Physical Layer: Capacity and Modulation

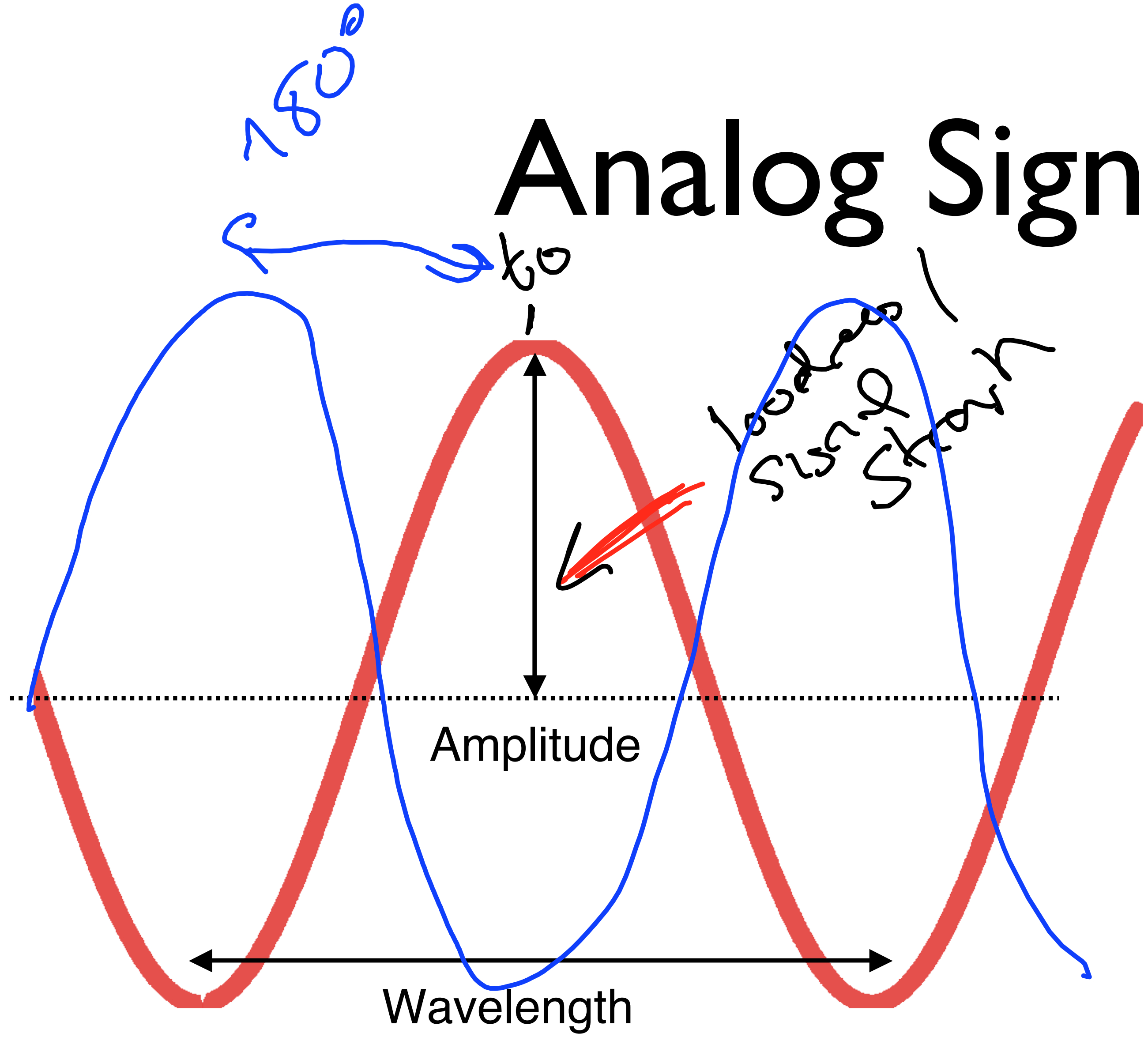
Shannon Limit

- There is a theoretical limit on how information a channel can carry (Shannon limit)

- Channel capacity = $B \log_2(1 + S/N)$
  - B is Bandwidth, S is Signal strength, N is Noise

