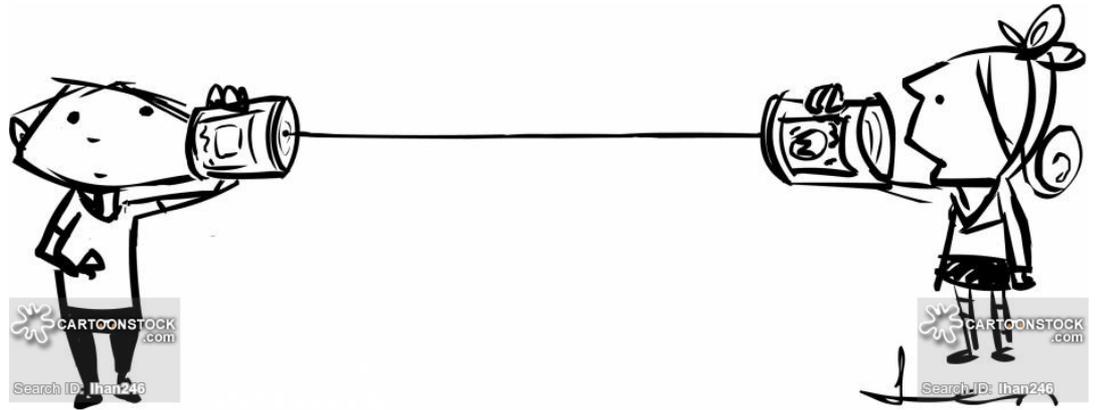


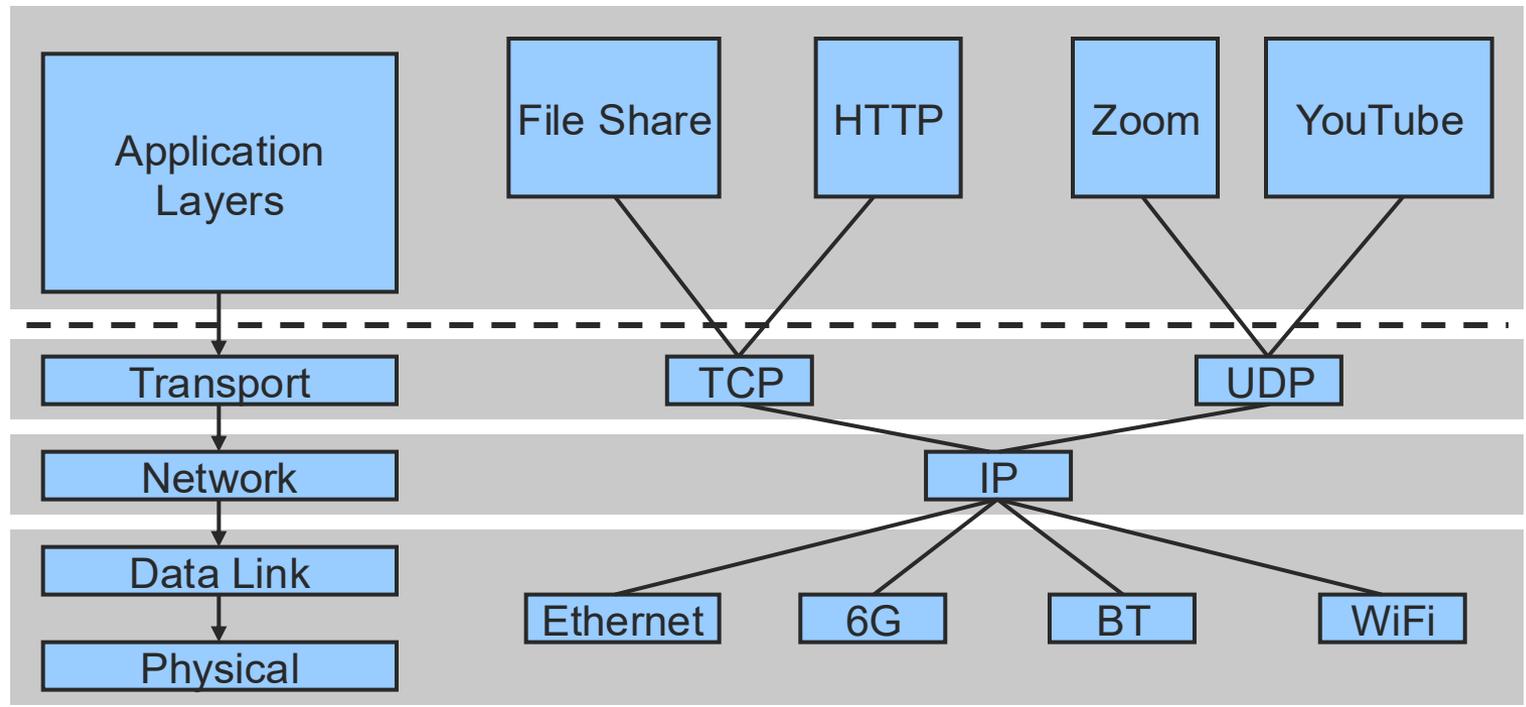
# Direct Link Networks - Encoding

Reading:  
Peterson and  
Davie, Chapter 2



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

# [ Where are we? ]

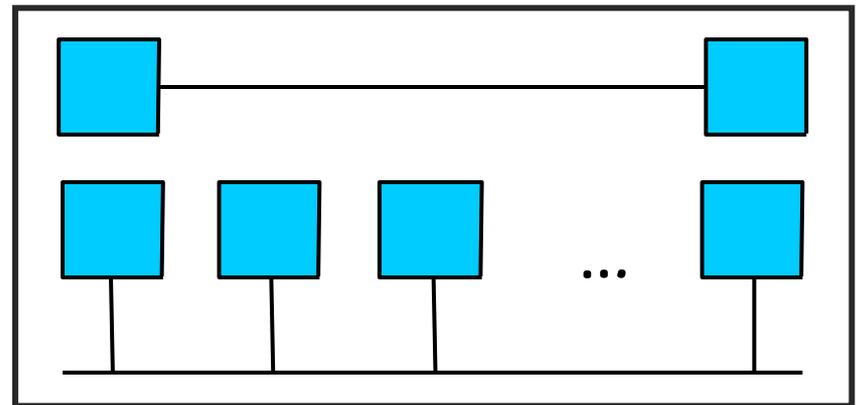


Today



# Direct Link Networks

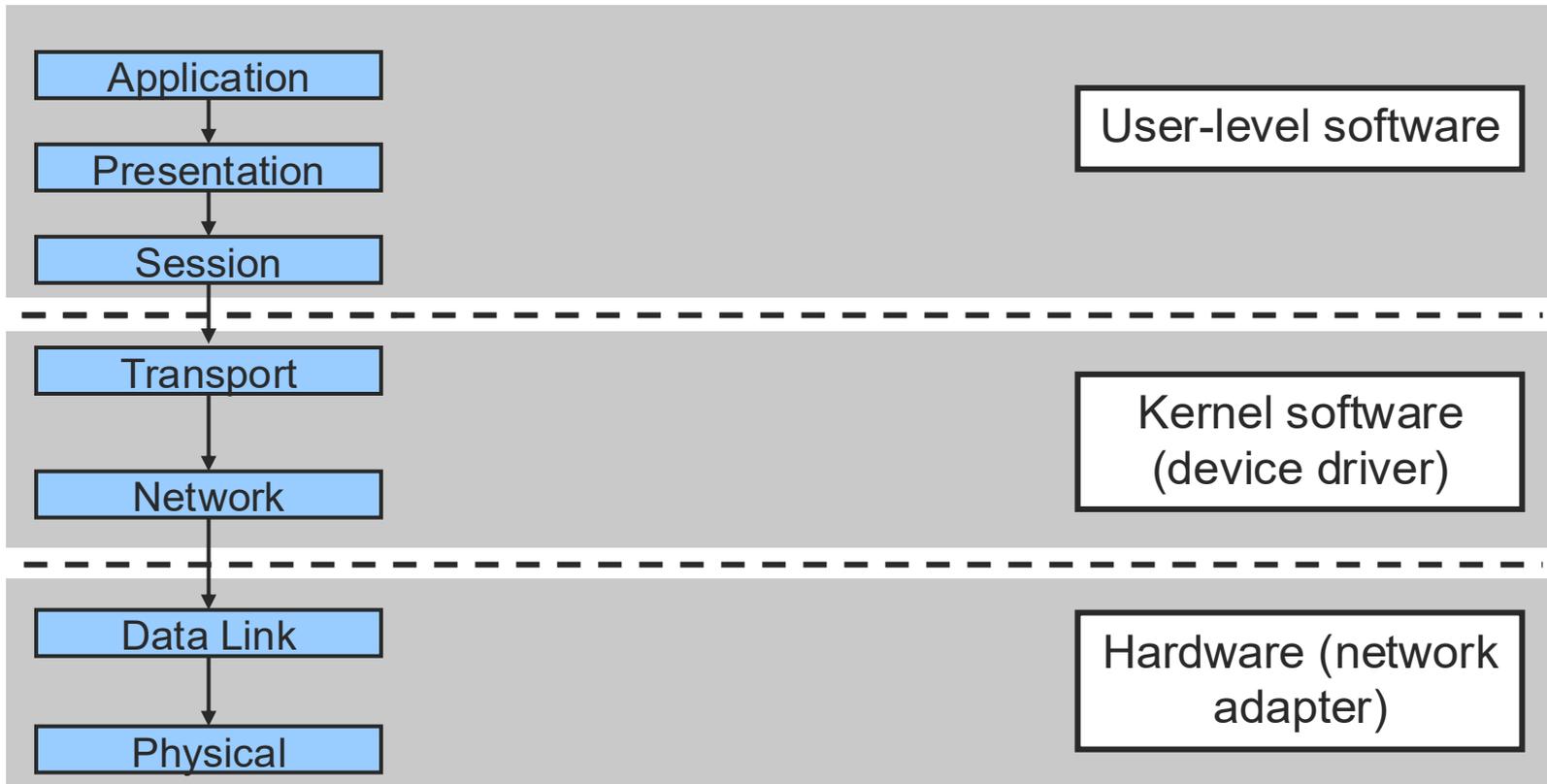
- All hosts are directly connected by a physical medium
- Key points
  - Encoding and Modulation
  - Framing
  - Error Detection
  - Medium Access Control



