Hardware building blocks
- Encoding
- Framing
- Error detection
- Multiple access media (MAC examples)
- Network adapters

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

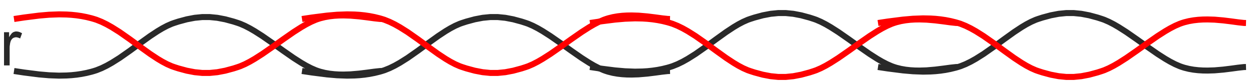
- Links
  - Physical medium
    - Copper wire with electronic signaling
    - Glass fiber with optical signaling
    - Wireless with electromagnetic (radio, infrared, microwave) signaling
    - Two cups and a string

Links - Copper

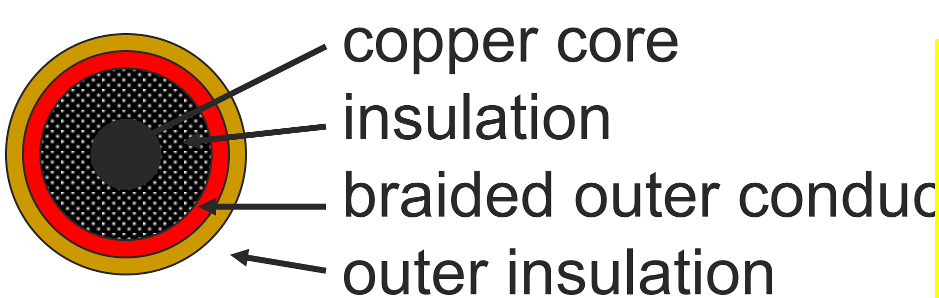
- Copper-based Media
  - Category 5/6 Twisted Pair 10-1Gbps 100m
  - ThinNet Coaxial Cable 10-100Mbps 200m
  - ThickNet Coaxial Cable 10-100Mbps 500m

more twists, less crosstalk, better signal over longer distances

twisted pair



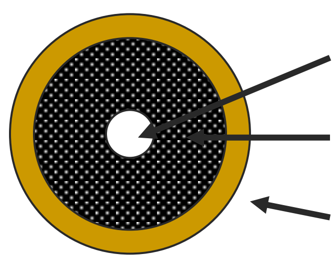
coaxial cable (coax)



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



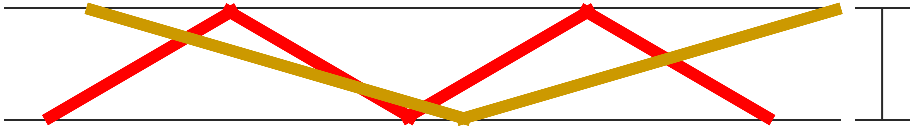
Links - Optical

- 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)

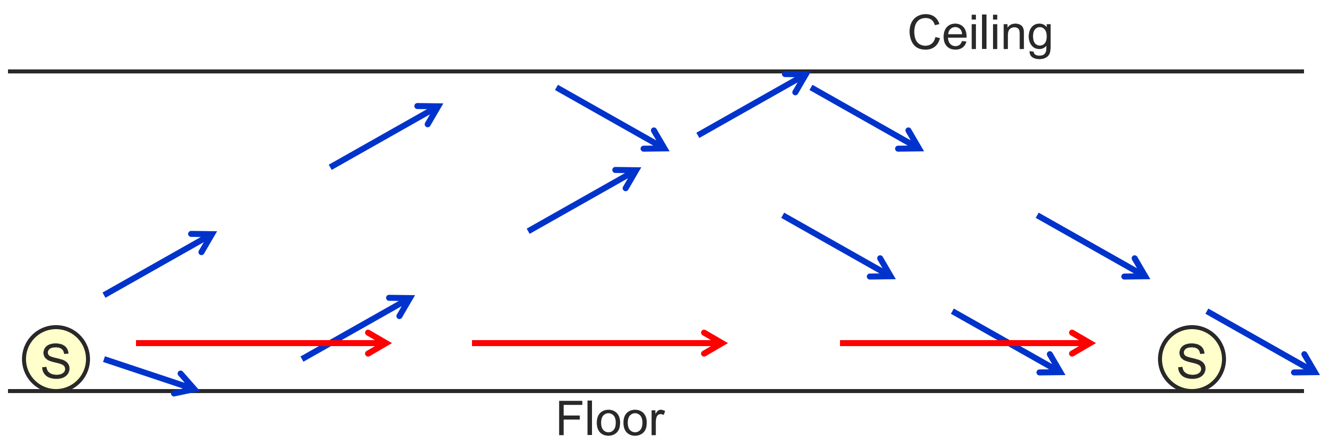
Links - Wireless

- 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

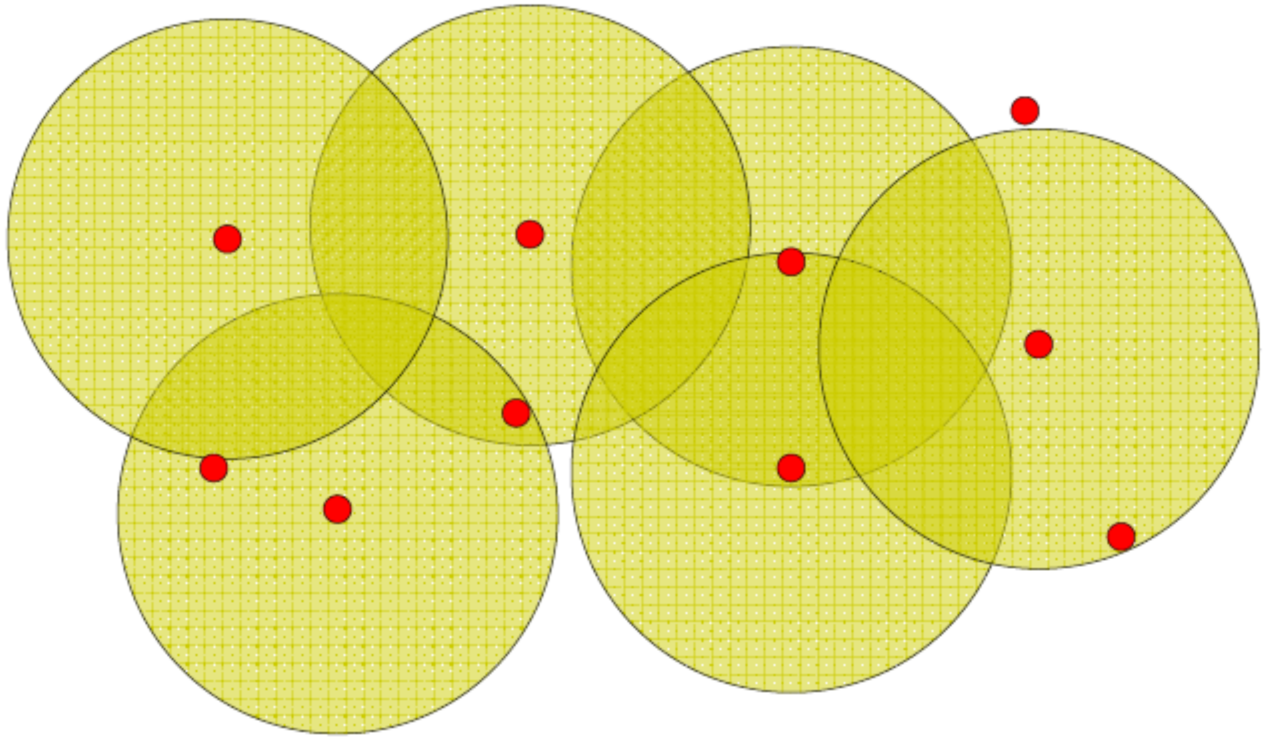
- Signal power attenuates by about ~r^2 factor for omni-directional antennas in free space
  - r is the distance between the sender and the receiver
- The exponent in the factor is different depending on placement of antennas
  - Less than 2 for directional antennas
  - Faster attenuation
    - Exponent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

Wireless Multipath Effects

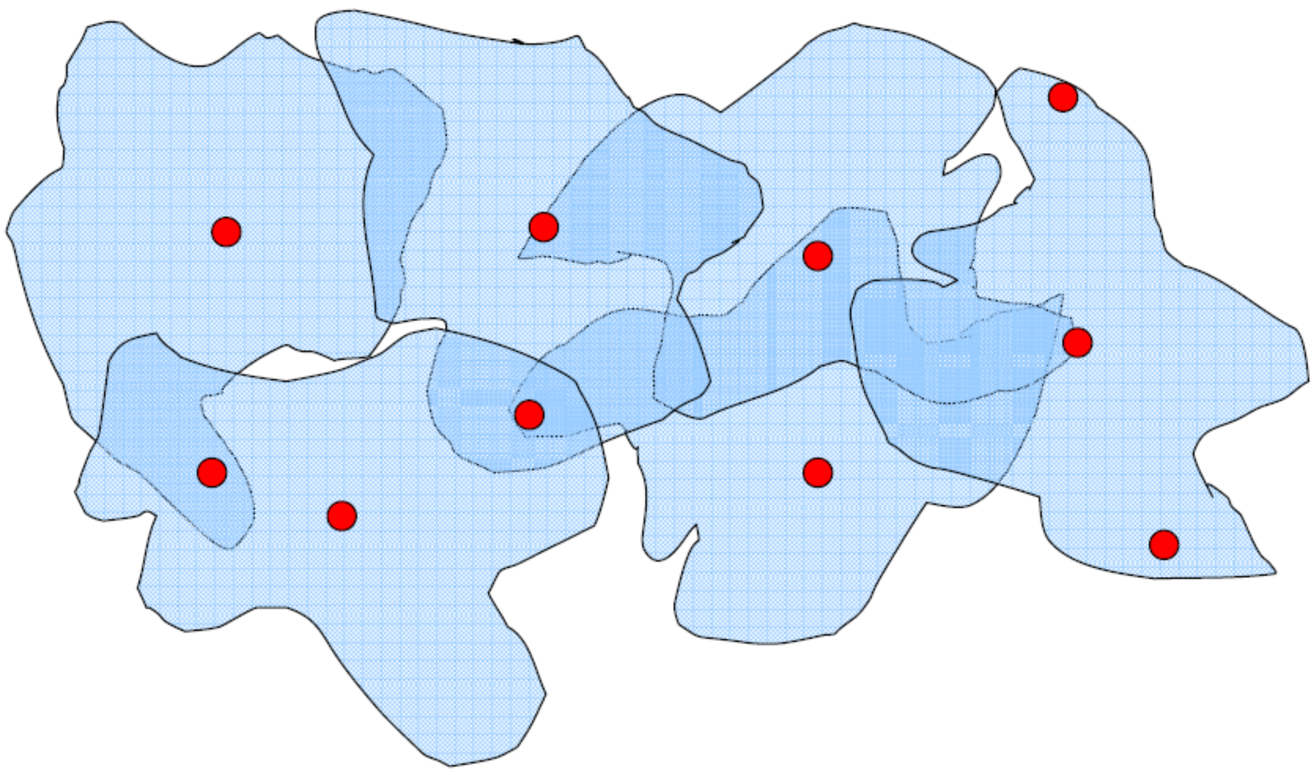


- Signals bounce off surfaces and interfere with one another
- What if signals are out of phase?
  - Orthogonal signals cancel each other and nothing is received!