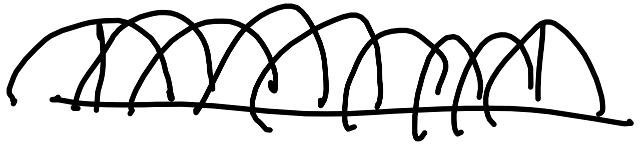
- Higher S/N requires lower noise (better/more expensive hardware), or stronger signal (higher voltages)
- Building hardware for very high bandwidths is difficult

Analog Signals



C ≈ 1ft/ns
1,000,000,000 ft/s
1ft : 1GHz
2.4GHz : 5in
5.6GHz : 2.4in

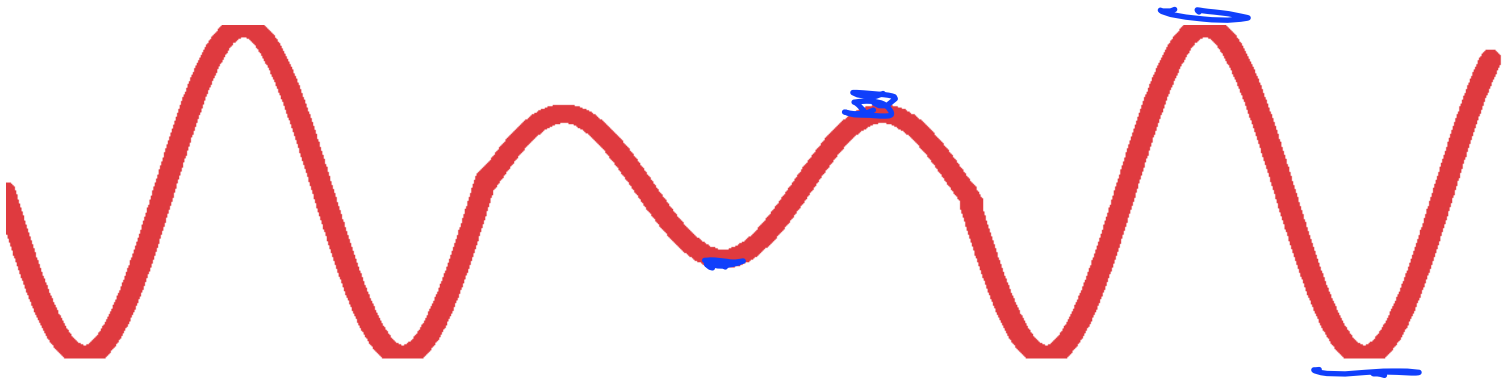
802.11b
1-11 (1,6,11)
20MHz



Frequency: 1/wavelength
Bandwidth: size of frequency range
Phase: timing of waves within a wavelength
Speed of light ~ 1 foot/nanosecond

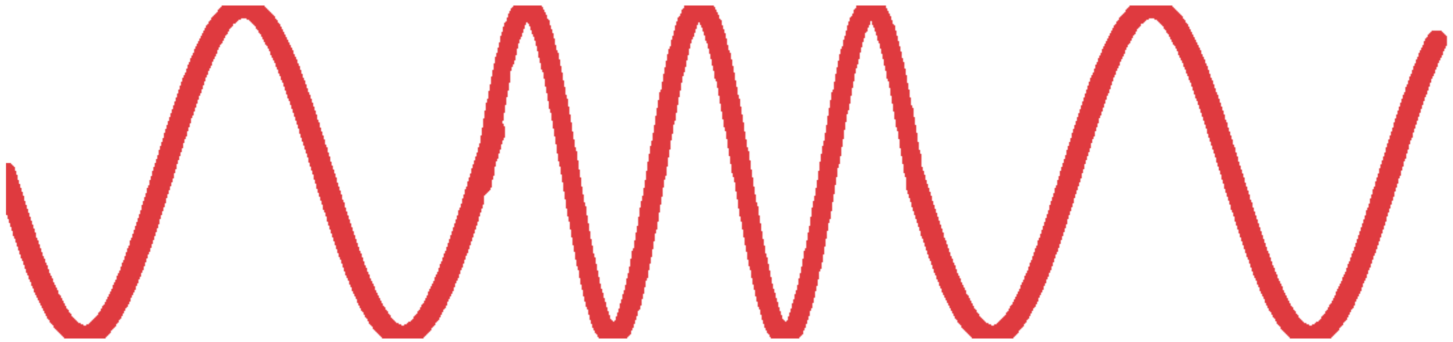
Modulation: ASK, FSK

Amplitude Shift Keying (ASK)