# Internet Protocols

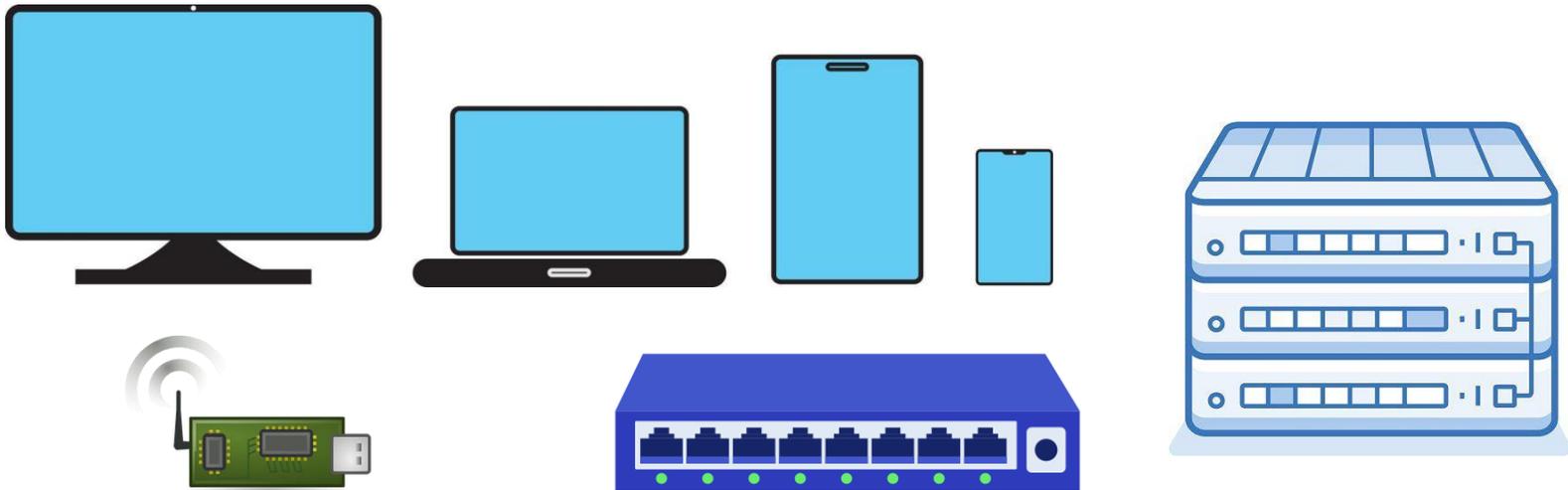
Encoding

Framing, error detection,  
medium access control



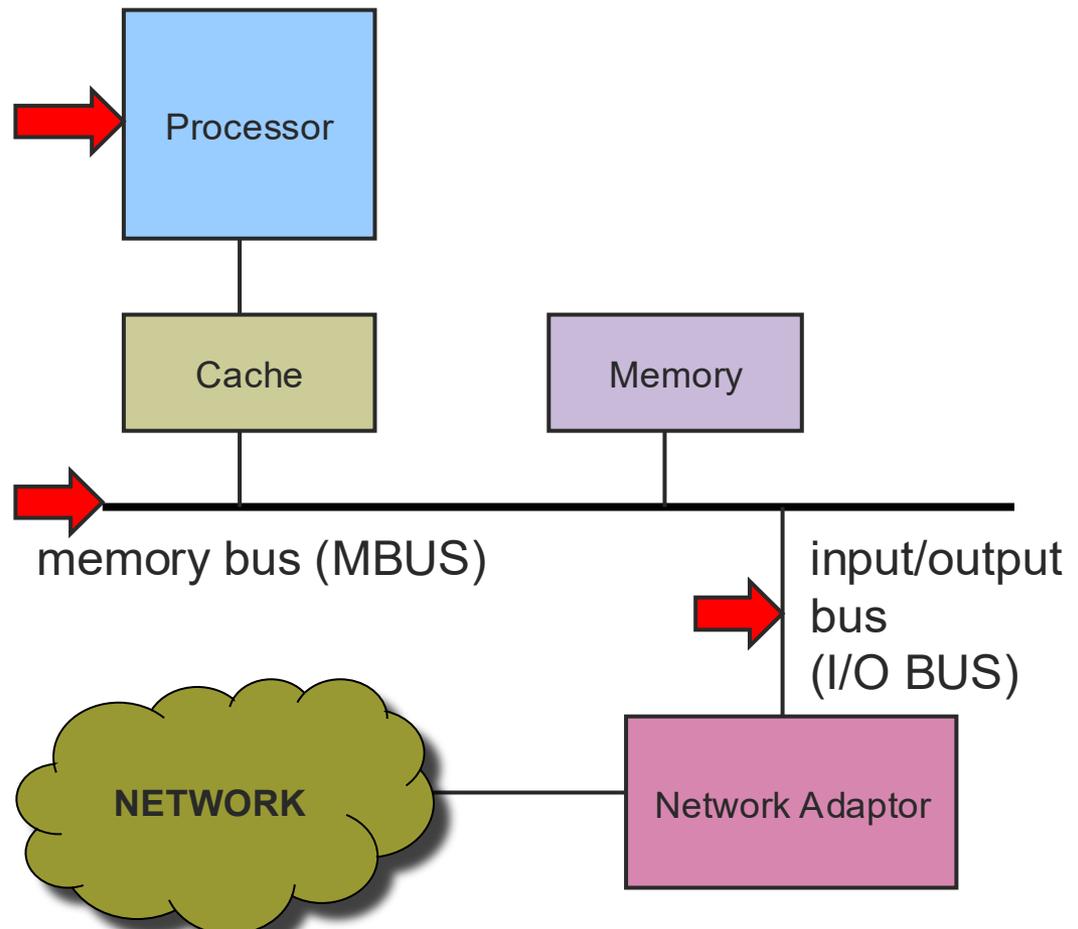
# Hardware Building Blocks

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



# Nodes: Desktop 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
- Light (morse code, Li-Fi)
- Two cups and a string



# [ Links - Copper ]

- Copper-based Media

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

more twists, less crosstalk, better signal over longer distances

10-100Mbps	500m
10-100Mbps	200m
up to 1Gbps	100m
up to 10Gbps	55m

Coaxial Cable



Twisted Pair



# [ Links - Optical ]

- Optical Media

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

Coaxial Cable



Twisted Pair



Fiber Optic



# [ Links - Optical ]

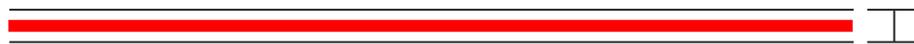
## ■ Single mode fiber

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

## ■ Multimode fiber

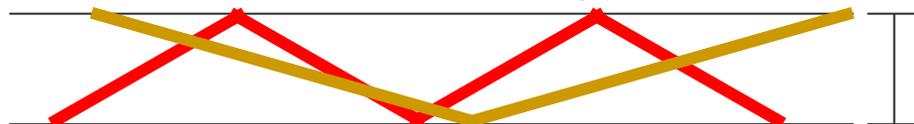
- Cheap to drive (LED's)
- Higher attenuation
- Easier to terminate

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)