What is a Wireless “Link”?



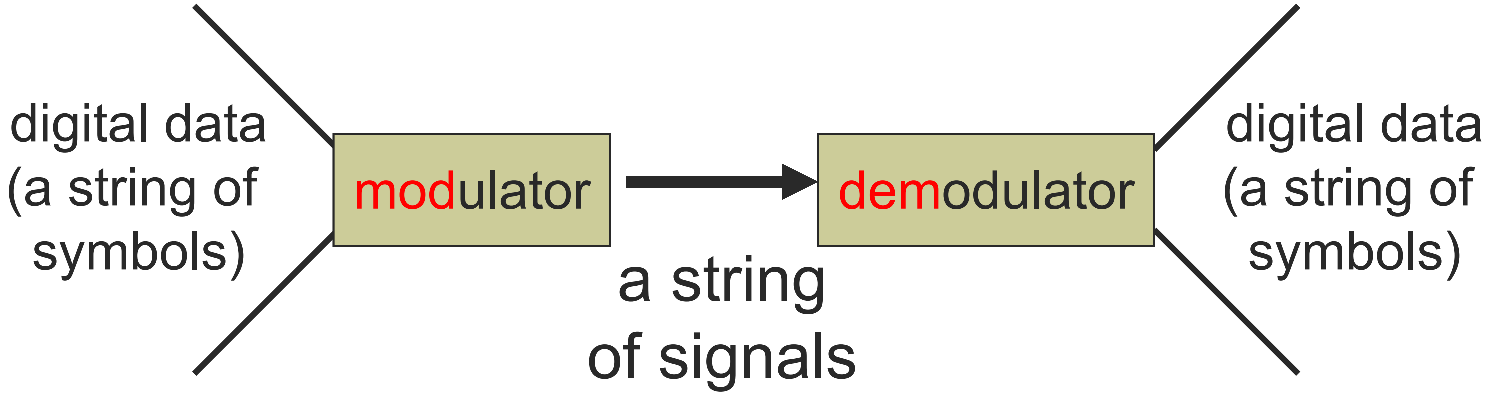
What is a Wireless “Link”?



Wireless Bit Errors

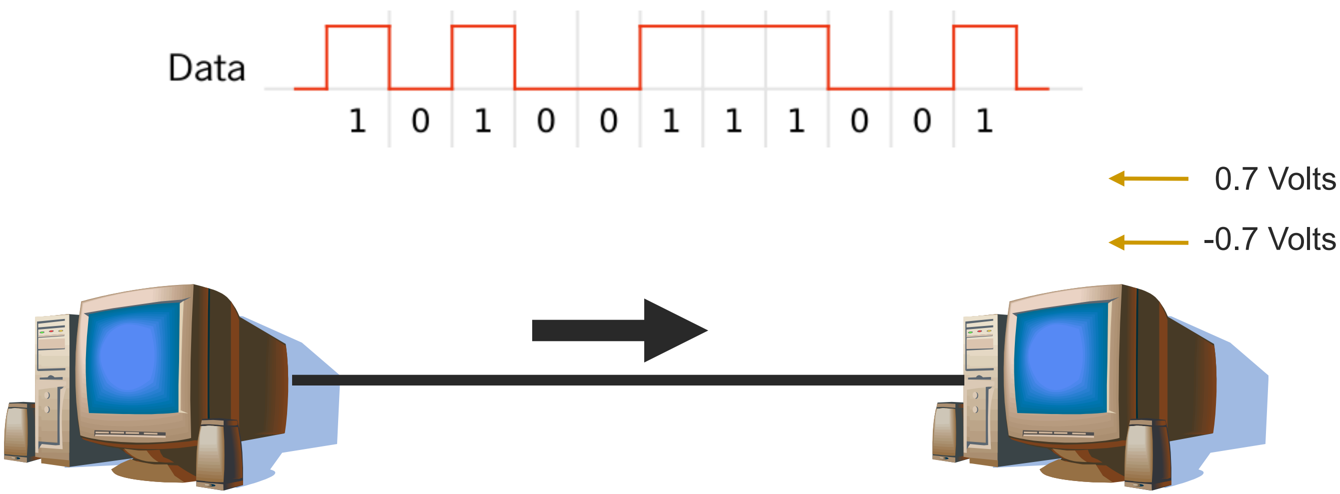
- The lower the SNR (Signal/Noise) the higher the Bit Error Rate (BER)
- How can we deal with this?
  - Make the signal stronger
- Why is this not always a good idea?
  - Increased signal strength requires more power
  - Increases the interference range of the sender, so you interfere with more nodes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

