Introduction to Computer Networks

Overview of the Physical Layer

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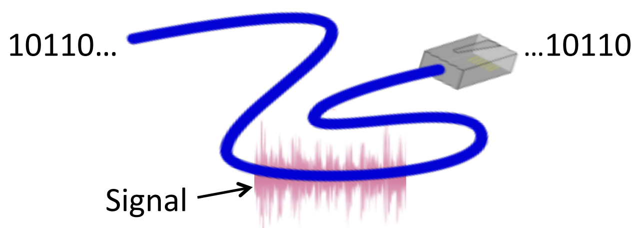
Where we are in the Course

- Beginning to work our way up starting with the Physical layer

Application
Transport
Network
Link
Physical

Scope of the Physical Layer

- Concerns how signals are used to transfer message bits over a link
  - Wires etc. carry analog signals
  - We want to send digital bits



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Topics

1. Properties of media
   - Wires, fiber optics, wireless
2. Simple signal propagation
   - Bandwidth, attenuation, noise
3. Modulation schemes
   - Representing bits, noise
4. Fundamental limits
   - Nyquist, Shannon

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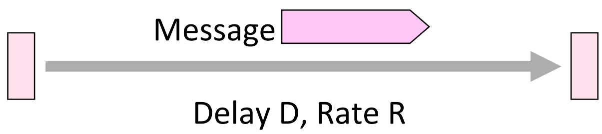
Simple Link Model

- We'll end with abstraction of a physical channel
  - Rate (or bandwidth, capacity, speed) in bits/second
  - Delay in seconds, related to length



- Other important properties:
  - Whether the channel is broadcast, and its error rate

Message Latency

- <u>Latency</u> is the delay to send a message over a link
  - <u>Transmission delay</u>: time to put M-bit message "on the wire"
  - <u>Propagation delay</u>: time for bits to propagate across the wire
  - Combining the two terms we have:

Message Latency

- Latency is the delay to send a message over a link
  - Transmission delay: time to put M-bit message "on the wire"

    T-delay = M (bits) / Rate (bits/sec) = M/R seconds

  - Propagation delay: time for bits to propagate across the wire

    P-delay = Length / speed of signals = L/⅔c = D seconds

  - Combining the two terms we have: Latency = M/R + D

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Metric Units

- The main prefixes we use:

Prefix	Exp.	prefix	exp.
K(ilo)	10^3	m(illi)	10^{-3}
M(ega)	10^6	μ(micro)	10^{-6}
G(iga)	10^9	n(ano)	10^{-9}

- Use powers of 10 for rates, 2 for storage
  - 1 Mbps = 1,000,000 bps, 1 KB = 1024 bytes
- "B" is for bytes, "b" is for bits

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Latency Examples

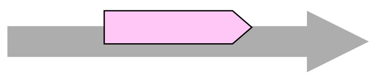
- "Dialup" with a telephone modem:
  - D = 5ms, R = 56 kbps, M = 1250 bytes
- Broadband cross-country link:
  - D = 50ms, R = 10 Mbps, M = 1250 bytes

Latency Examples (2)

- "Dialup" with a telephone modem:
  D = 5ms, R = 56 kbps, M = 1250 bytes
  L = 5ms + (1250 x 8)/(56 x 10^3) sec = 184ms!
- Broadband cross-country link:
  D = 50ms, R = 10 Mbps, M = 1250 bytes
  L = 50ms + (1250 x 8) / (10 x 10^6) sec = 51ms
- A long link or a slow rate means high latency
  - Often, one delay component dominates

Bandwidth-Delay Product

- Messages take space on the wire!



- The amount of data in flight is the <u>bandwidth-delay (BD) product</u>
  - Measure in bits, or in messages
  - Small for LANs, big for "long fat" pipes

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Bandwidth-Delay Example

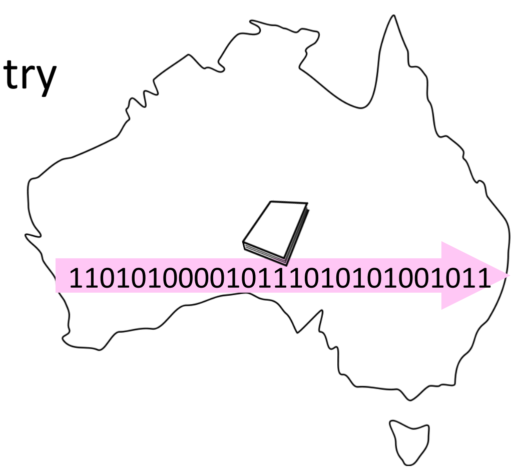
- Fiber at home, cross-country

  R=40 Mbps, D=50ms

  BD $= 40 \times 50 \times 10^3$ bits

  $= 250$ KB

- That's quite a lot of data "in the network"!