1 0 1

Frequency Shift Keying (FSK)



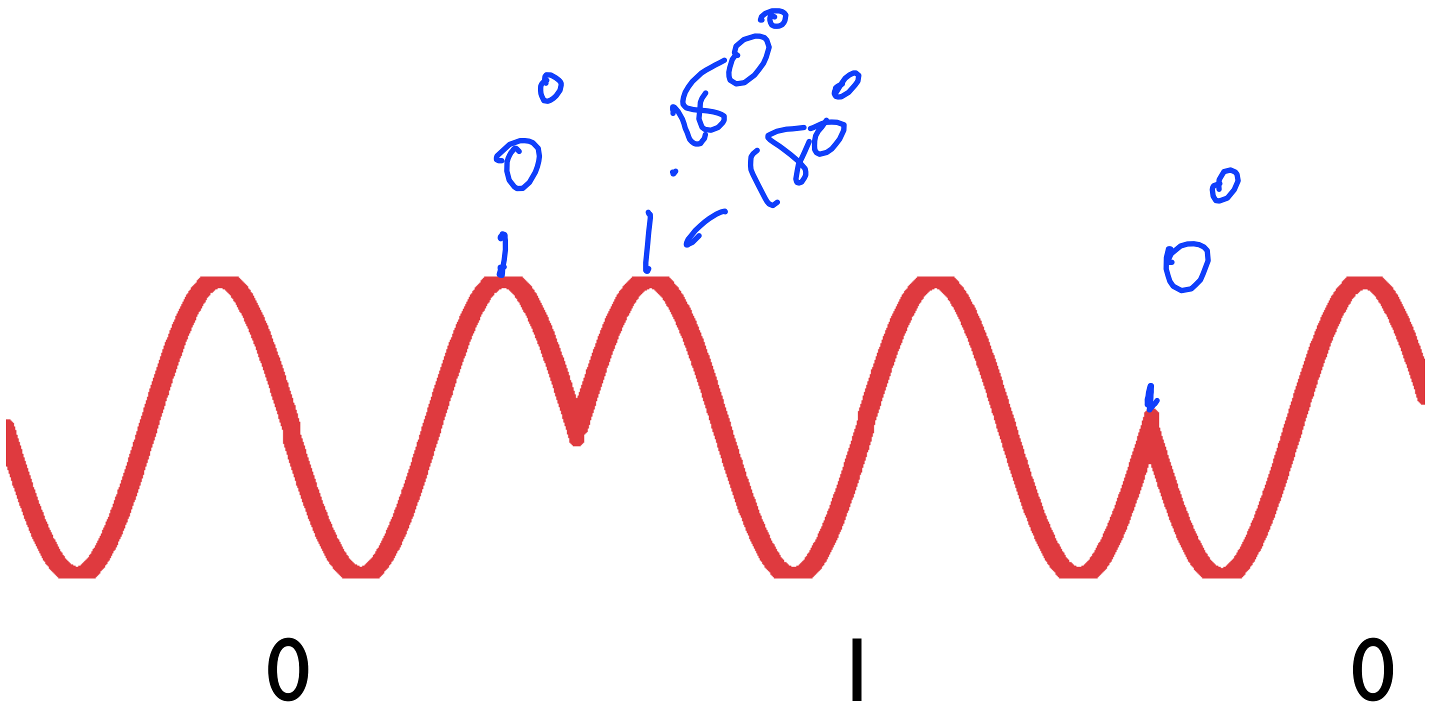
1 0 1

Amplitude Shift Keying

- ASK works well in wired networks because signal strength does not decrease much with distance
  - Used in most common wired Ethernet systems
- PAM-5: five level pulse amplitude modulation (-2, -1, 0, +1, +2)
  - Used in 100BASE-T and 1000BASE-T Ethernet (100Mbps and gigabit)
- PAM-16: sixteen level pulse amplitude modulation
  - Used in 10GBASE-T Ethernet (10 gigabit)

