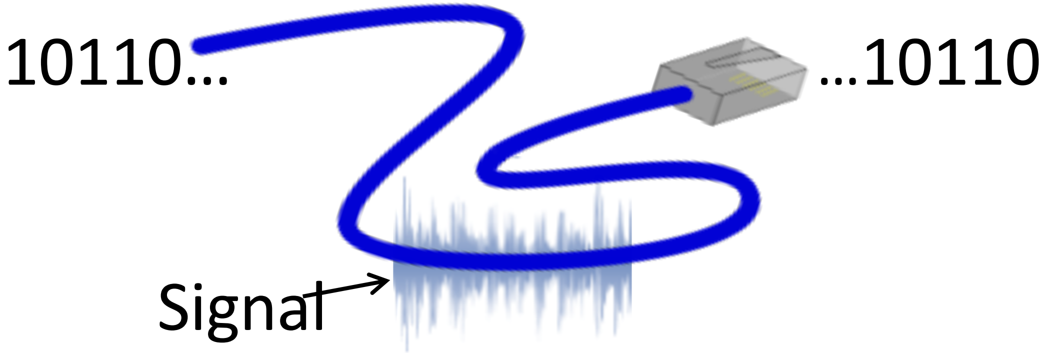
Physical Layer

Physical Layer

- Transfers bits through signals overs links
  - Wires etc. carry analog signals
  - We want to send digital bits