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Media (Wires, etc.) (§2.2, 2.3)

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Types of Media

- Media propagate signals that carry bits of information
- We'll look at some common types:
  - Wires »
  - Fiber (fiber optic cables) »
  - Wireless »

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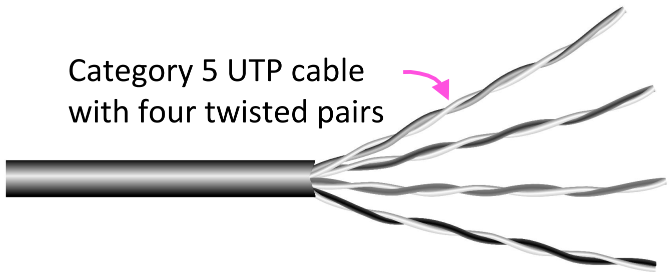
Wires – Twisted Pair

- Very common; used in LANs and telephone lines
  - Twists reduce radiated signal



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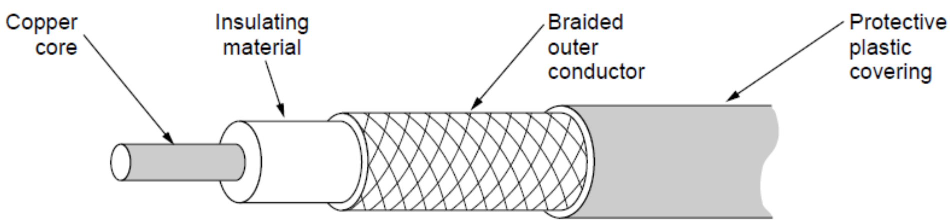
Wires – Coaxial Cable

- Also common. Better shielding for better performance



- Other kinds of wires too: e.g., electrical power

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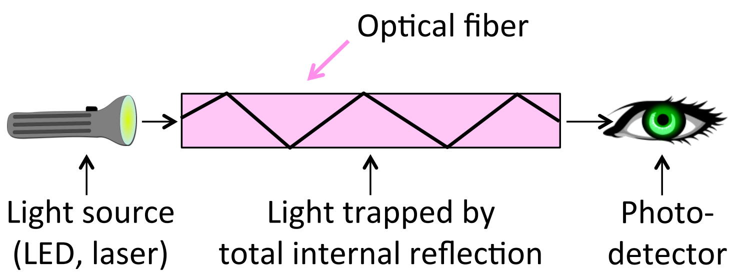
Fiber

- Long, thin, pure strands of glass
  - Enormous bandwidth over long distances



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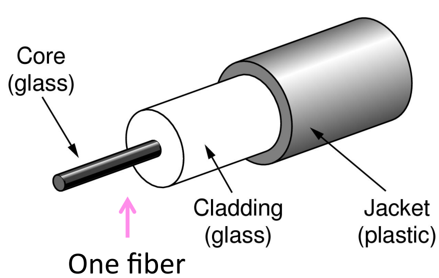
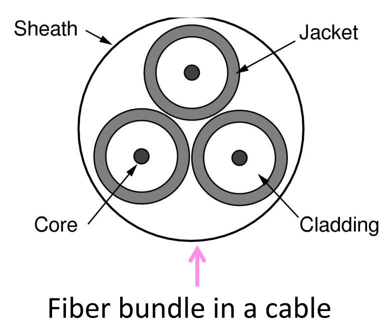
Fiber (2)

- Two varieties: multi-mode (shorter links, cheaper) and single-mode (up to ~100 km)





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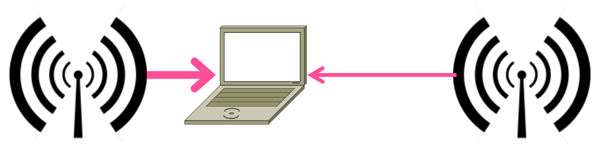
Wireless

- Sender radiates signal over a region
  - In many directions, unlike a wire, to potentially many receivers
  - Nearby signals (same freq.) <u>interfere</u> at a receiver; need to coordinate use