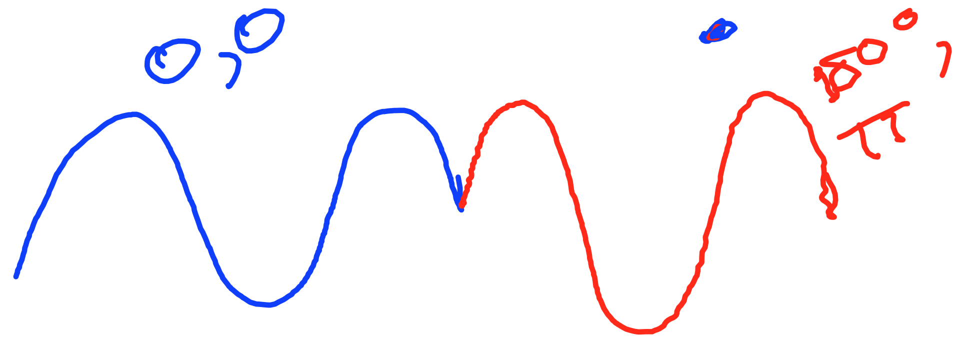
Modulation: PSK

Phase Shift Keying (PSK)

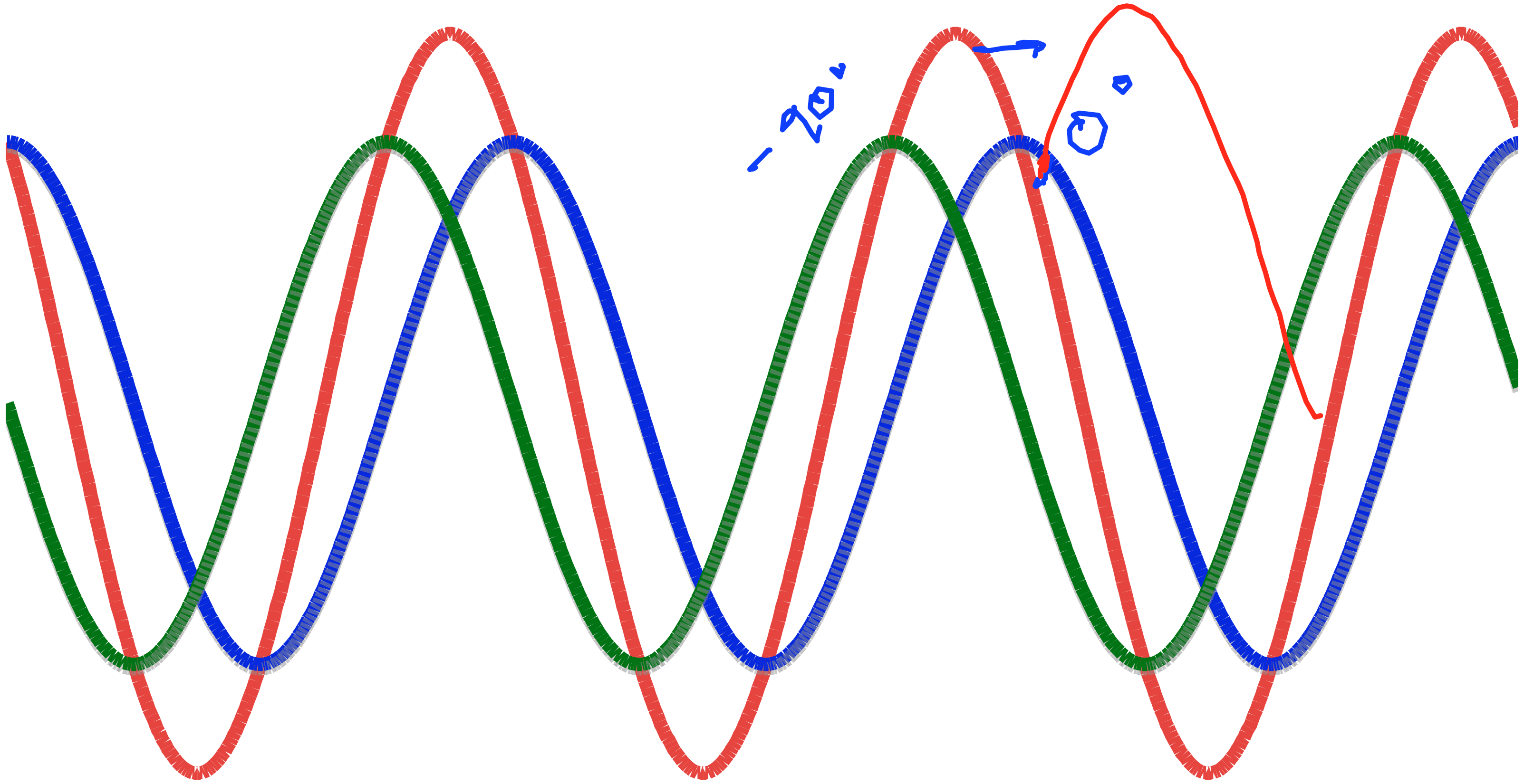


Phase Shift Keying

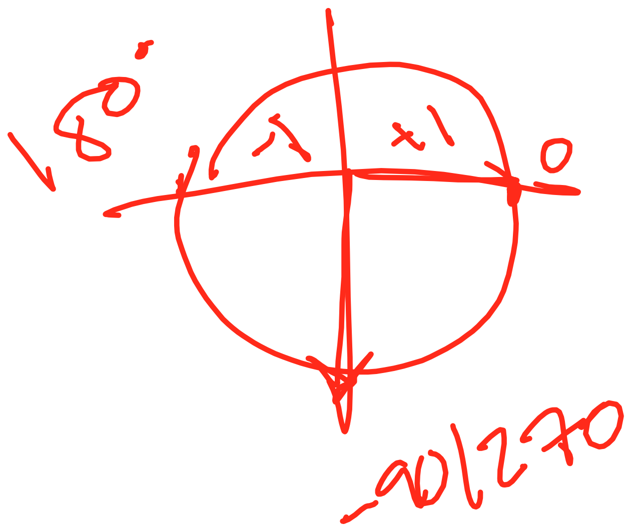
- PSK works well when there can be significant variations in signal strength
  - DSL, cable modems, wireless all use phase shift keying
- Binary phase shift keying (BPSK)
  - Two phases: (0, π)/(0, 180°)
  - Used in 1Mbps and 2Mbps 802.11b (WiFi)
- Quadrature phase shift keying (QPSK)
  - Four phases: (0, π/2, π, 3π/2)/(0, 90°, 180°, 270°)
  - Used in 5.5Mbps and 11Mbps 802.11b (WiFi)