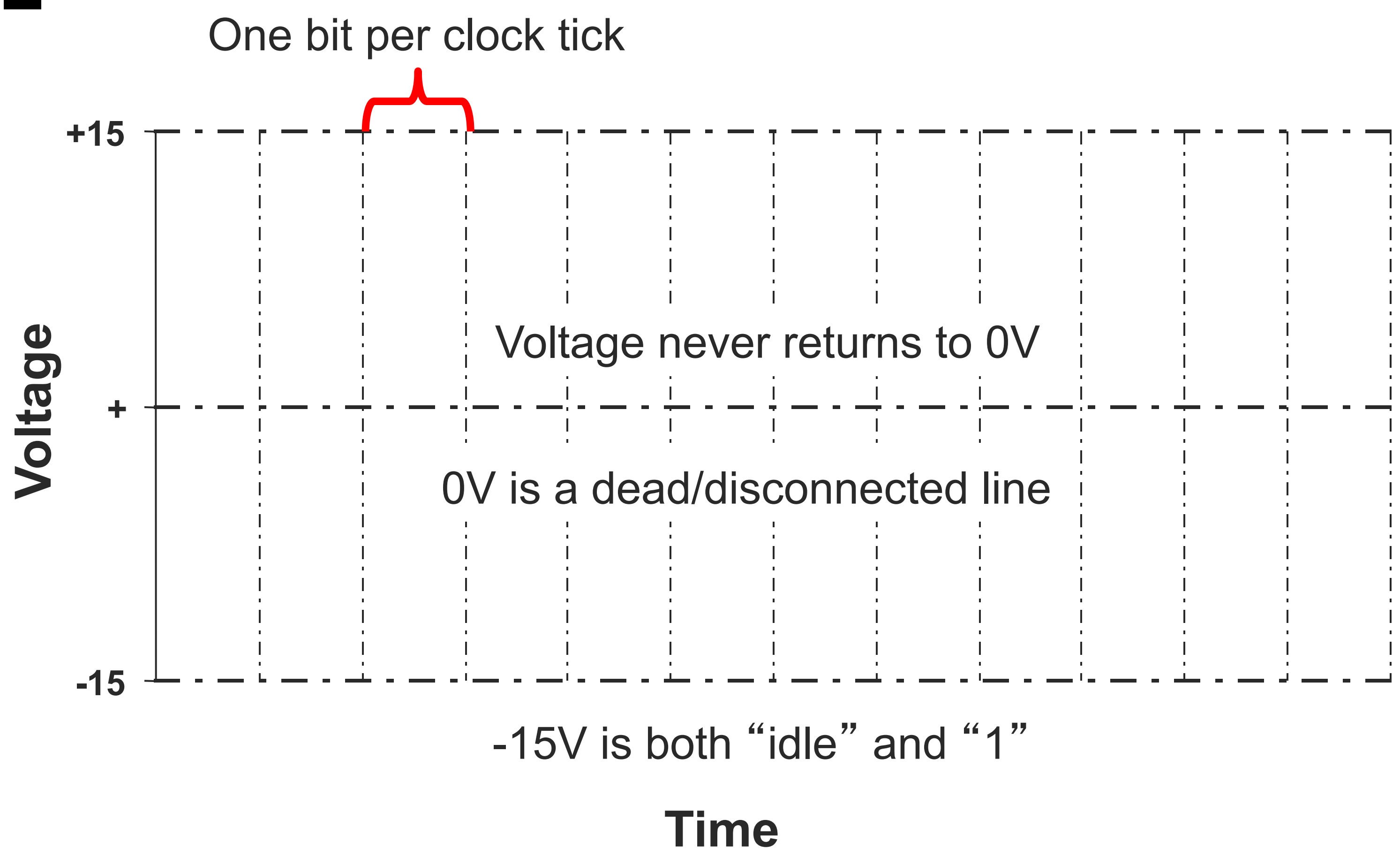
Analog vs. Digital Transmission

- 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

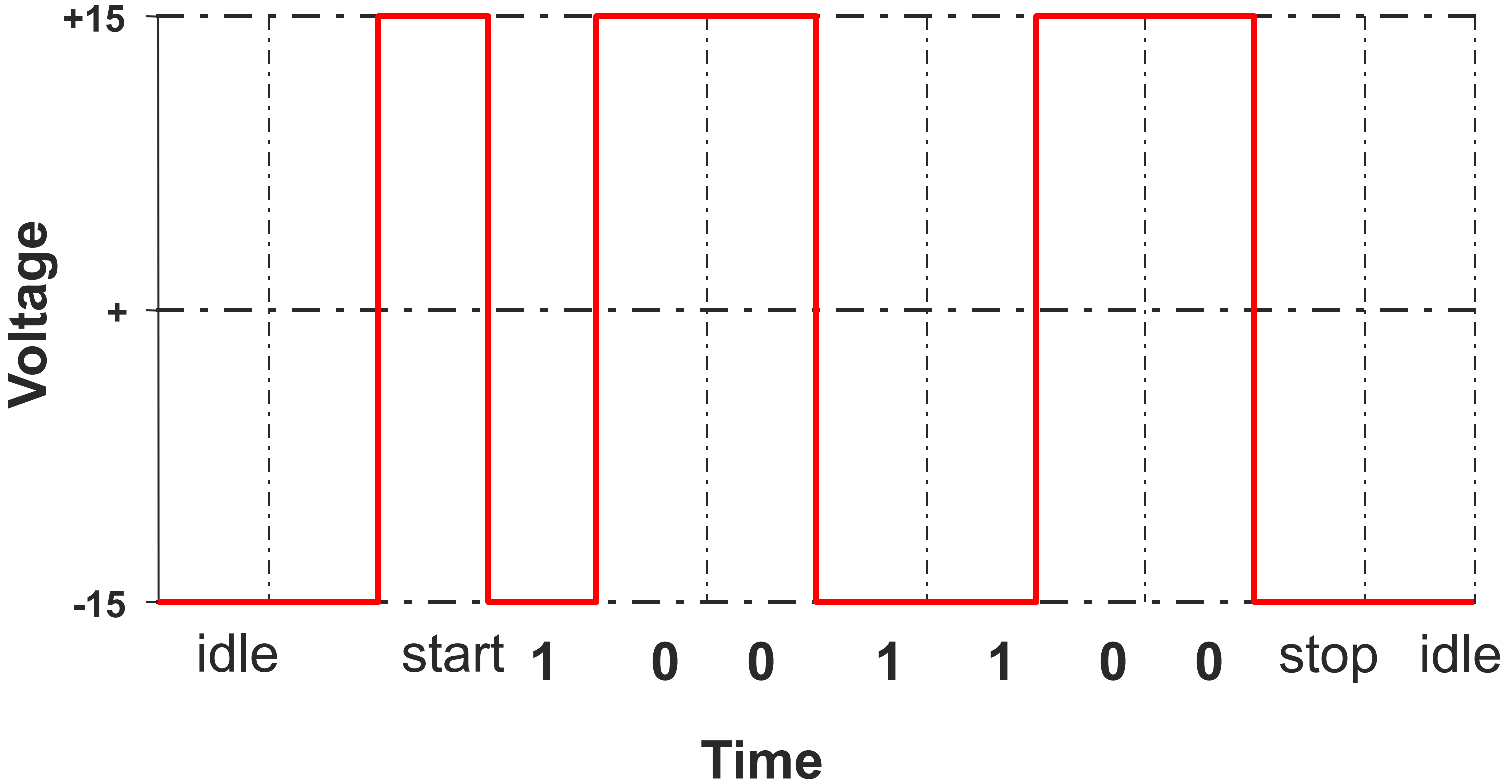
RS-232 Timing Diagram



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

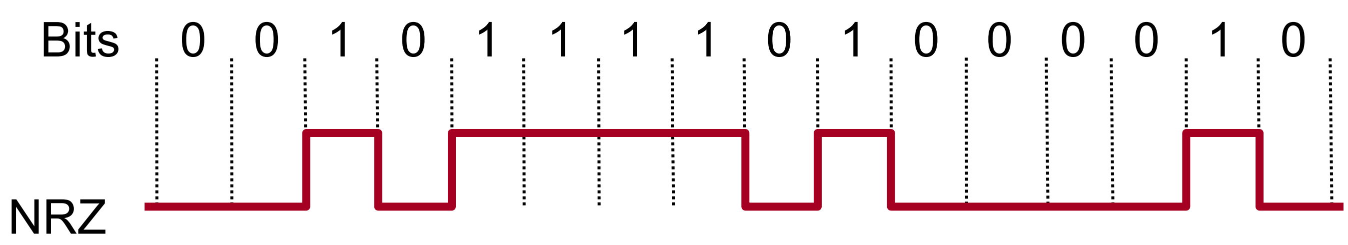


Voltage Encoding

- 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

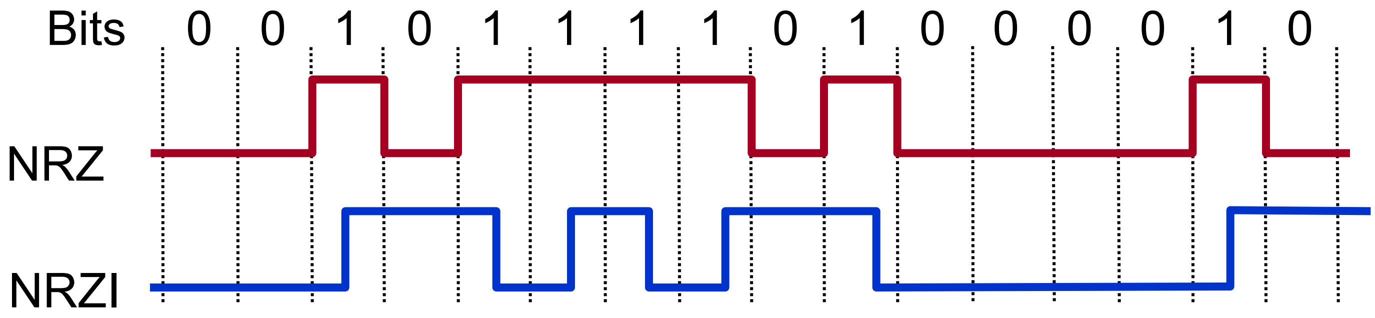
Non-Return to Zero (NRZ)

- Signal to Data
  - High ⇨ 1
  - Low ⇨ 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



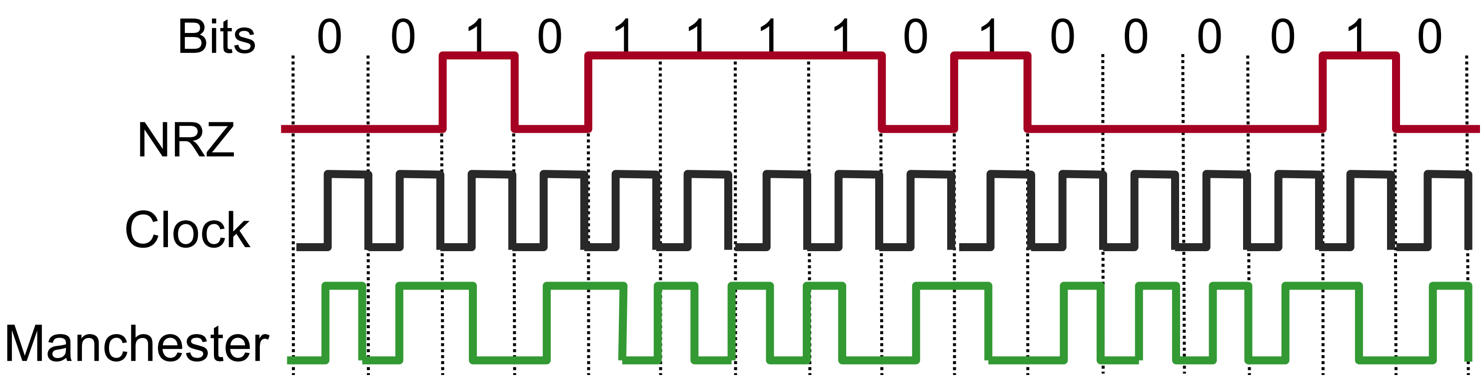
Non-Return to Zero Inverted (NRZI)

- Signal to Data
  - Transition ⇨ 1
  - Maintain ⇨ 0
- Comments
  - Solves series of 1s, but not 0s



Manchester Encoding

- Signal to Data
  - XOR NRZ data with clock
  - High to low transition ⇨ 1
  - Low to high transition ⇨ 0
- Comments
  - (used by IEEE 802.3—10 Mbps Ethernet)
  - Solves clock recovery problem
  - Only 50% efficient (½ 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

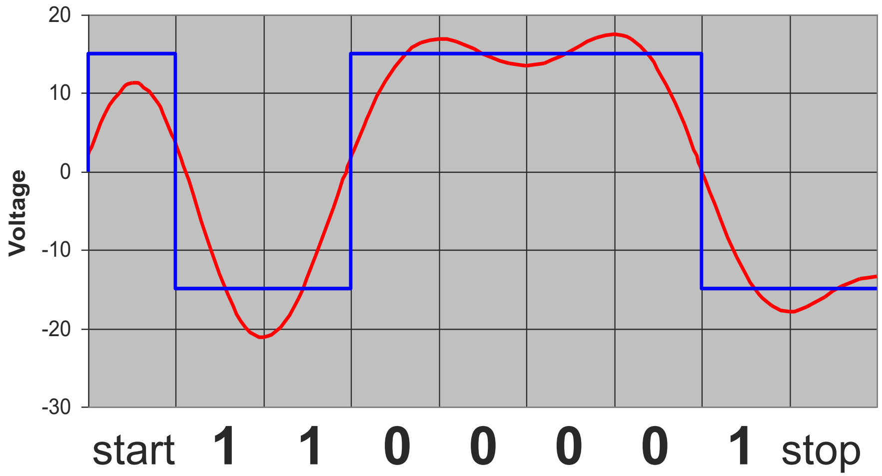
- 0000 ⇒ 11110
- 0001 ⇒ 01001
- 0010 ⇒ 10100
- 0011 ⇒ 10101
- 0100 ⇒ 01010
- 0101 ⇒ 01011
- 0110 ⇒ 01110
- 0111 ⇒ 01111
- 1000 ⇒ 10010
- 1001 ⇒ 10011
- 1010 ⇒ 10110
- 1011 ⇒ 10111
- 1100 ⇒ 11010
- 1101 ⇒ 11011
- 1110 ⇒ 11100
- 1111 ⇒ 11101