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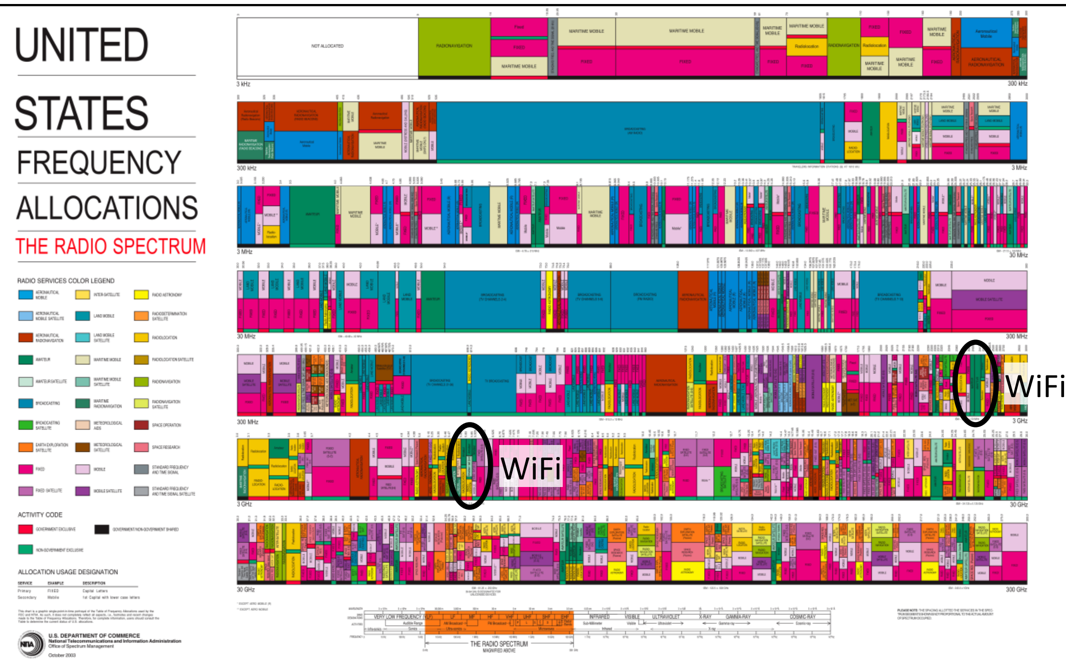

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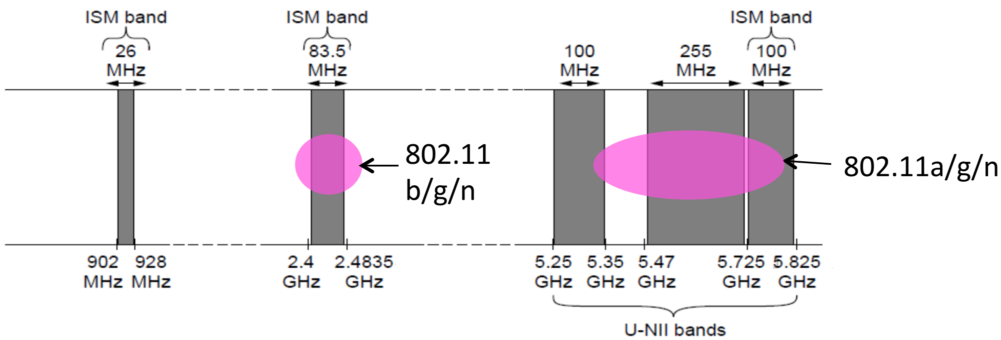
Wireless (2)

- Microwave, e.g., 3G, and unlicensed (ISM) frequencies, e.g., WiFi, are widely used for computer networking



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Signals (§2.2)

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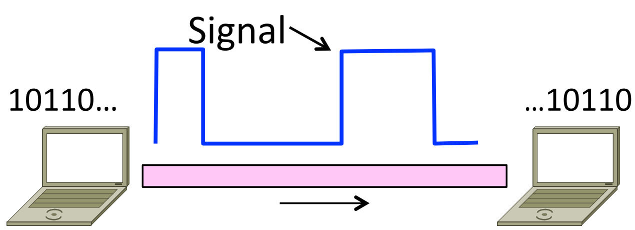
Topic

- Analog signals encode digital bits. We want to know what happens as signals propagate over media