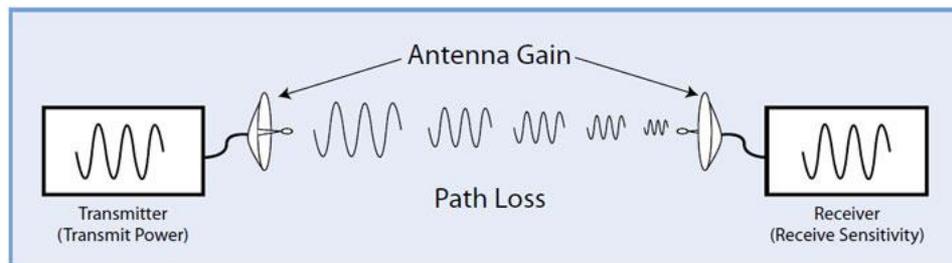


# [ Links - Wireless ]

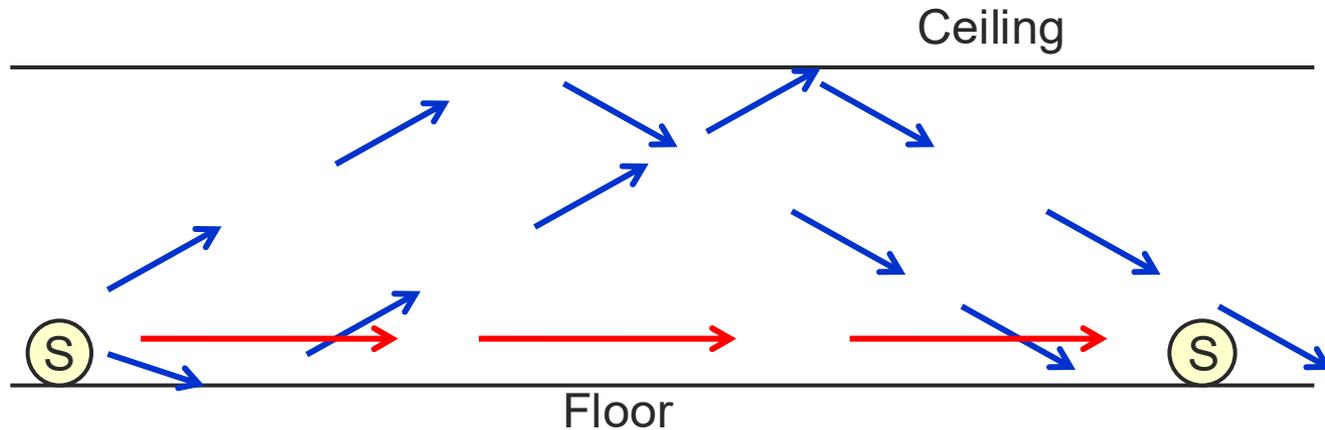


# Links - Wireless Path Loss

- Path loss
  - Signal attenuation as a function of distance
  - Signal-to-noise ratio (SNR—Signal Power/Noise Power) decreases, make signal unrecoverable
- 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



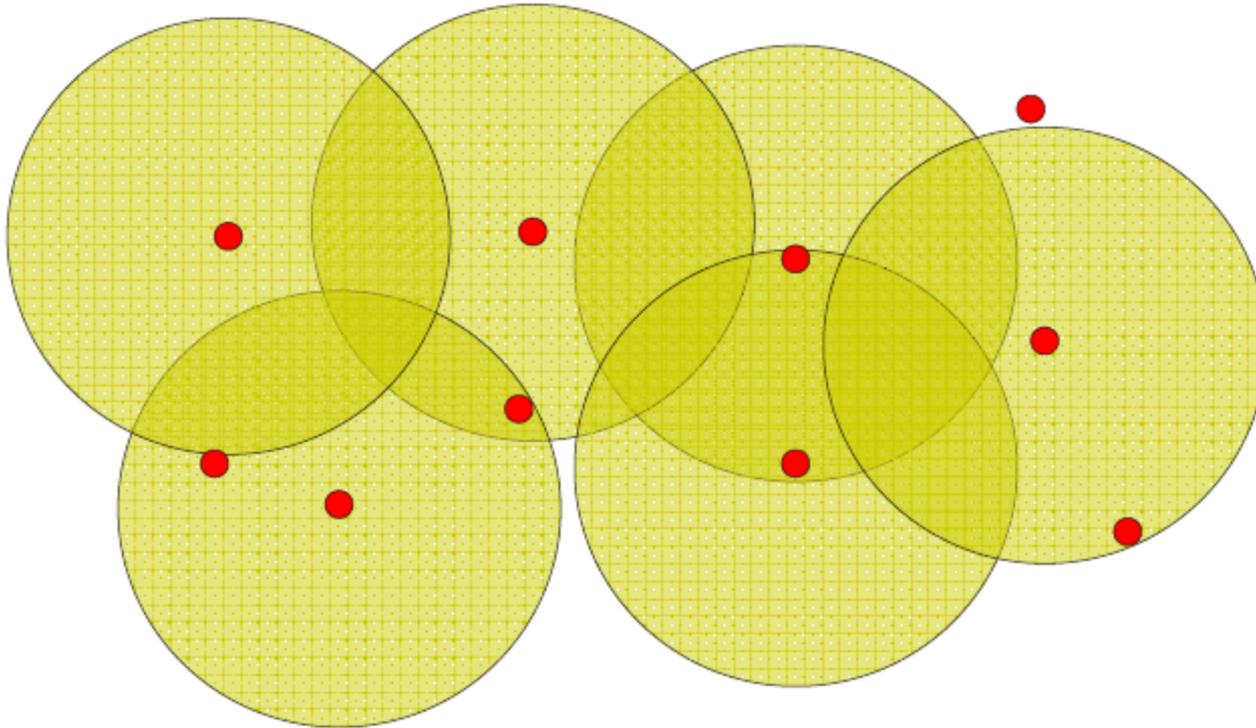
# Links - Wireless Multipath



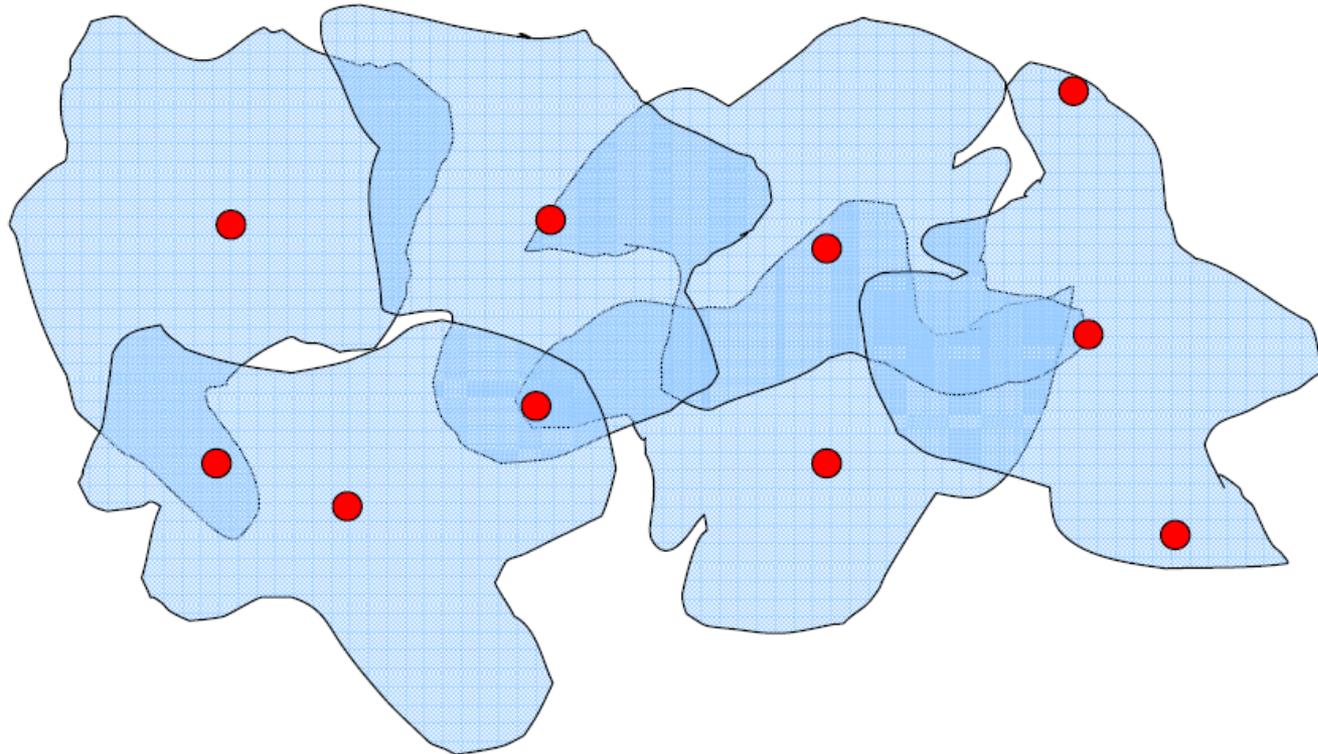
- Signals bounce off surfaces and interfere with one another
- What if signals are out of phase?
  - Orthogonal signals cancel each other and nothing is received!