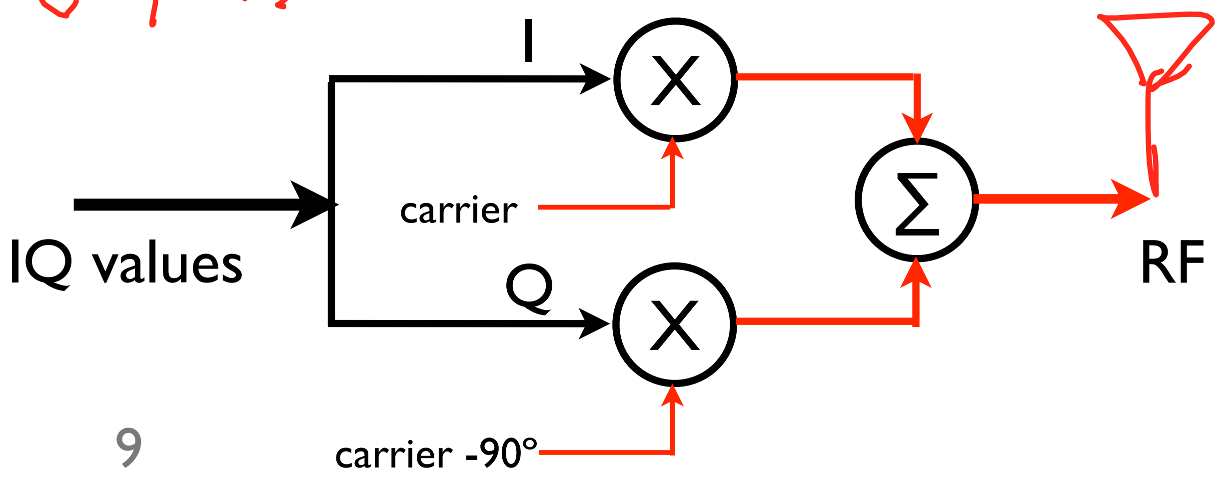
Shifting Phase



I/Q Modulation

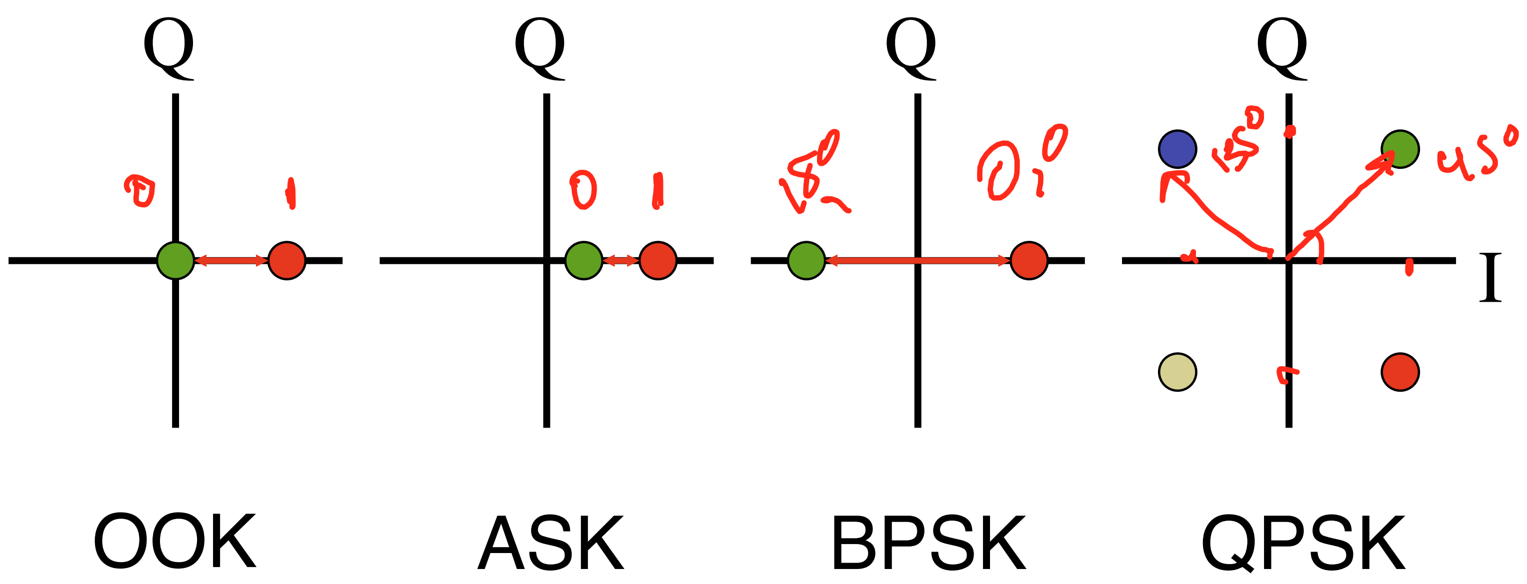


- I: *in-phase* component (0°)
- Q: *quadrature* component (-90°)
- A symbol is a linear combination of I and Q
  - Binary phase shift keying (BPSK)
    - Two phases: 0°, 180°
    - (I,Q) = (1,0) (-1,0)
  - Quadrature phase shift keying (QPSK)
    - Four phases: 0°, 270°, 180°, 90°
    - (I,Q) = (1,0) (0,1) (-1,0) (0,-1)