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

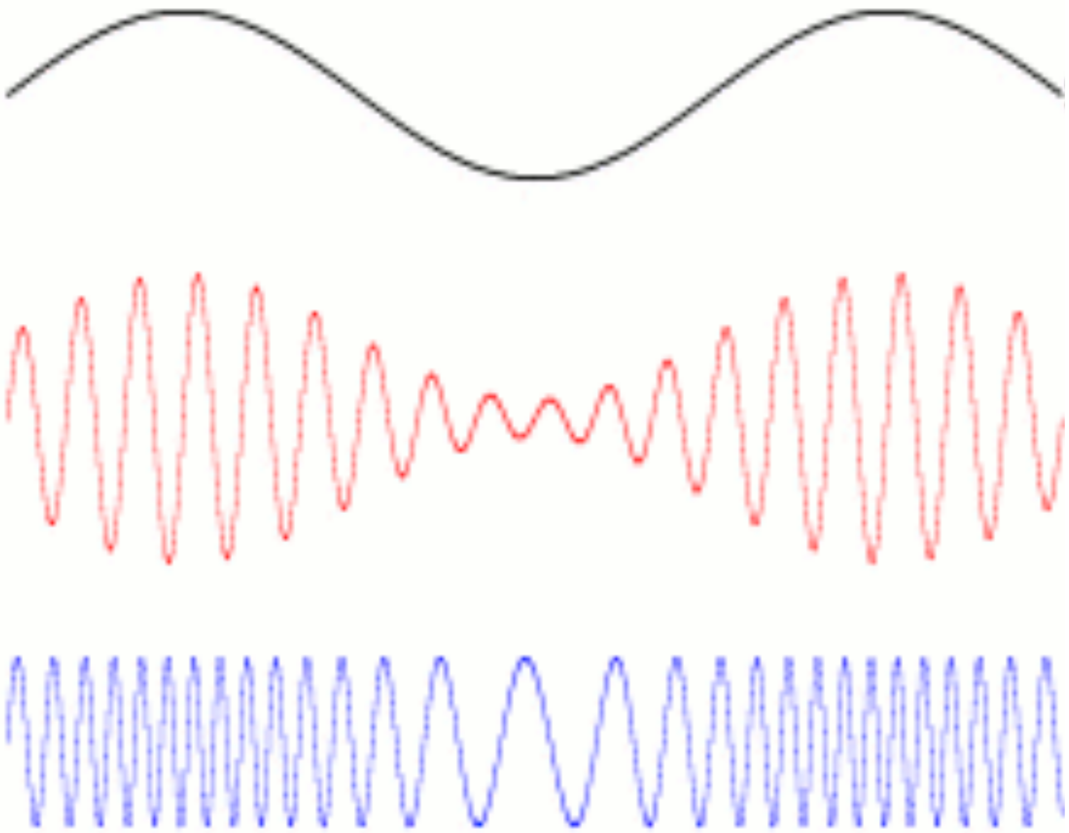


Binary Voltage Encodings

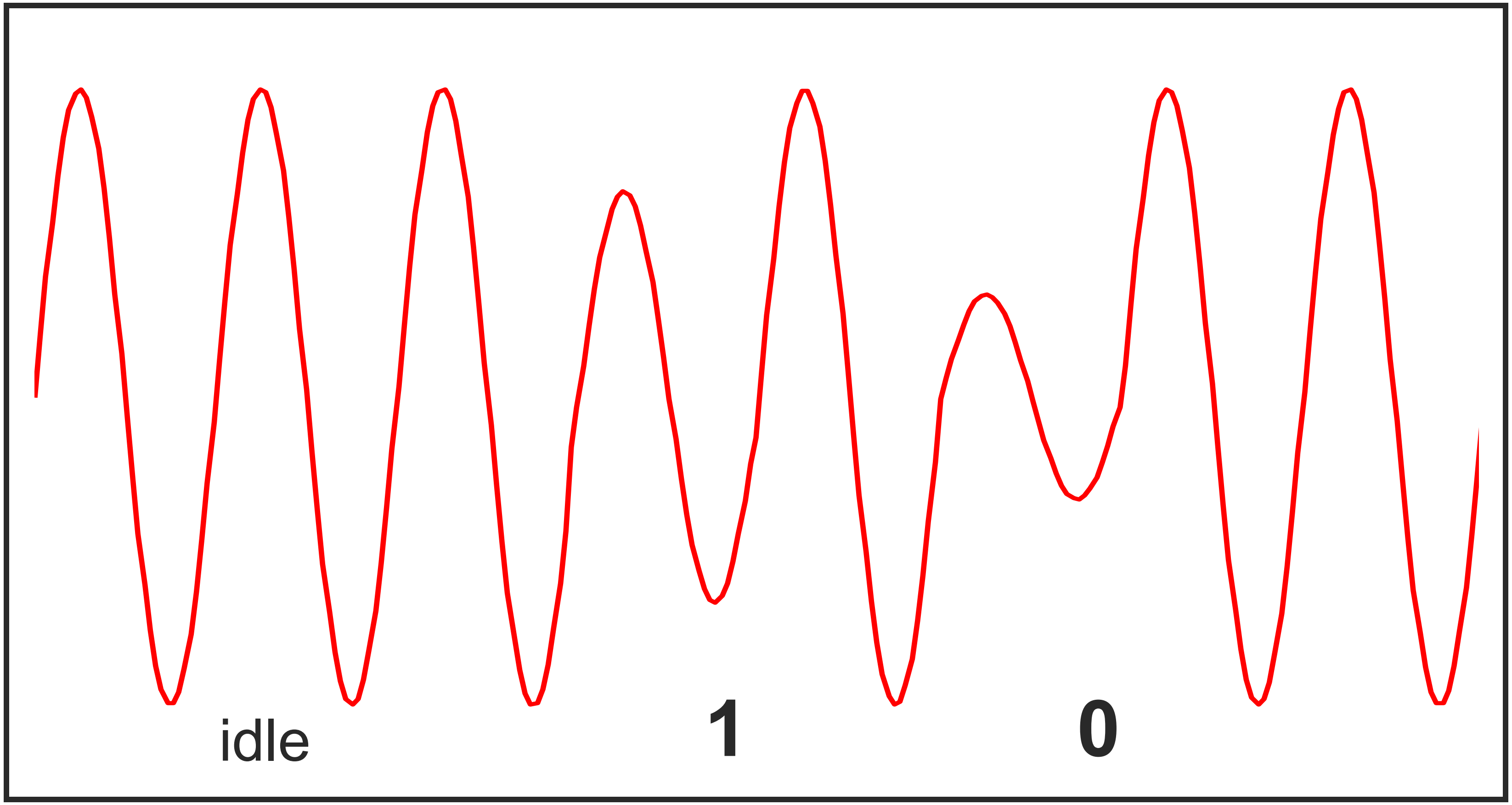
- Problem with binary voltage (square wave) encodings
  - Very wide (Infinite) frequency range required, implying
    - Significant dispersion
    - Uneven attenuation
  - Prefer to use a narrower frequency band
- Types of modulation
  - Amplitude (AM)
  - Frequency (FM)
  - Phase/phase shift
  - Combinations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

Example: AM/FM for continuous signal

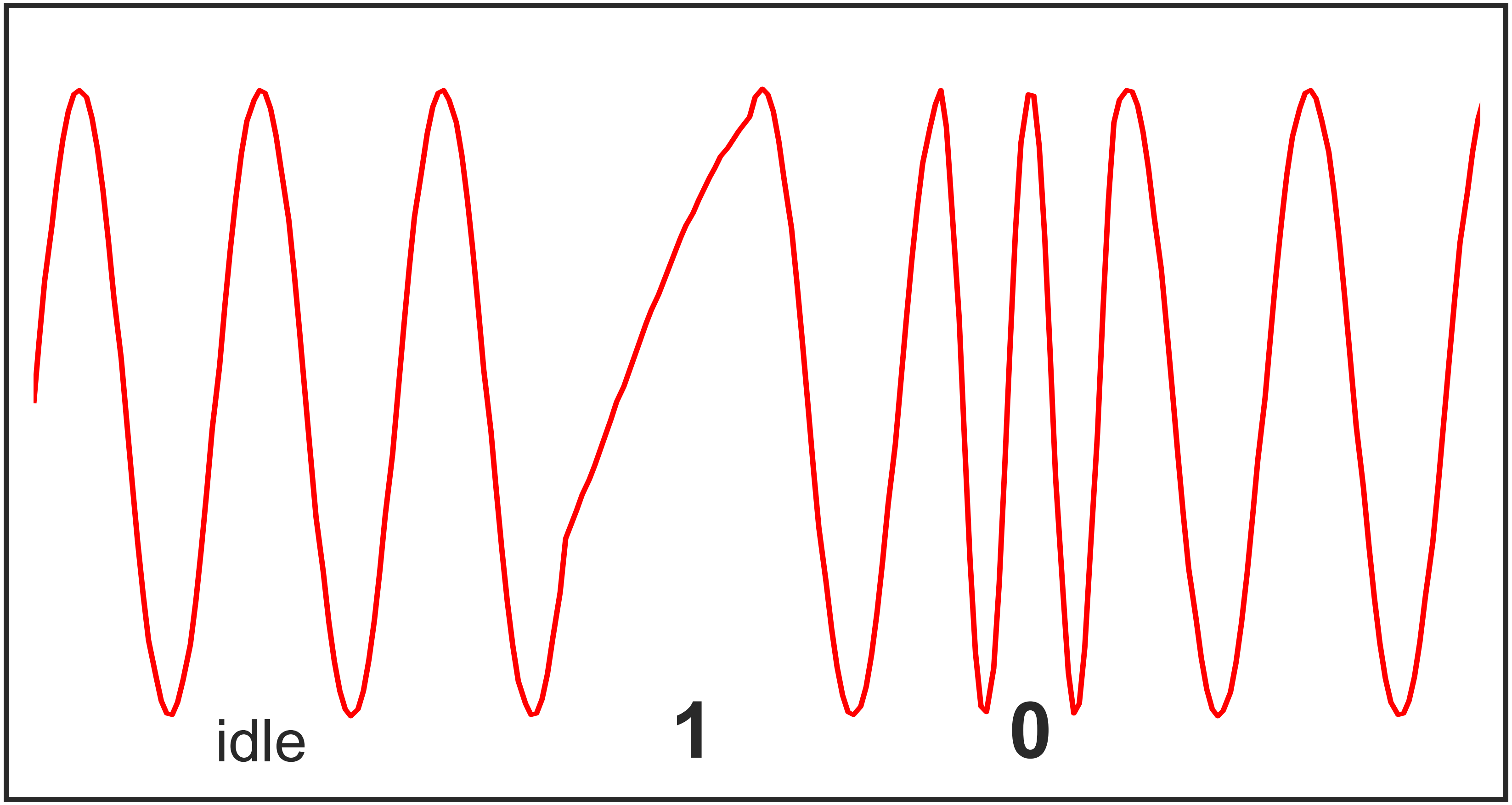
- Original signal
- Amplitude modulation
- Frequency modulation