# [ What is a Wireless “Link”? ]



# [ What is a Wireless “Link”? ]



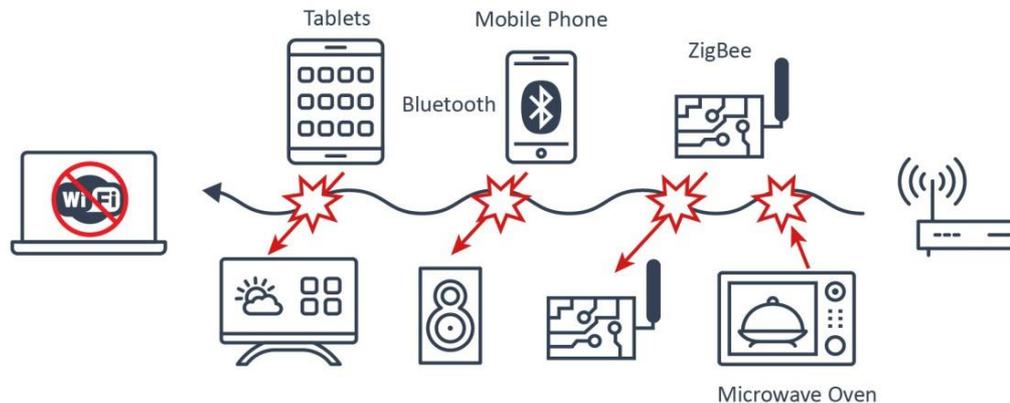
# [ Links - Wireless Bit Errors ]

- 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

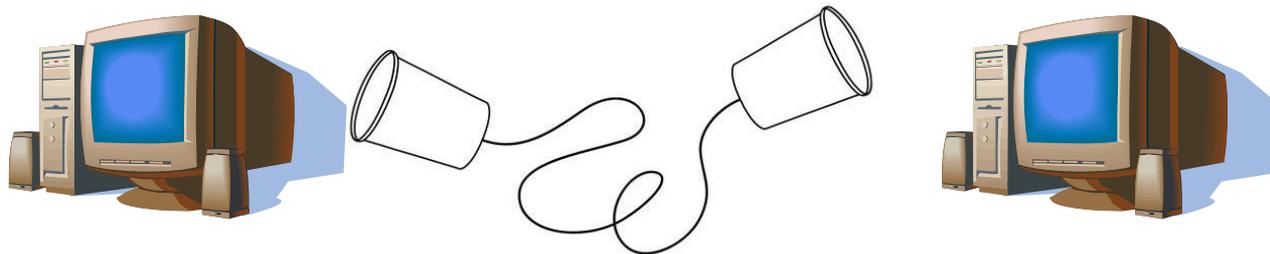
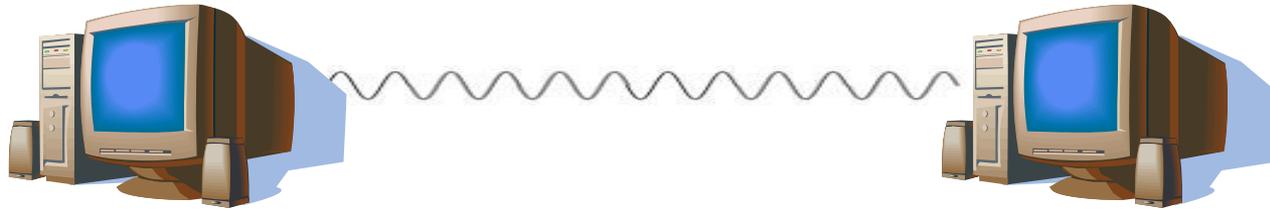


# Links – Wireless Interference

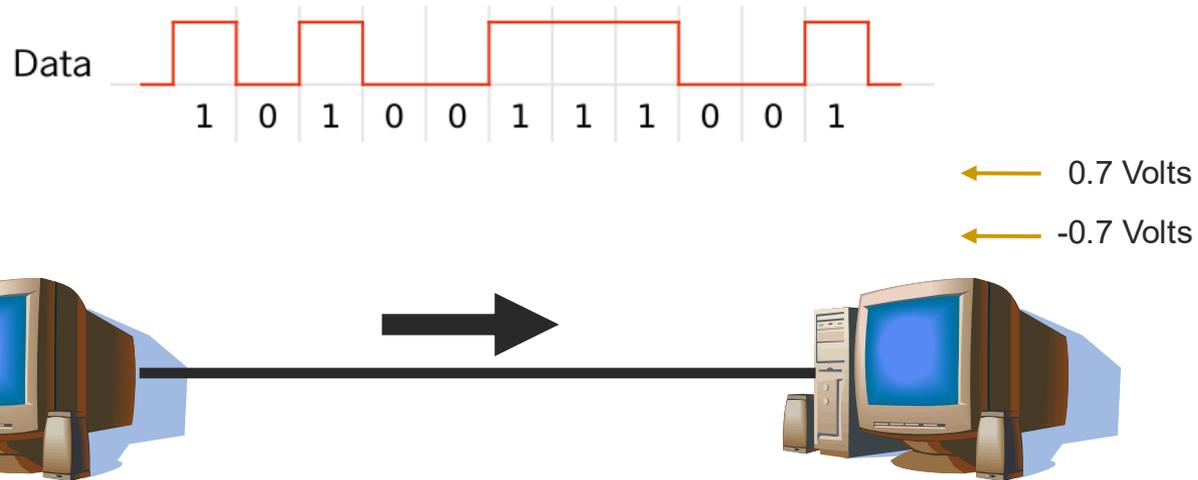
- Internal interference (from other users)
  - Hosts within range of each other collide with one another's transmission
- External interference
  - Microwave is turned on and blocks your signal



# How can two hosts communicate?



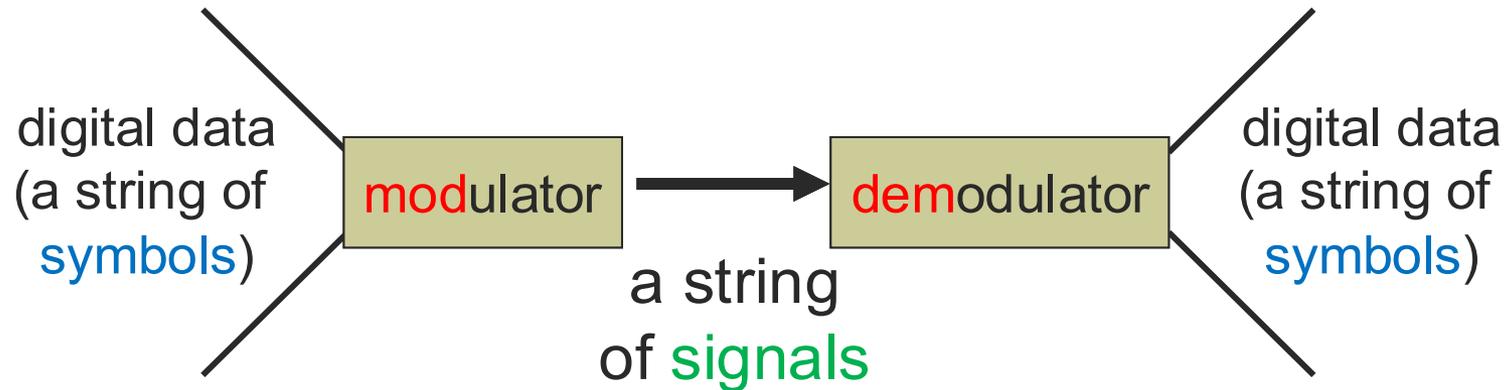
# How can two hosts communicate?