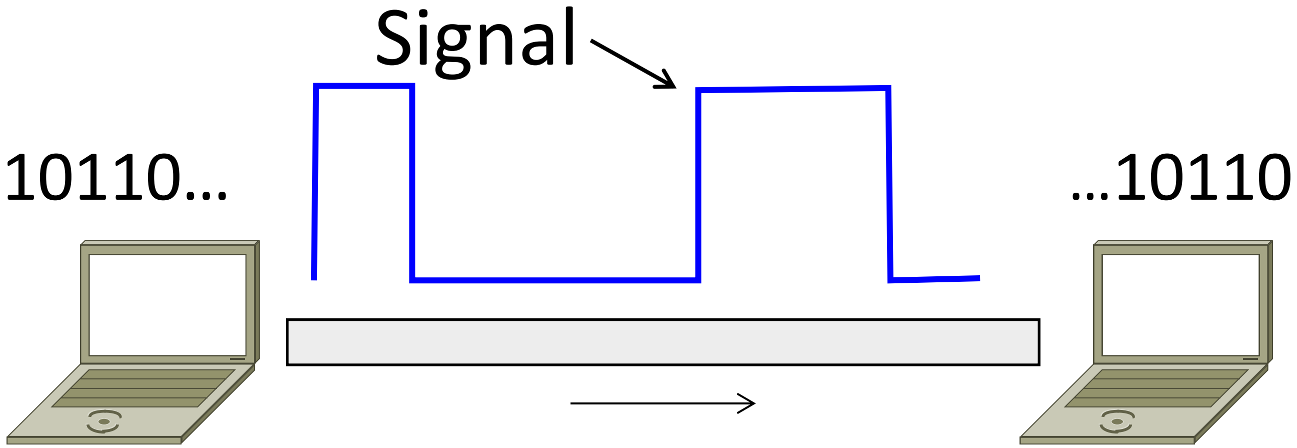
Topics

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

Coding and Modulation

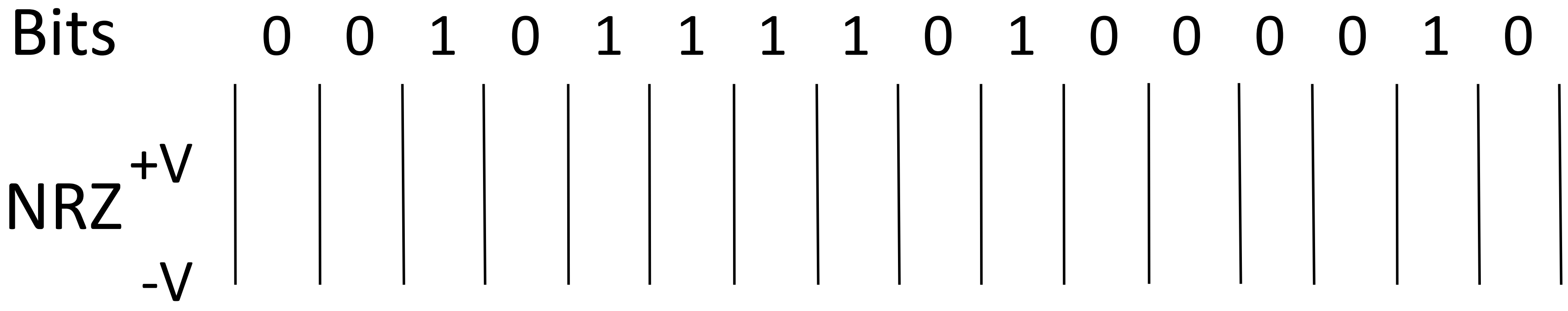
Topic

- How can we send information across a link?
  - This is the topic of coding and modulation
  - Modem (from modulator–demodulator)



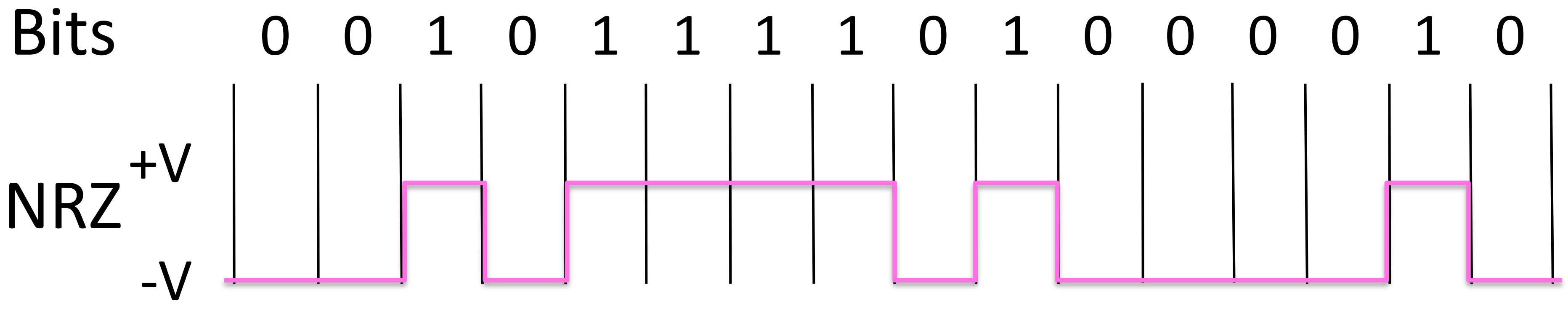
A Simple Coding Scheme

- 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 Coding Scheme (2)

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



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

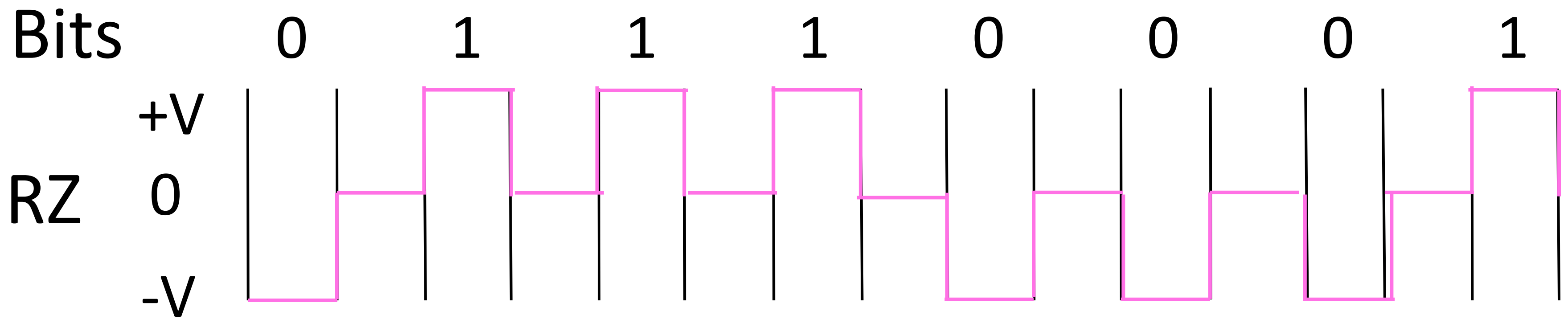
- Um, how many zeros was that?
  - Receiver needs frequent signal transitions to decode bits