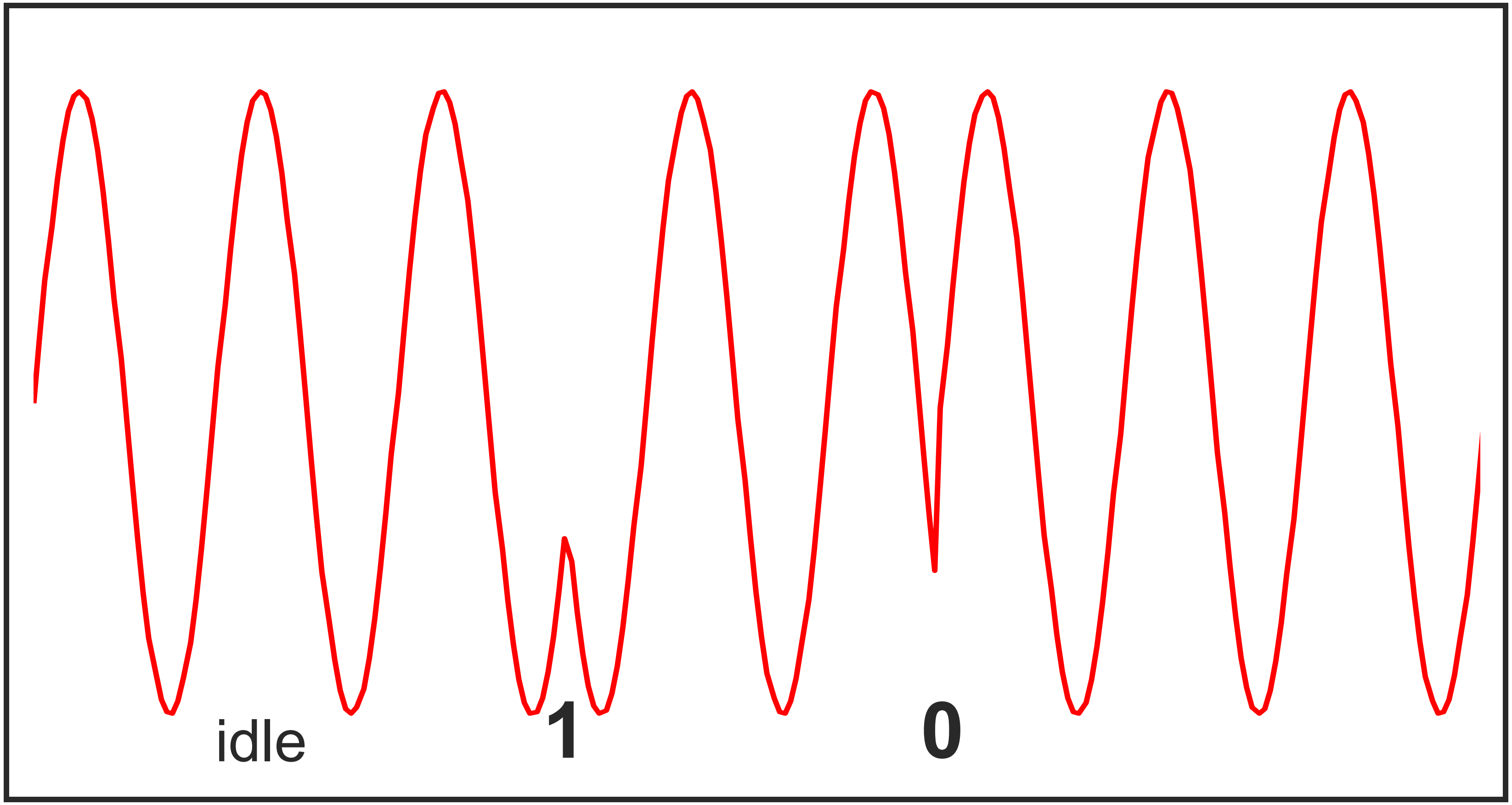
Amplitude Modulation



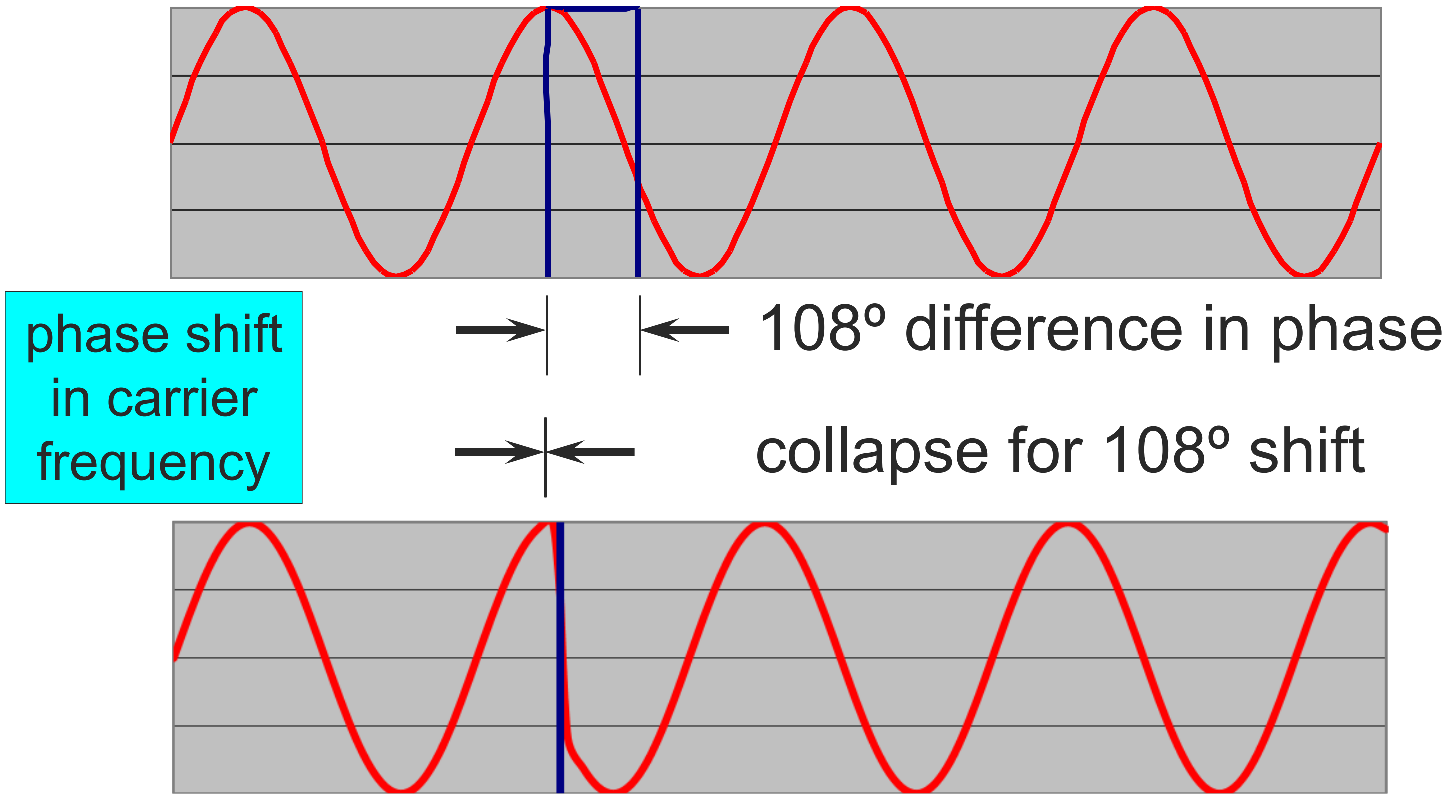
Frequency Modulation



Phase Modulation



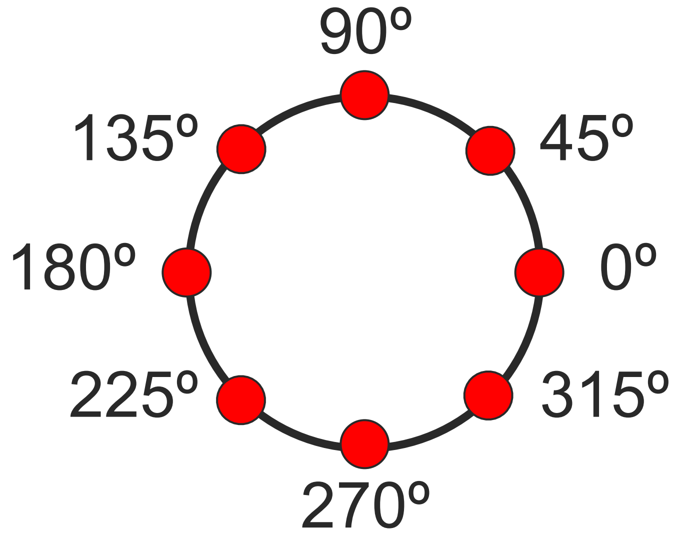
Phase Modulation



Phase Modulation Algorithm

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

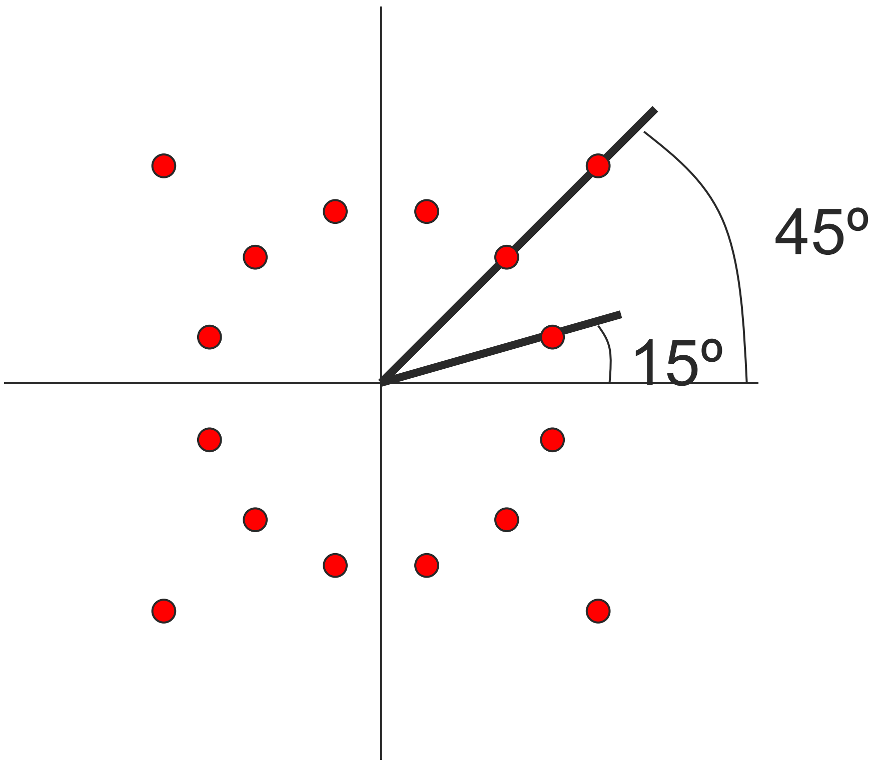
[8-symbol example]