- Encode information on modulated “Carrier signal”



# Encoding



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



# [ 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**



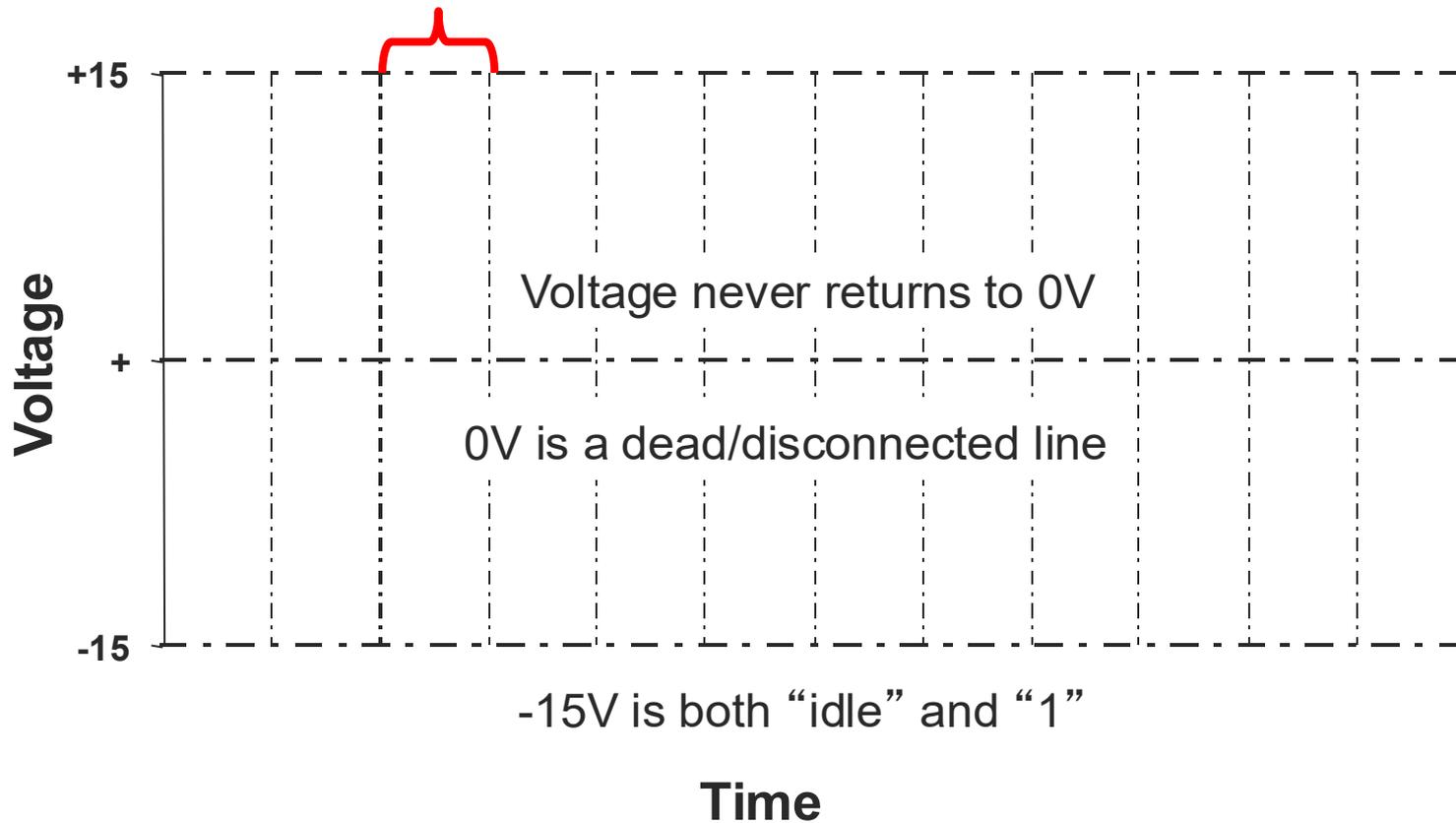
# [ Example: RS-232 ]

- 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

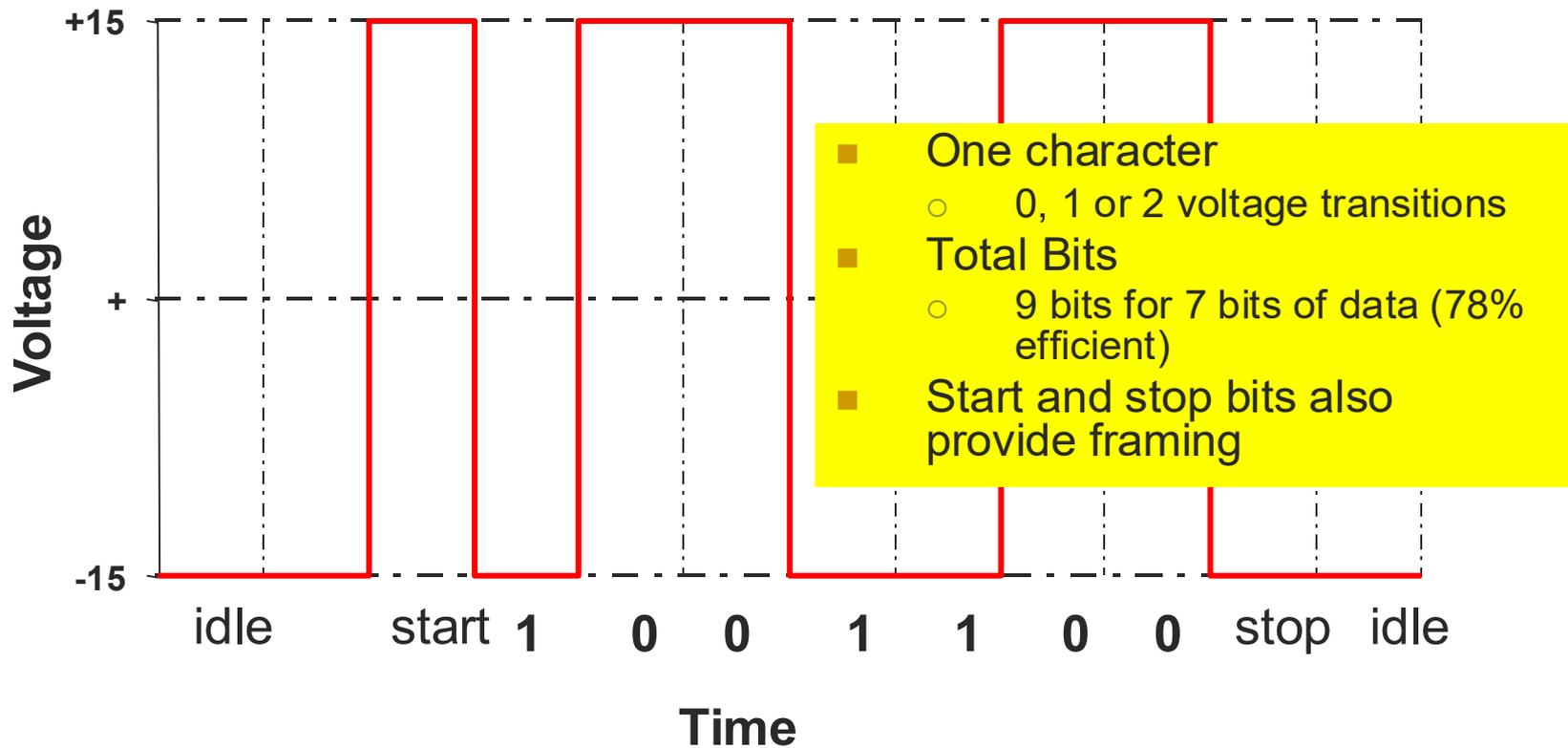


# [ RS-232 Timing Diagram ]

One bit per clock tick



# [ RS-232 Timing Diagram ]



# Binary Voltage Encoding

- Common encodings
  - Non-return to zero (NRZ)
  - NRZ inverted (NRZI)
  - Manchester (used by IEEE 802.3—10 Mbps Ethernet)
  - 4B/5B



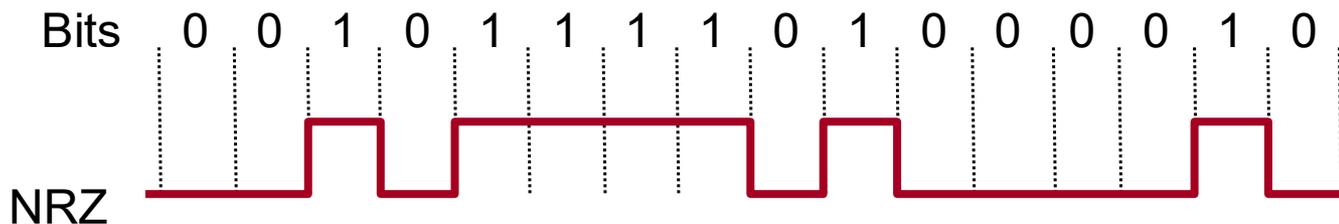
# [ Non-Return to Zero (NRZ) ]