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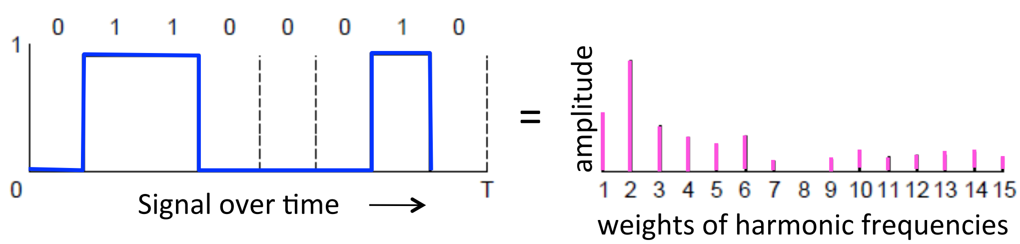
Frequency Representation

- A signal over time can be represented by its frequency components (called Fourier analysis)

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi n f t) + \sum_{n=1}^{\infty} b_n \cos(2\pi n f t)$$



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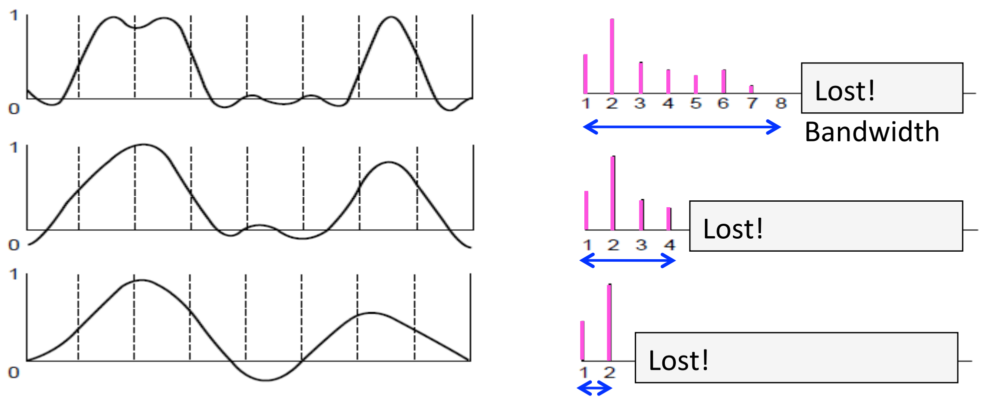
Effect of Less Bandwidth

- Less bandwidth degrades signal (less rapid transitions)



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Signals over a Wire

- What happens to a signal as it passes over a wire?
  - The signal is delayed (propagates at ⅔c)
  - The signal is attenuated (goes for m to km)
  - Noise is added to the signal (later, causes errors)
  - Frequencies above a cutoff are highly attenuated

EE: Bandwidth = width of frequency band, measured in Hz
CS: Bandwidth = information carrying capacity, in bits/sec

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Signals over a Wire (2)

- Example:

Sent signal

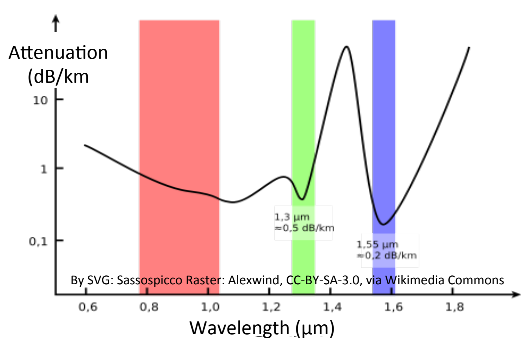
1: Attenuation:

2: Bandwidth:

3: Noise:

Signals over Fiber

- Light propagates with very low loss in three very wide frequency bands
  - Use a carrier to send information



Signals over Wireless (§2.2)

- Signals transmitted on a carrier frequency
- Travel at speed of light, spread out and attenuate faster than $1/dist^2$
- Multiple signals on the same frequency interfere at a receiver
- Other effects are highly frequency dependent, e.g., multipath at microwave frequencies