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

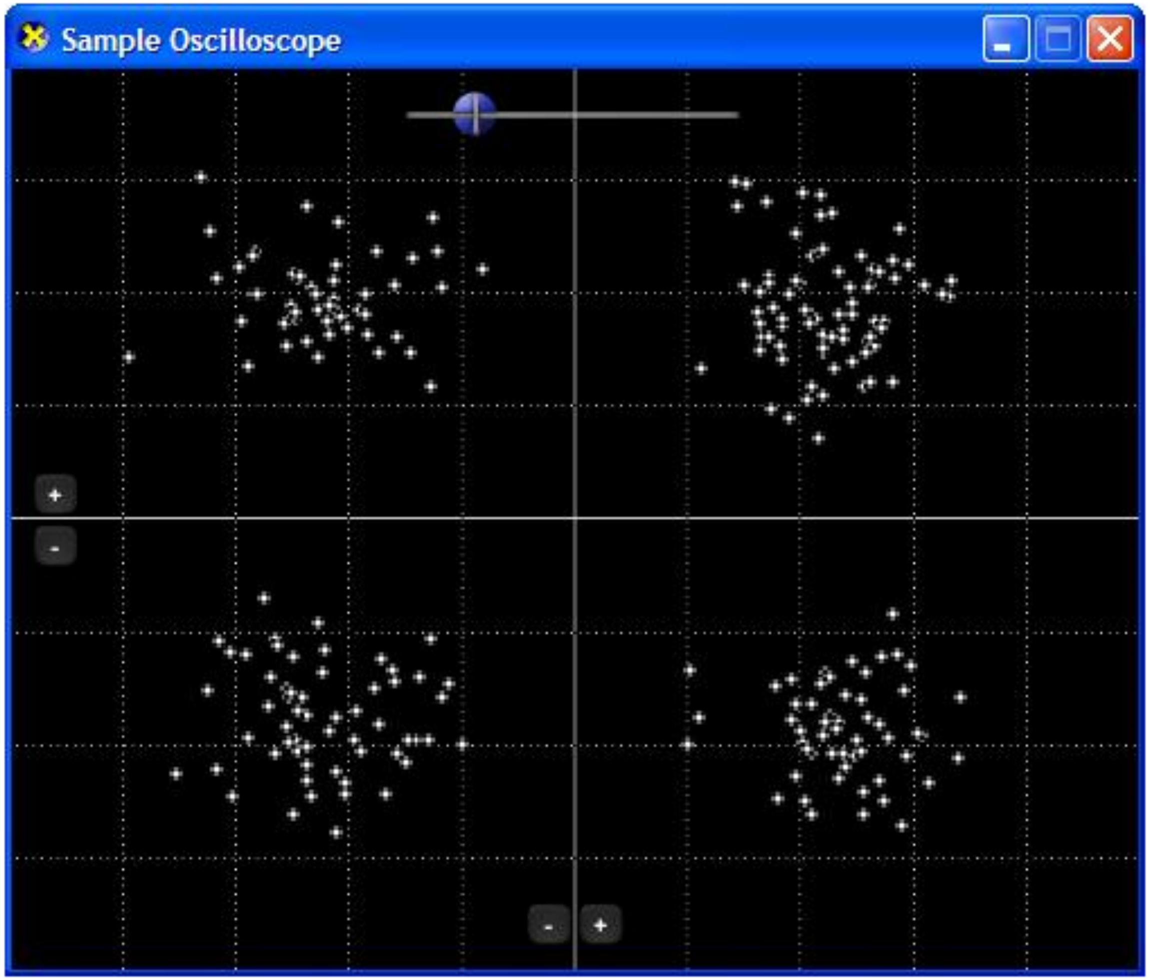
Constellation Pattern for V.32 QAM



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

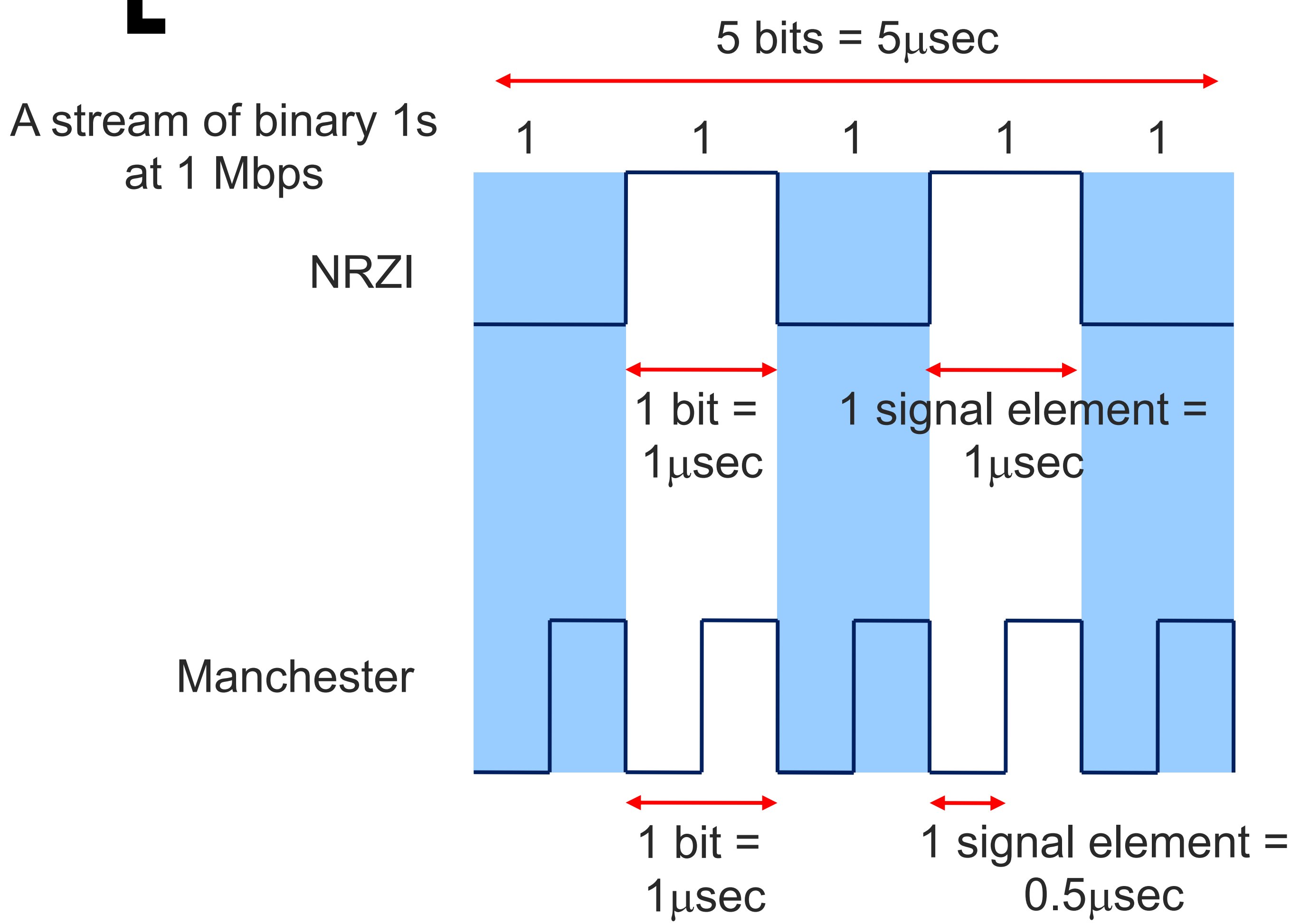
Example constellation



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 x 2400 = 9600 bps
- Points in constellation diagram
  - Chosen to maximize error detection
  - Process called trellis coding

Modulation (Baud) Rate

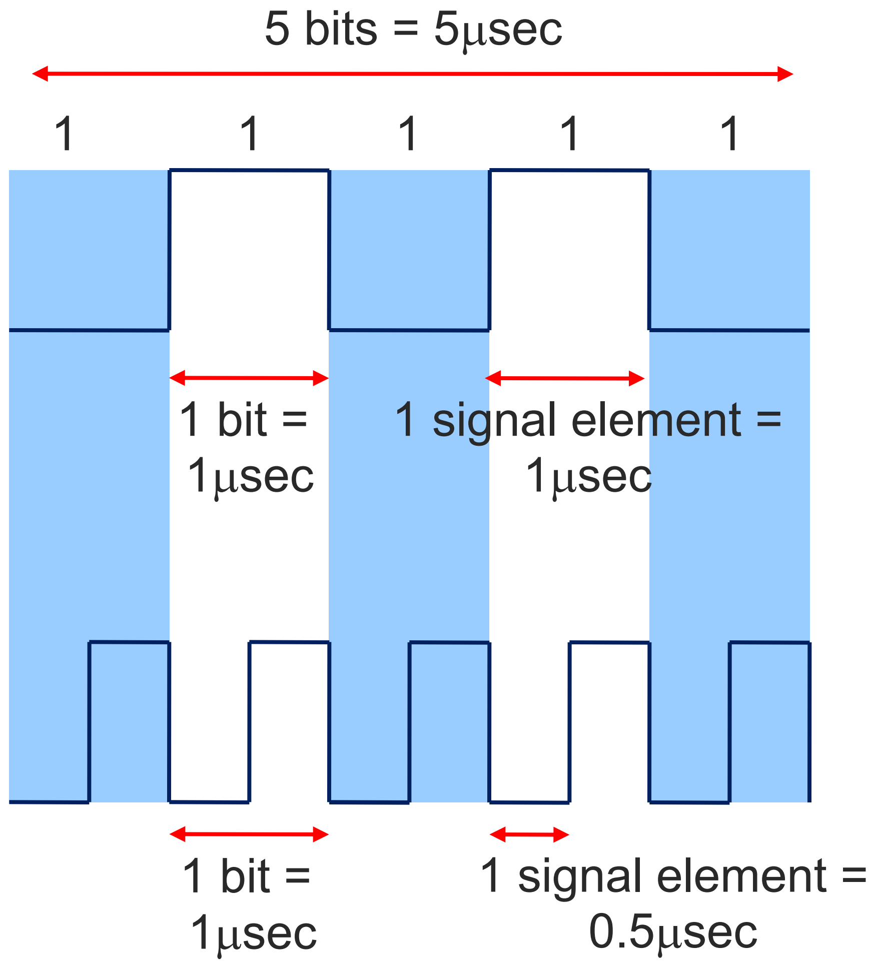


What is a bit?