- 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



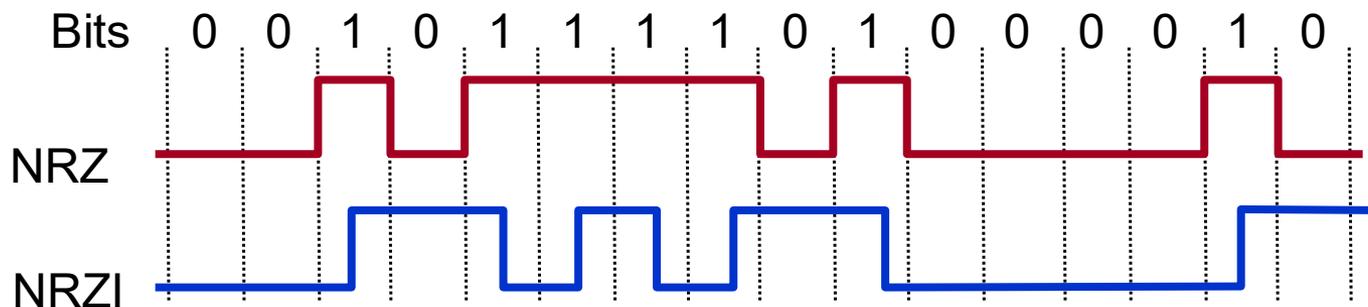
# Non-Return to Zero Inverted (NRZI)

- Signal to Data

- Transition  $\Rightarrow$  1
- Maintain  $\Rightarrow$  0

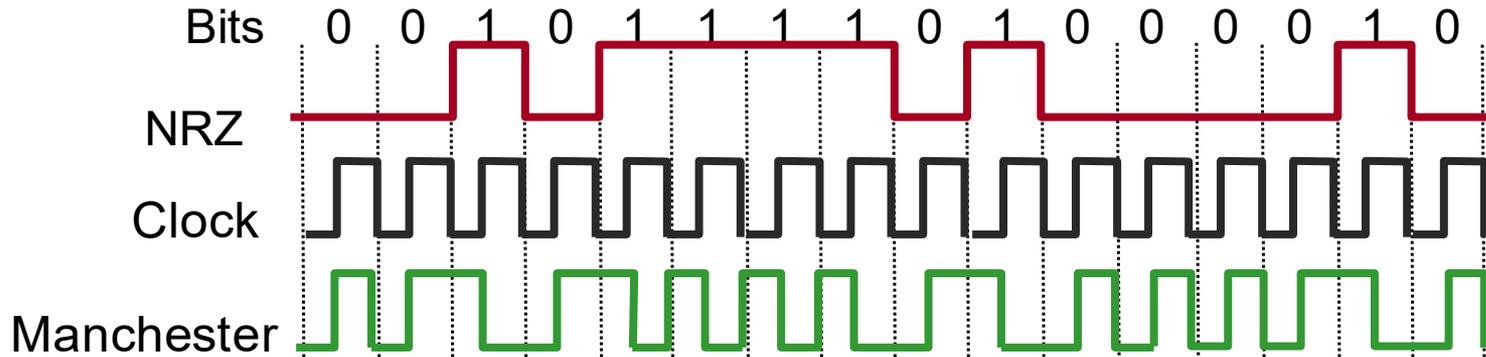
- Comments

- 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 ]

- Types of modulation
  - Amplitude (AM)
  - Frequency (FM)
  - Phase/phase shift
  - Combinations of these