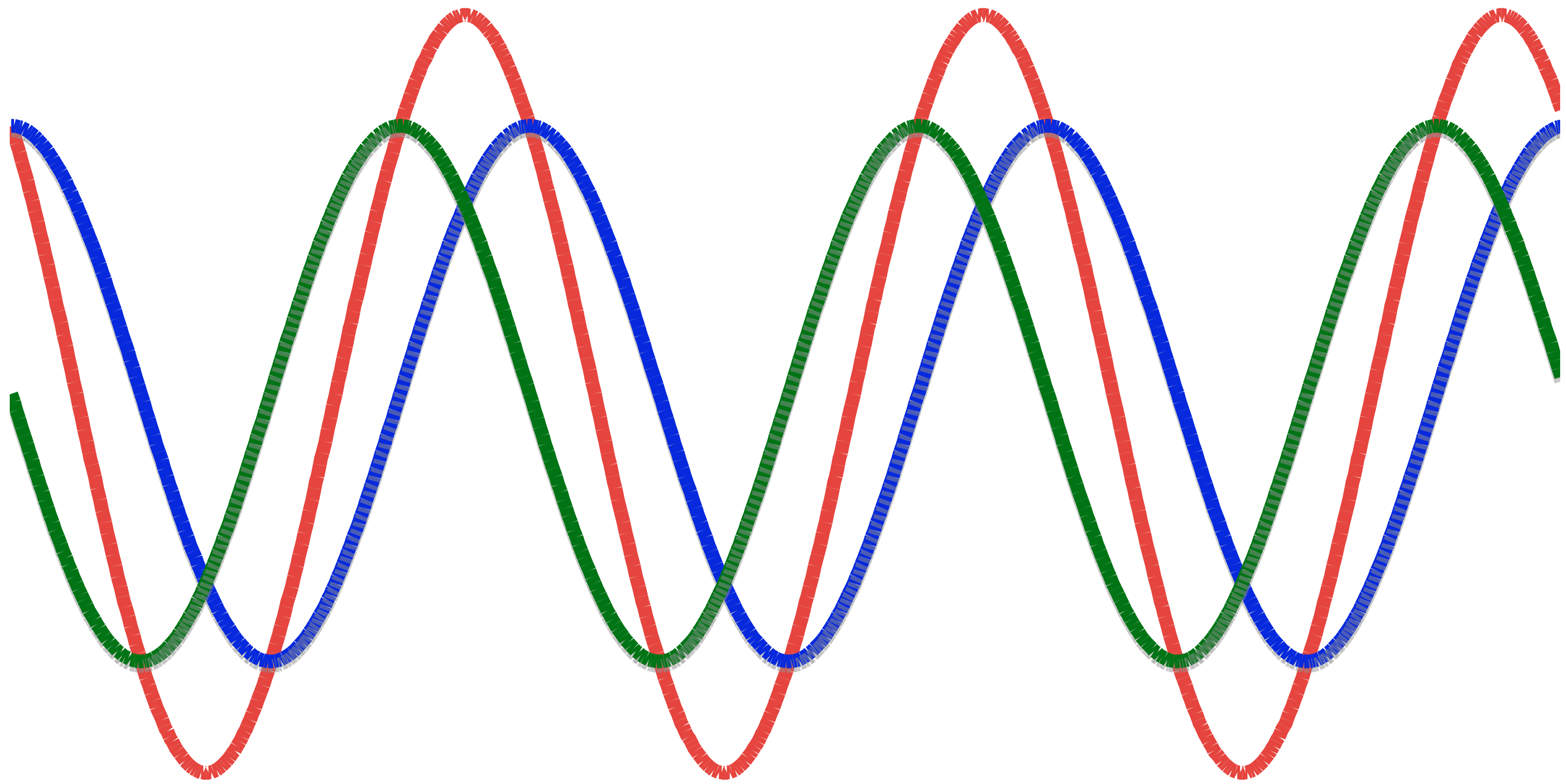


I/Q Constellations

- For phase shift keying, can represent symbols in an *I/Q constellation*, a 2D plot of the IQ values
  - Angle of vector: phase of signal
  - Length of vector: amplitude of signal



Shifting Phase



Symbols vs. Bits

0110011..

- A symbol is the unit of transfer at the physical layer
- A symbol can contain more than one bit
  - BPSK: 1 bit per symbol (0, 1)
  - QPSK: 2 bits per symbol (00, 01, 10, 11)
- Example: wired 100BASE-T Ethernet (100Mbps, Cat-5 cable)
  - 5 voltage levels of PAM-5 (-2, -1, 0, +1 +2)