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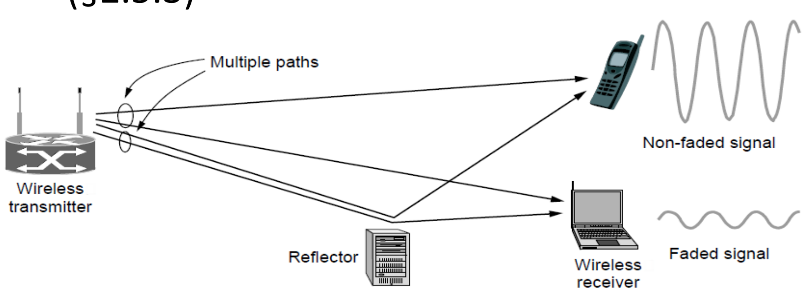
Wireless Multipath

- Signals bounce off objects and take multiple paths
  - Some frequencies attenuated at receiver, varies with location
  - Messes up signal; handled with sophisticated methods (§2.5.3)



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Modulation (§2.5)

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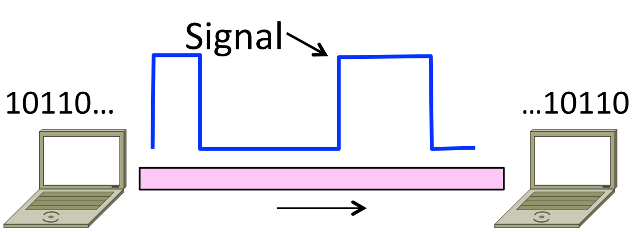
Topic

- We've talked about signals representing bits. How, exactly?
  - This is the topic of modulation



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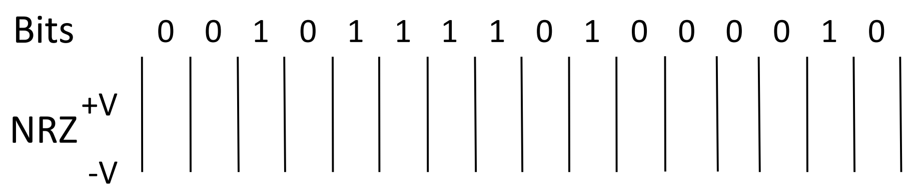
A Simple Modulation

- Let a high voltage (+V) represent a 1, and low voltage (-V) represent a 0
  - This is called NRZ (Non-Return to Zero)



A Simple Modulation (2)

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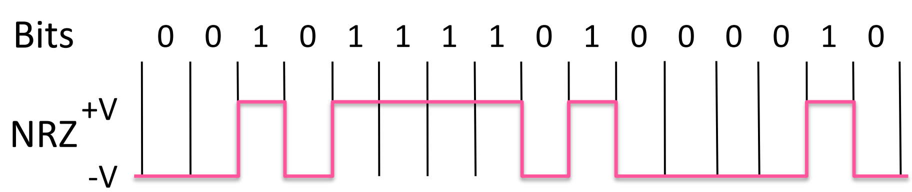

Many Other Schemes

- Can use more signal levels, e.g., 4 levels is 2 bits per symbol
- Practical schemes are driven by engineering considerations
  - E.g., clock recovery »

Clock Recovery

- Um, how many zeros was that?
  - Receiver needs frequent signal transitions to decode bits

    1 0 0 0 0 0 0 0 0 0 … 0

- How do we address this problem?

Clock Recovery – 4B/5B

- Map every 4 data bits into 5 code bits with a transition that are sent
  - 0000 → 11110, 0001 → 01001, 1110 → 11100, … 1111 → 11101
  - Has at most 3 zeros in a row

Clock Recovery – 4B/5B (2)

- 4B/5B code for reference:
  - 0000→11110, 0001→01001, 1110→11100, … 1111→11101

- Message bits: 1 1 1 1 0 0 0 0 0 0 0 1

Coded Bits:

Signal:

Passband Modulation

- What we have seen so far is <u>baseband</u> modulation for wires
  - Signal is sent directly on a wire
- These signals do not propagate well on fiber / wireless
  - Need to send at higher frequencies
- <u>Passband</u> modulation carries a signal by modulating a carrier

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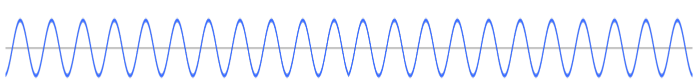
Passband Modulation (2)

- Carrier is simply a signal oscillating at a desired frequency:



- We can modulate it by changing:
  - Amplitude, frequency, or phase

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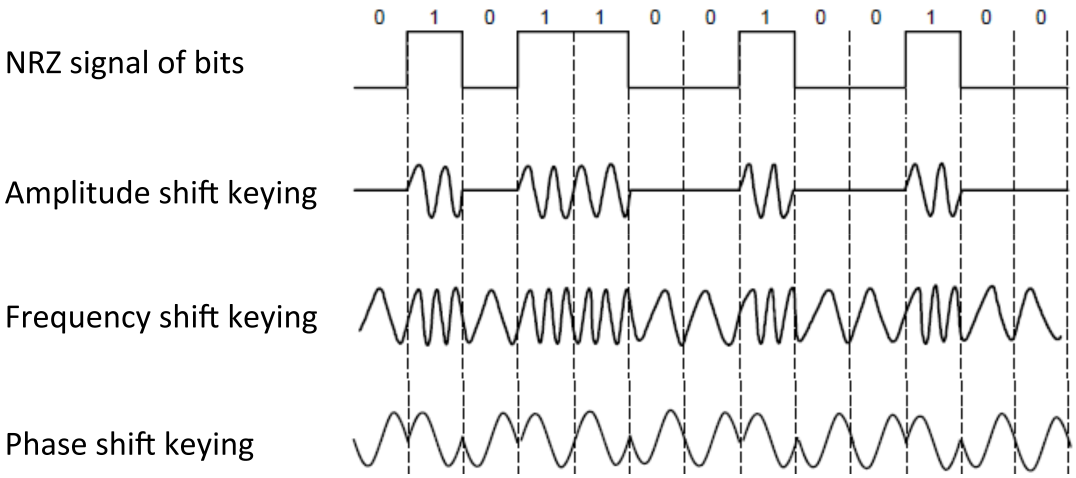
Passband Modulation (3)



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Fundamental Limits (§2.2)

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Topic

- How rapidly can we send information over a link?
  - Nyquist limit (~1924) »
  - Shannon capacity (1948) »
- Practical systems are devised to approach these limits

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Key Channel Properties

- The bandwidth (B), signal strength (S), and noise strength (N)
  - B limits the rate of transitions
  - S and N limit how many signal levels we can distinguish

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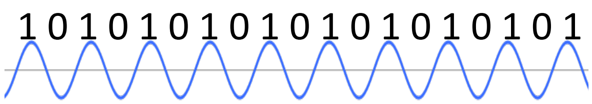
Nyquist Limit

- The maximum symbol rate is 2B



- Thus if there are V signal levels, ignoring noise, the maximum bit rate is:

$$R = 2B \log_2 V \text{ bits/sec}$$

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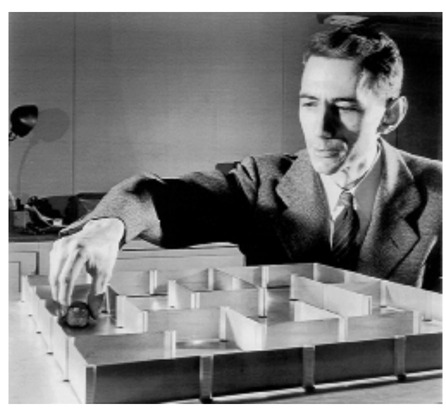
Claude Shannon (1916-2001)

- Father of information theory
  - "A Mathematical Theory of Communication", 1948
- Fundamental contributions to digital computers, security, and communications

Electromechanical mouse that "solves" mazes!



Credit: Courtesy MIT Museum

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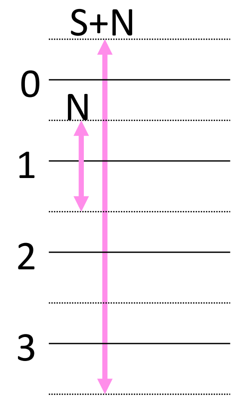
Shannon Limit

- How many levels we can distinguish depends on S/N
  - Or SNR, the Signal-to-Noise Ratio
  - Note noise is random, hence some errors
- SNR given on a log-scale in deciBels:
  - $SNR_{dB} = 10\log_{10}(S/N)$



Shannon Limit (2)

- Shannon limit is for capacity (C), the maximum information carrying rate of the channel:

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

Wired/Wireless Perspective

- Wires, and Fiber

  Engineer SNR for data rate

  – Engineer link to have requisite SNR and B

  → Can fix data rate

- Wireless

  Adapt data rate to SNR

  – Given B, but SNR varies greatly, e.g., up to 60 dB!

  → Can't design for worst case, must adapt data rate

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