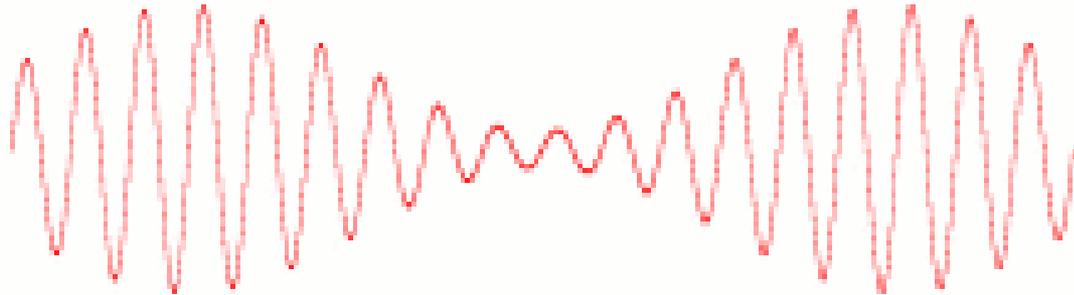


# Example: AM/FM for continuous signal

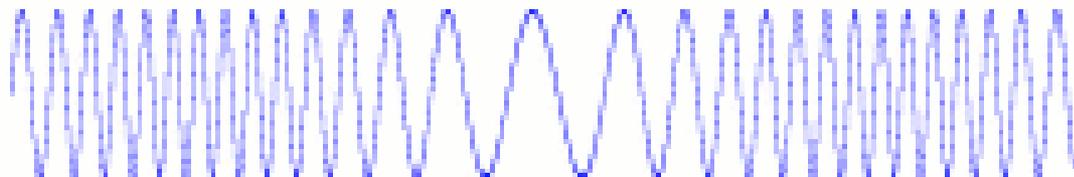
- Original signal



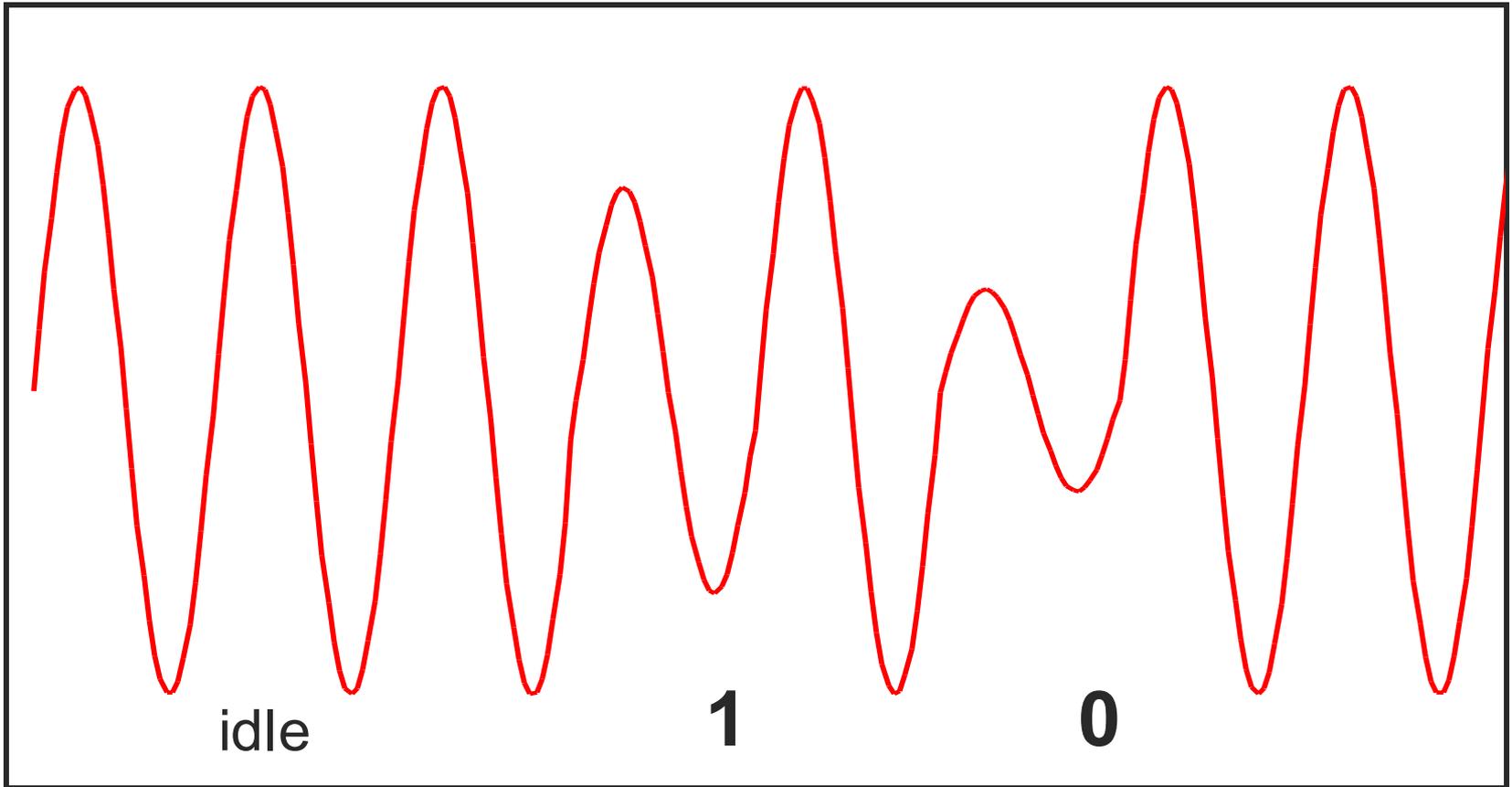
- Amplitude modulation



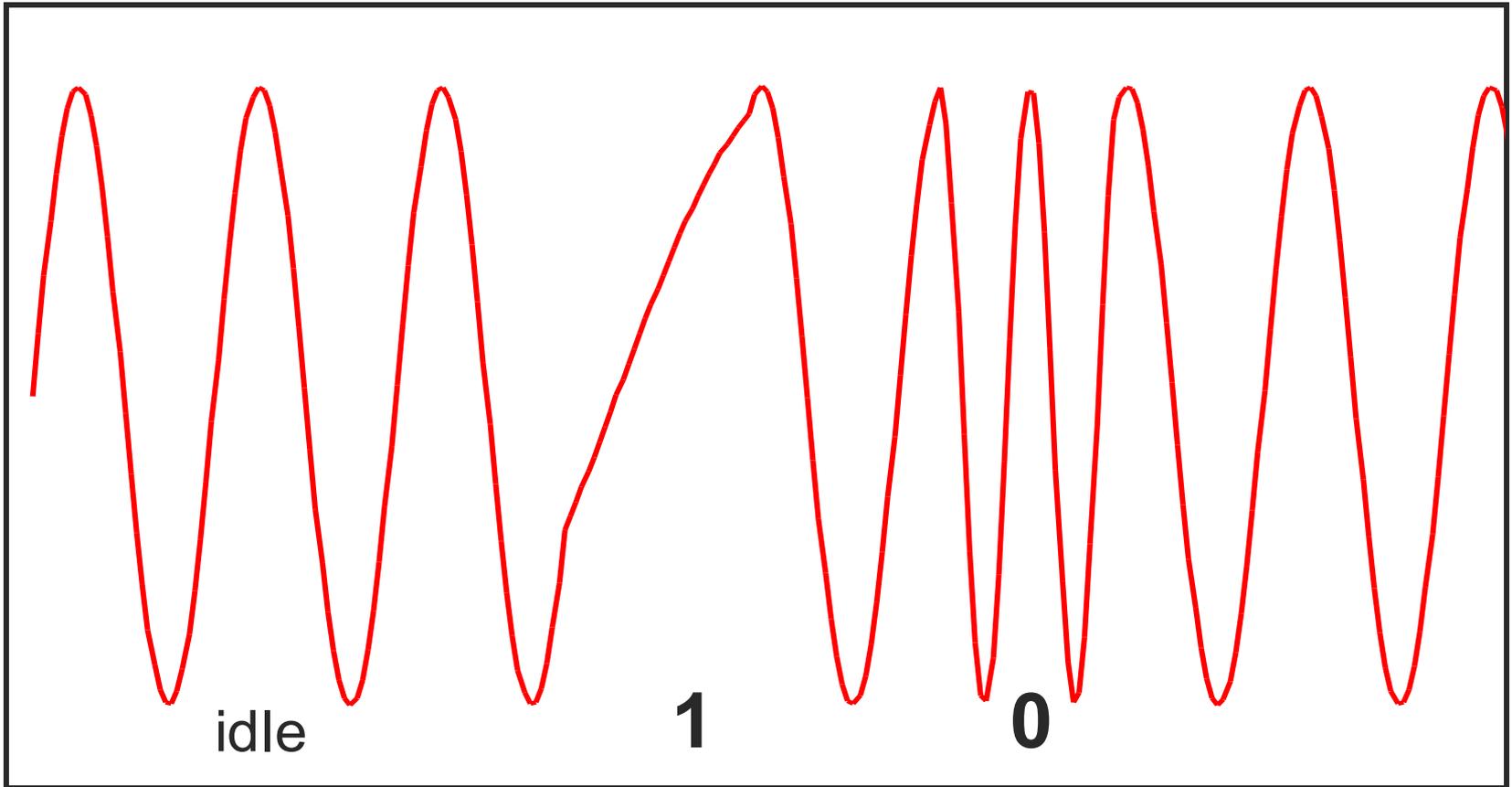
- Frequency modulation



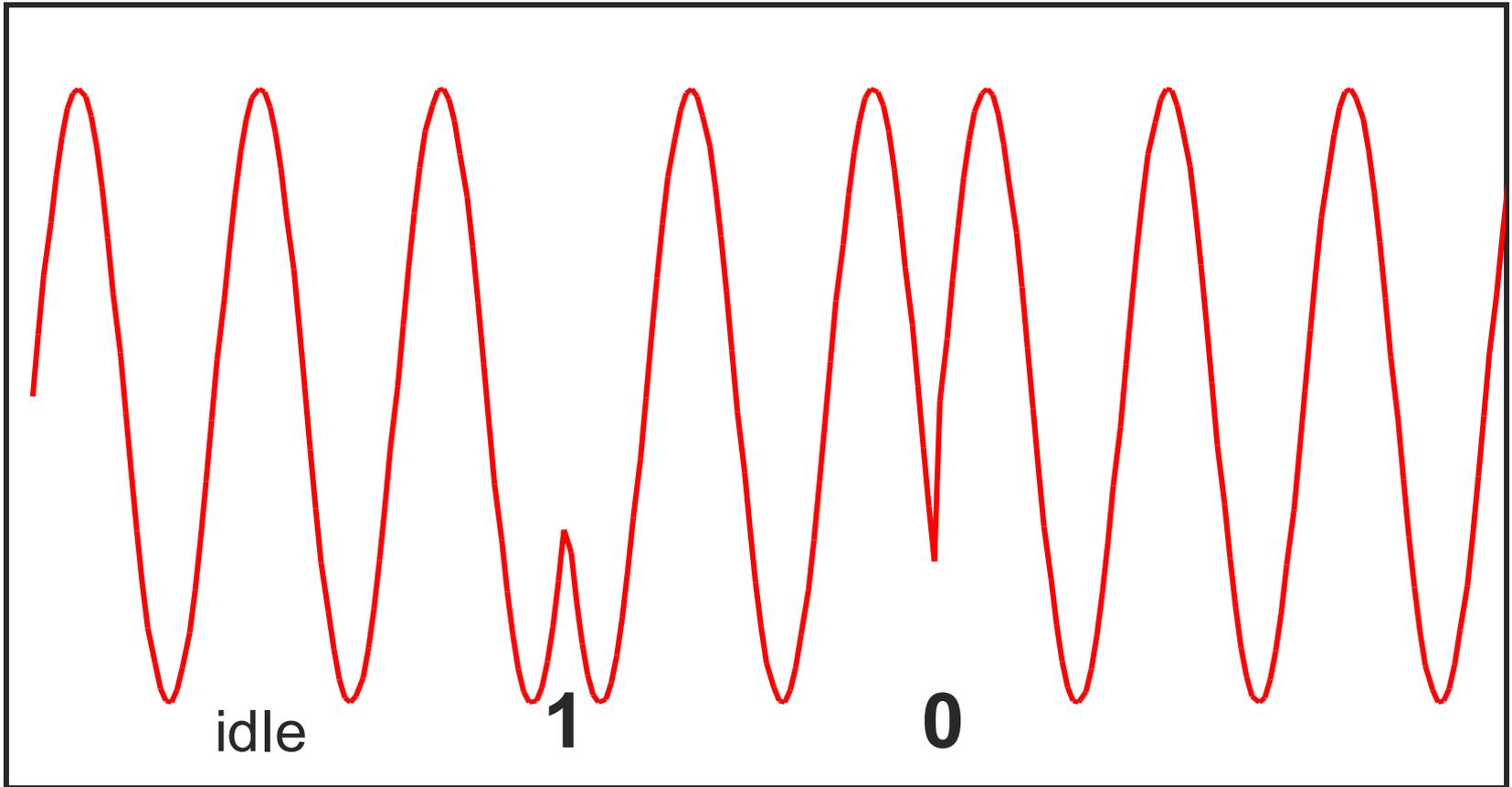
# [ Amplitude Modulation ]



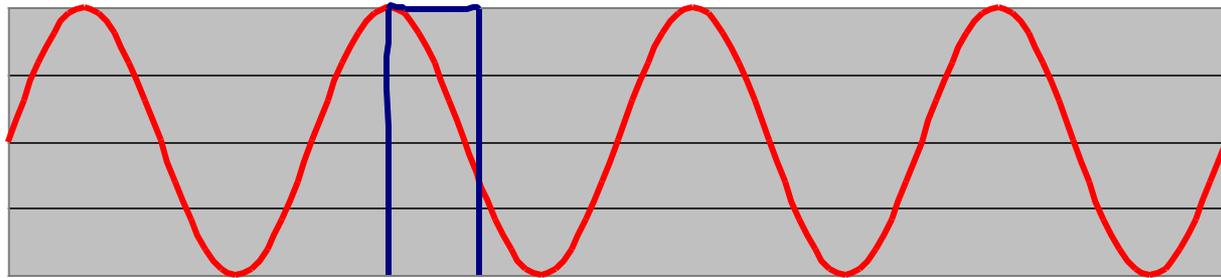
# [ Frequency Modulation ]