What is a signal element?

Modulation (Baud) Rate

A stream of binary 1s at 1 Mbps



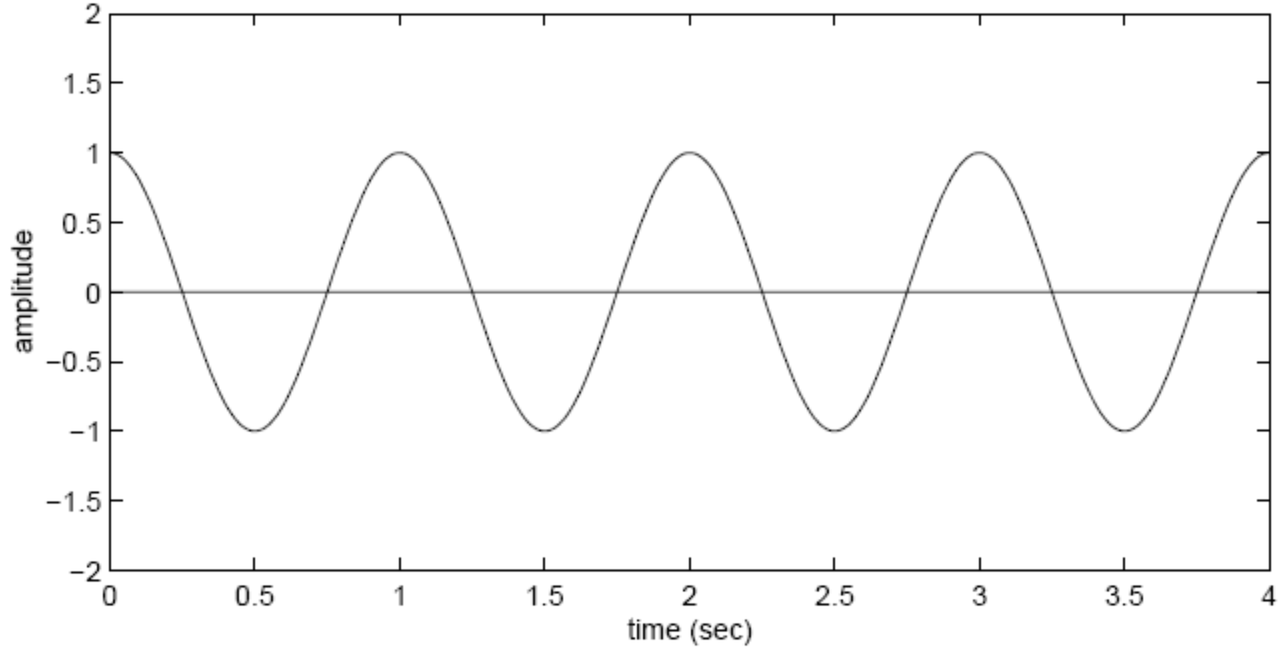
What is the data rate?

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

What is the modulation rate?

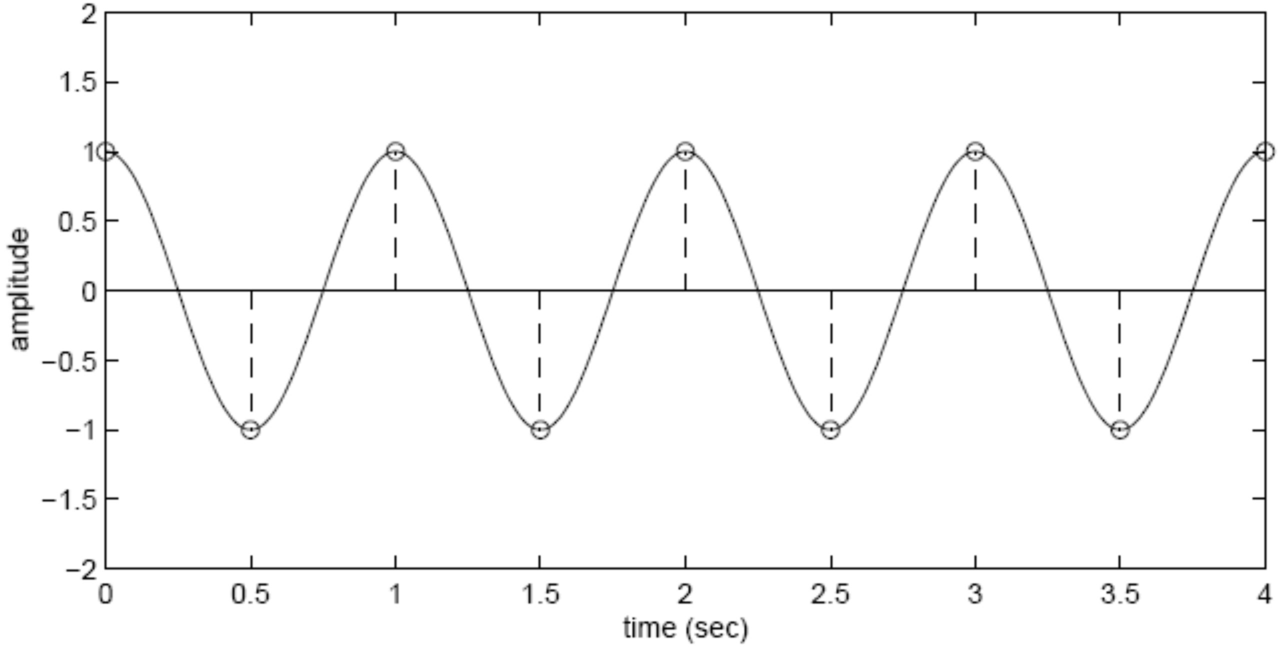
Modulation Rate
= Baud Rate
= Rate at which signal elements are generated
= R (NRZI)
= 2R (Manchester)

Sampling



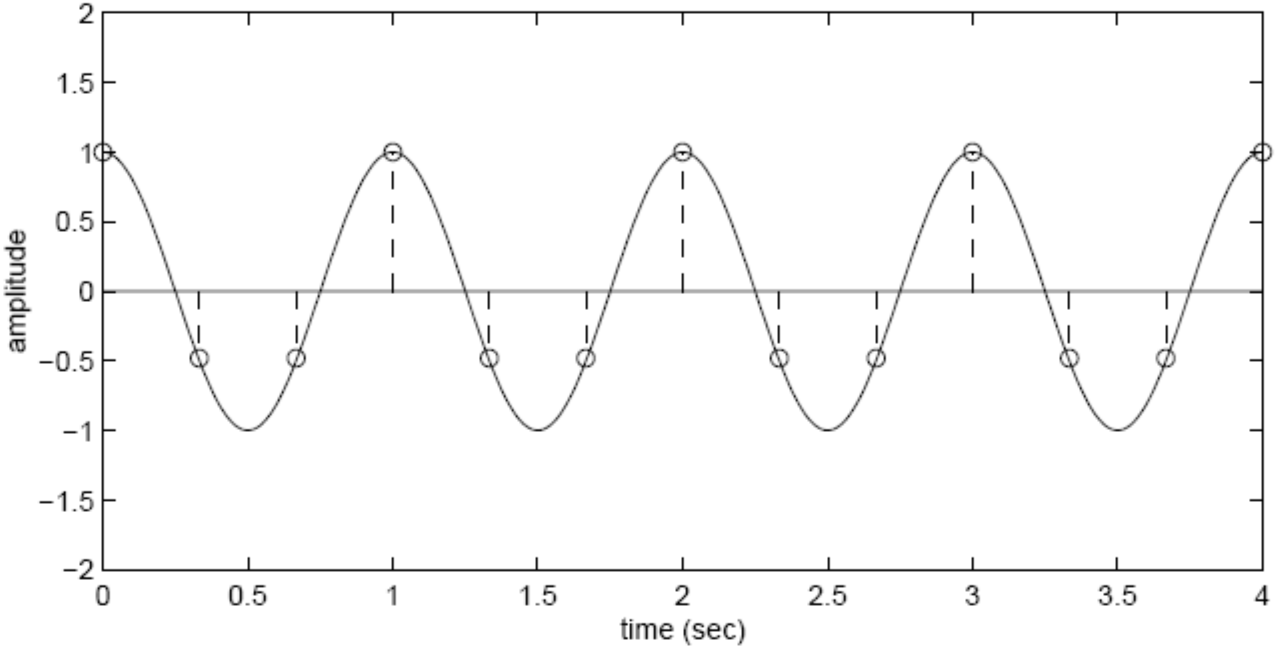
- Suppose you have the following 1Hz signal being received
- How fast to sample, to capture the signal?

Sampling



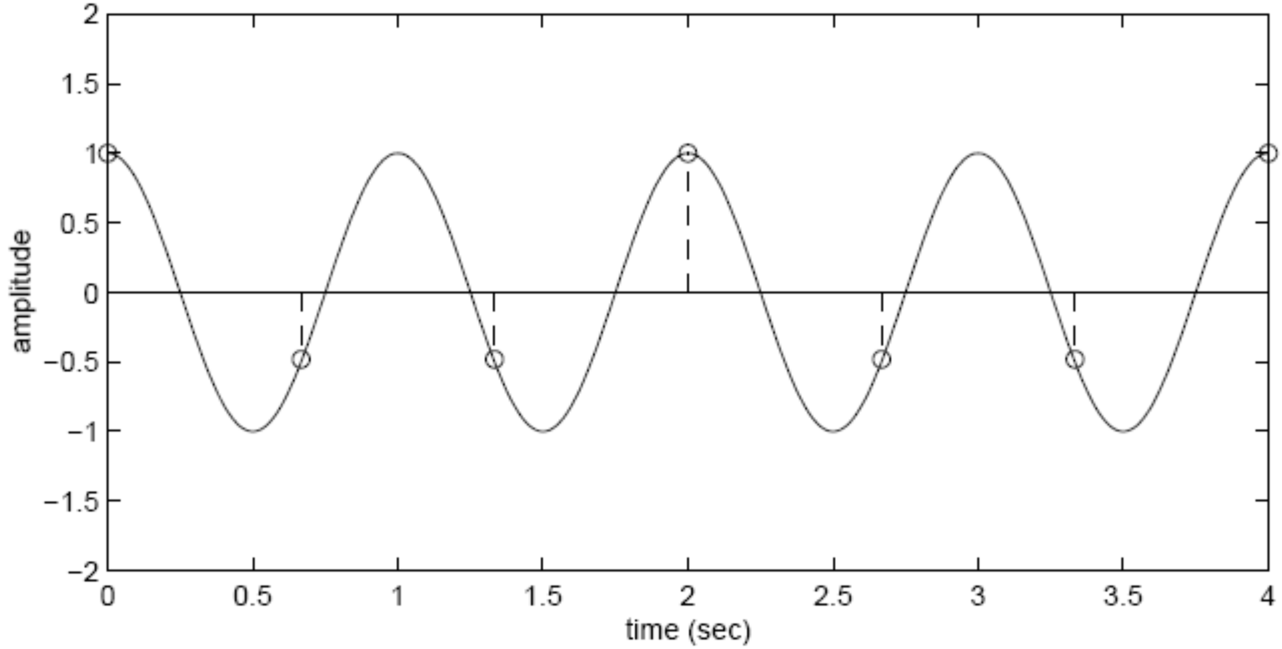
- Sampling a 1 Hz signal at 2 Hz is enough
  - Captures every peak and trough