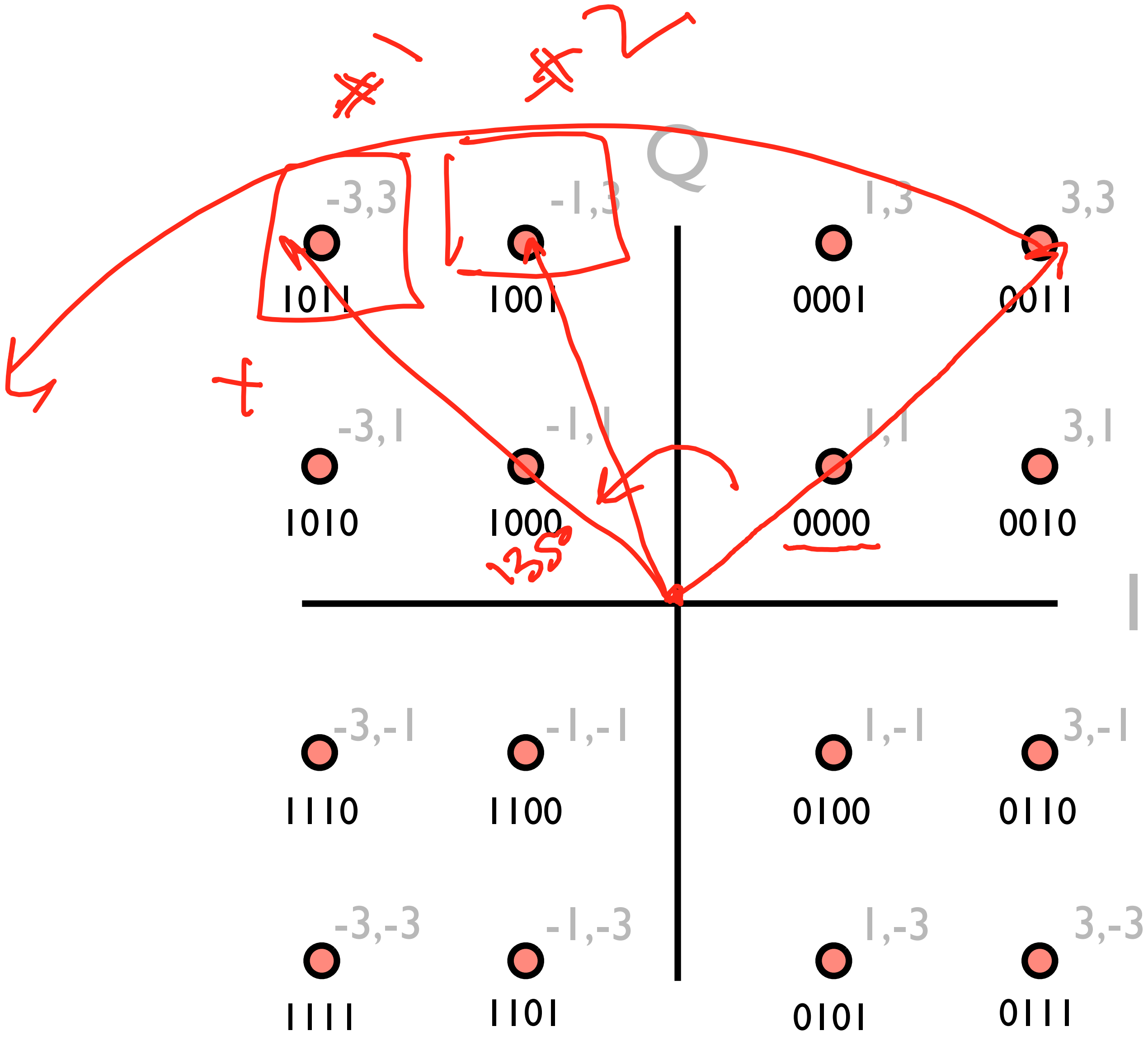
QAM

Phase and amplitude keying

- Amplitude shift keying and on/off keying use only amplitude to encode symbols
- Phase shift keying uses only phase to encode symbols
- Quadrature Amplitude Modulation (QAM) uses both amplitude and phase
  - 16-QAM: 16 symbols, 4 bits/symbol
  - 256-QAM: 256 different symbols, 8 bits/symbol

Example: 16-QAM

(constellation used in HSPDA, 3G data standard)



1011 1001
#1
105°

Examples Today

- ASK/OOK: Wired Ethernet
- FSK: NWS "Weatheradio," Bluetooth
- BPSK: 802.11abgn, WiMAX
- QPSK: 802.11abgn, 802.15.4, HSPDA, LTE, WiMAX
- 16-QAM: 802.11abgn, HSPDA, LTE, WiMAX
- 64-QAM: 802.11abgn, LTE, WiMAX

Overview

- Many ways to represent bits in terms of analog signals: frequency, amplitude, phase
- Wired Ethernet uses amplitude (ASK)
- Most technologies today use phase (PSK) or phase and amplitude (QAM)
- Can represent a QAM symbol as a linear combination of the In-phase component (I) and the Quadrature component (Q)
  - How actual circuits do it
  - Nice visualization in a 2D plot