# [ Phase Modulation ]



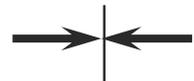
# [ Phase Modulation ]



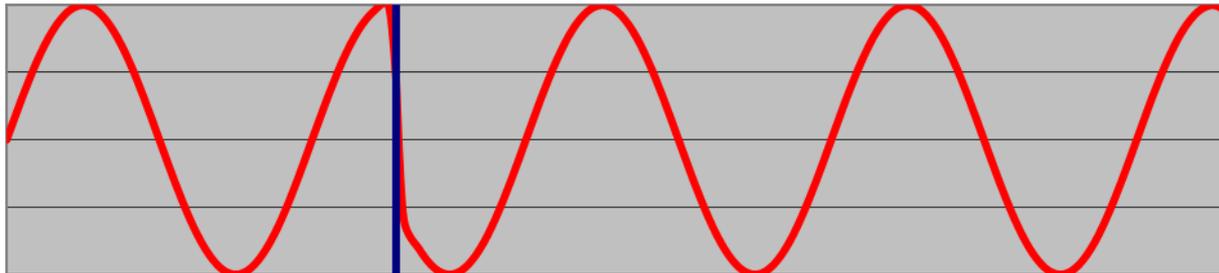
phase shift  
in carrier  
frequency



108° difference in phase



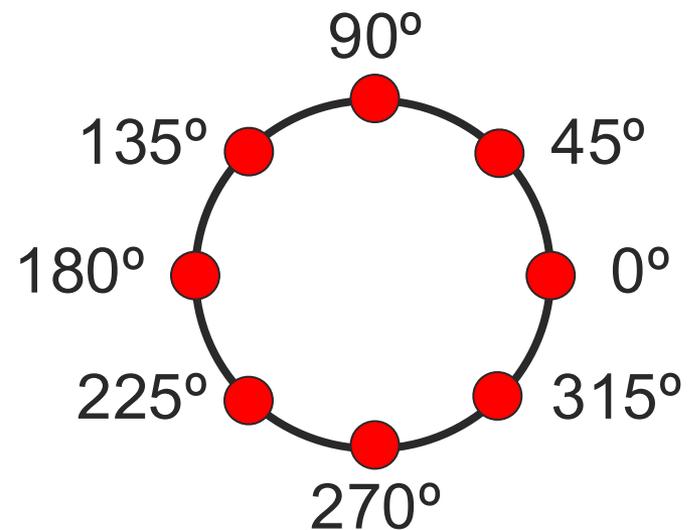
collapse for 108° shift



# 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

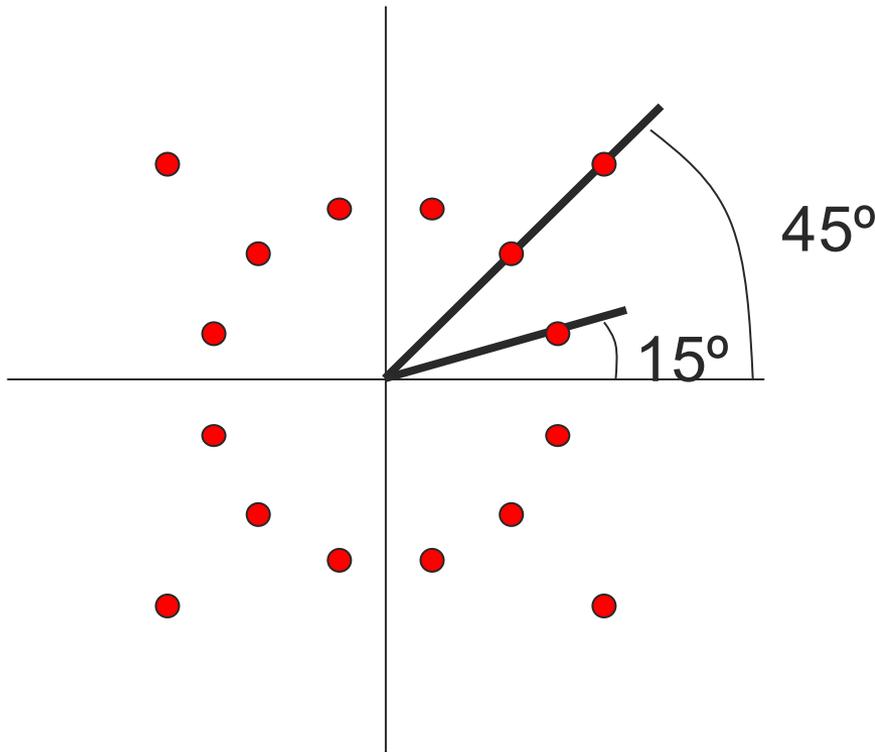


# Quadrature Amplitude Modulation (QAM)

- Uses a combination of amplitude and phase modulation
  - Sends one of N signals each clock cycle
- Each transition represents a symbol
  - Transmission rate = symbols per second
- Each symbol contains multiple bits
  - Ex. 16 QAM:  $\log^2 16 = 4$  bits
- Points in constellation diagram
  - Chosen to maximize error detection



# Quadrature Amplitude Modulation (QAM)

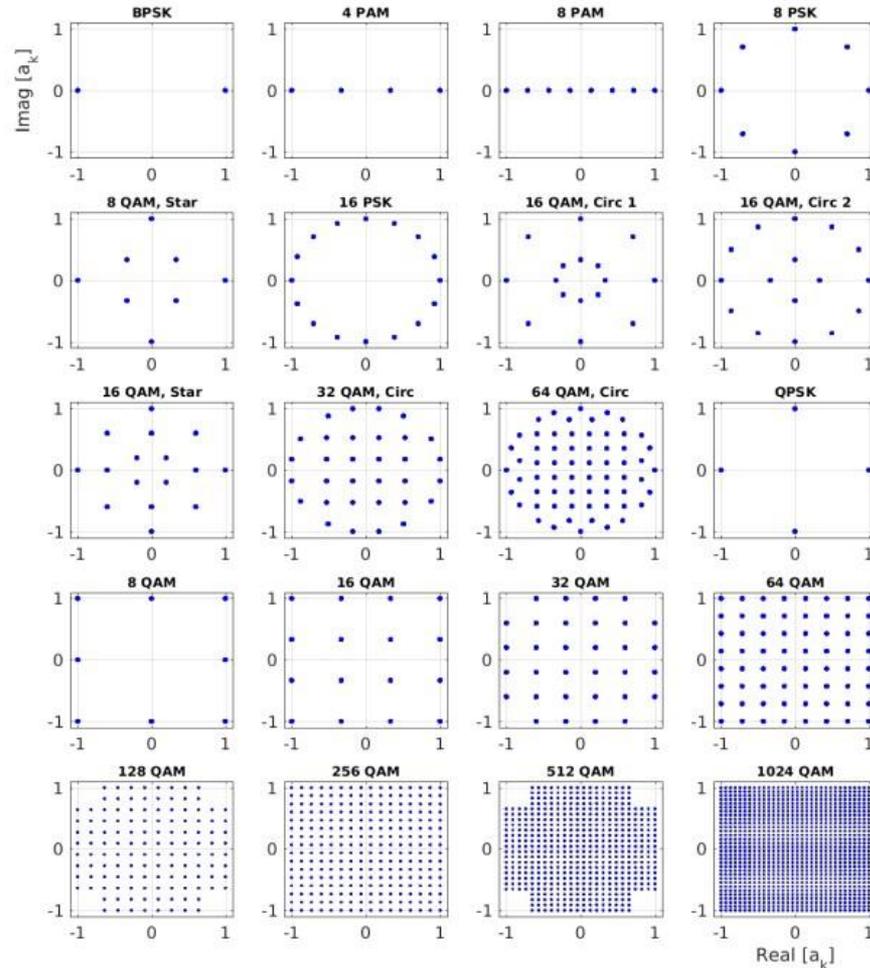


16-symbol example

- Combine amplitude and phase modulation
  - Send one of N signals each clock cycle
    - Angle is phase shift
    - Radial distance is new amplitude
- Each transition = a symbol
  - Transmission rate = symbols per second
- Each symbol = multiple bits
  - Ex. 16 QAM:  $\log^2 16 = 4$  bits
- Points in constellation diagram
  - Chosen to maximize error detection



# [ Example up to 1024 QAM ]



# 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
  - $B = 1200 \text{ Hz}$
  - $N =$  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)
    - 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 ]

- Telephone channel
  - 3400 Hz at 40 dB SNR

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

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

$$\text{decibels (db)} = 10 \log_{10}(P1 / P2)$$

- 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

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

$$S/N = 10,000$$

- $C = 3400 \log_2 (10001) = 44.8$  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

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



# 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