Sampling



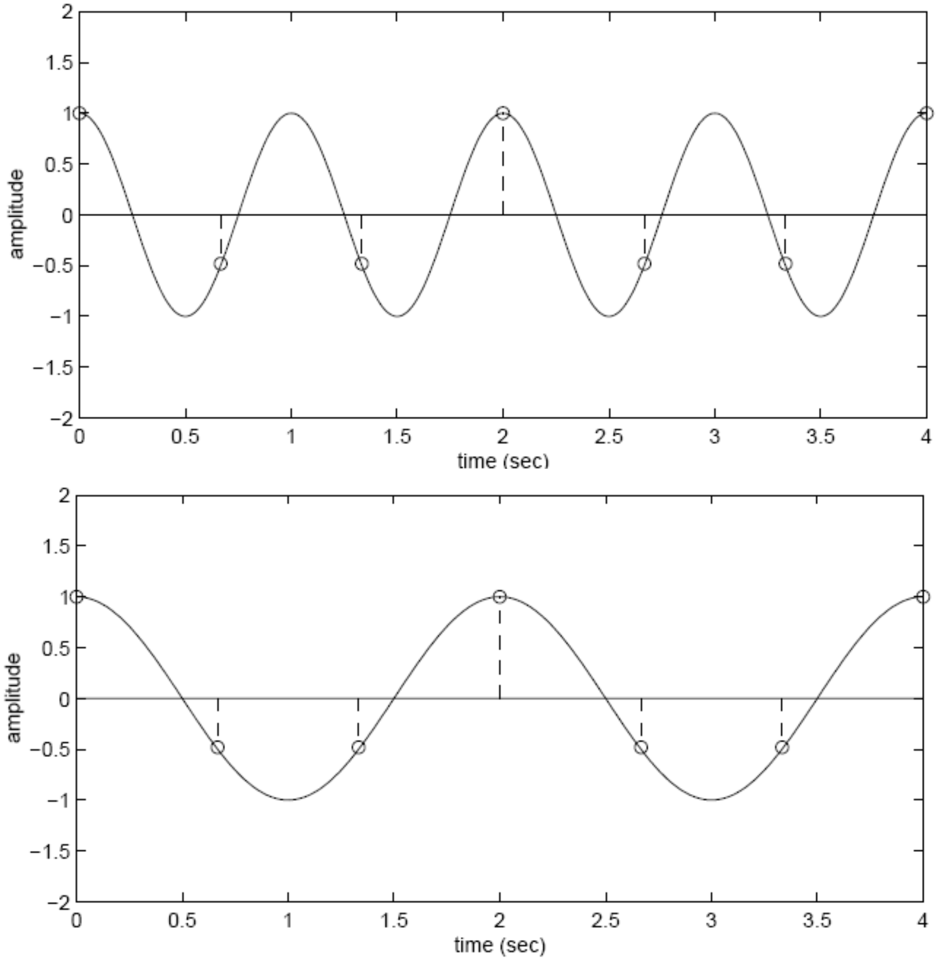
- Sampling a 1 Hz signal at 3 Hz is also enough
  - In fact, more than enough samples to capture variation in signal

Sampling



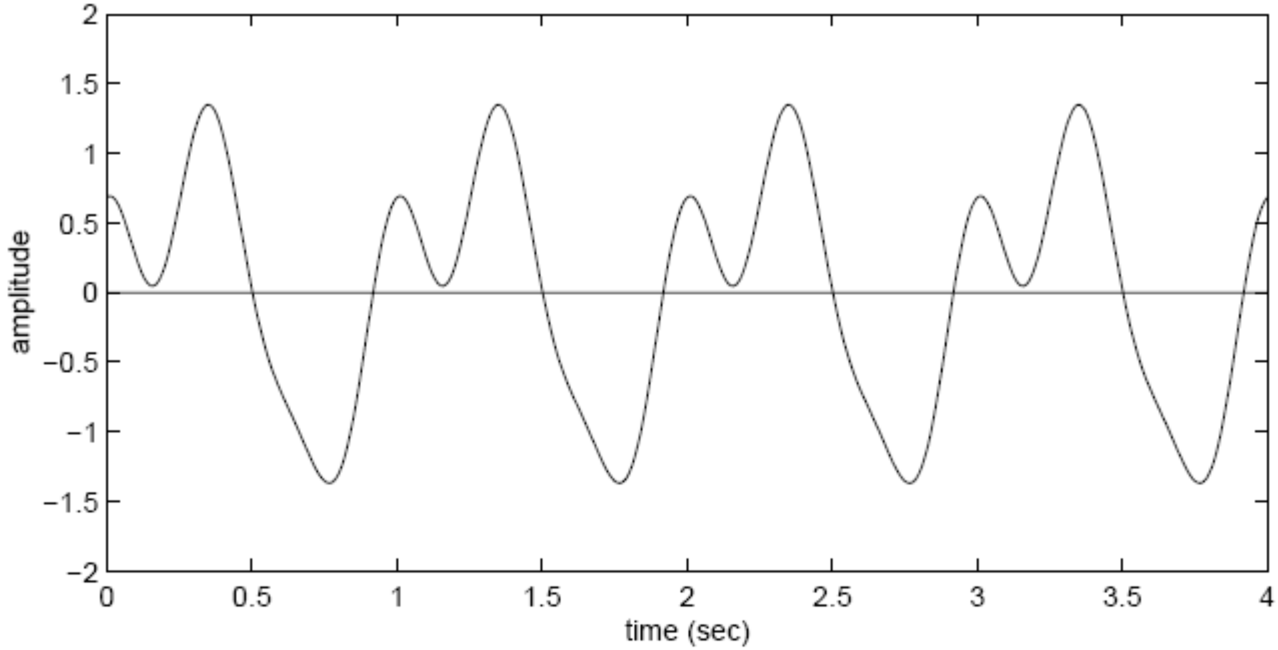
- Sampling a 1 Hz signal at 1.5 Hz is not enough
  - Why?

Sampling



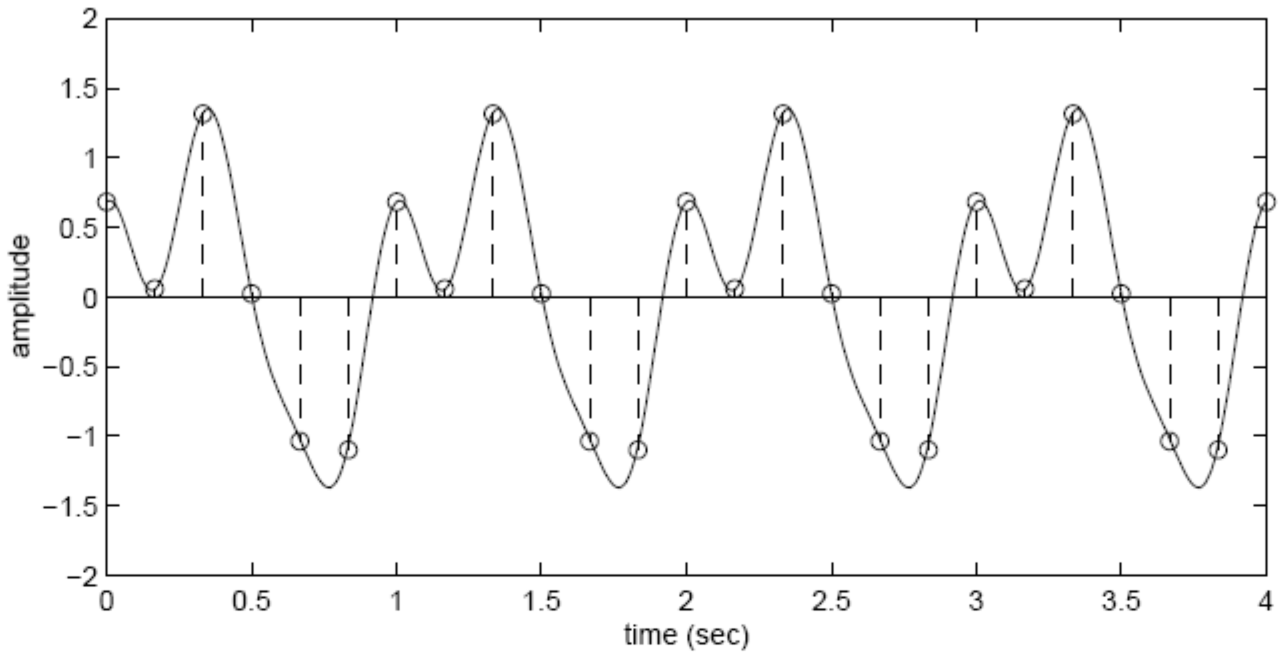
- Sampling a 1 Hz signal at 1.5 Hz is not enough
  - Can't distinguish between multiple possible signals
  - Problem known as **aliasing**

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 → $2B$

$$2B \log_2 N$$

$\log_2 N$ ← 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 s
per seco

Number of bits per
signal

- Nyqu Nyquist,
  1920

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**

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 Hz
  - N = each pulse encodes 16 symbols
  - C =

Noiseless Capacity

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

    $= 2400 \times 4 = 9600$ 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

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

- 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

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

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

    $S/N = 10{,}000$
  - $C = 3400 \log_2 (10001) = 44.8$ kbps

More examples of Nyquist and Shannon Formulas

- Spectrum of a channel between 3 MHz and 4 MHz ; SNR_{dB} = 24 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 ; SNR_{dB} = 24 dB

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

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

$$SNR = 251$$

- 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?

$$C = 2B \log_2 M$$

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

$$4 = \log_2 M$$

$$M = 16$$

- 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