- Several possible designs
  - E.g., Manchester coding and scrambling (§2.5.1)

Ideas?

Answer 1: A Simple Coding

- Let a high voltage (+V) represent a 1, and low voltage (-V) represent a 0
- Then go back to 0V for a "Reset"
  - This is called RZ (Return to Zero)



Answer 2: Clock Recovery – 4B/5B

- Map every 4 data bits into 5 code bits without long runs of zeros
  - 0000 → 11110, 0001 → 01001, 1110 → 11100, … 1111 → 11101
  - Has at most 3 zeros in a row
  - Also invert signal level on a 1 to break up long runs of 1s (called NRZI, §2.5.1)

Answer 2: 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:

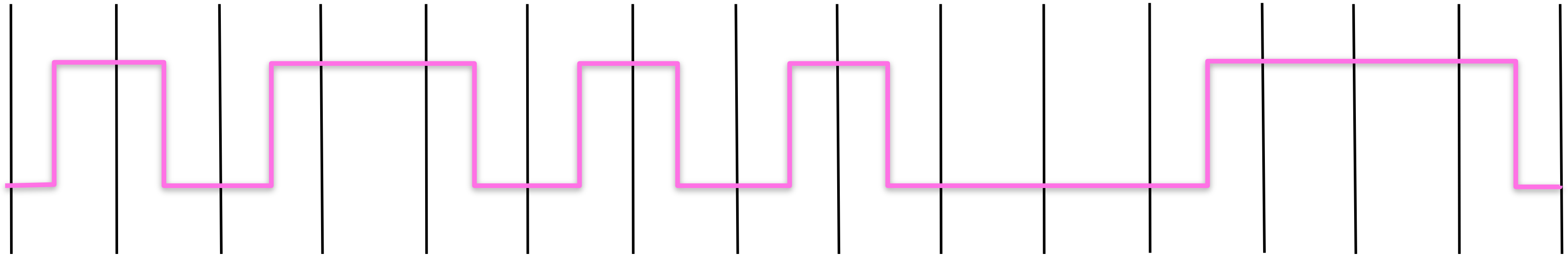
Signal:

Clock Recovery – 4B/5B (3)

- 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: 1 1 1 0 1 1 1 1 1 0 0 1 0 0 1

Signal:

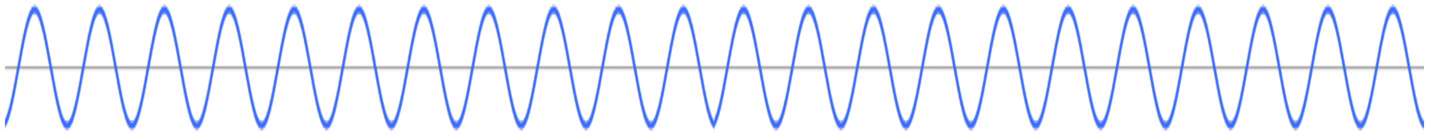


Coding vs. Modulation

- What we have seen so far is coding
  - Signal is sent directly on a wire
- These signals do not propagate well as RF
  - Need to send at higher frequencies
- Modulation carries a signal by modulating a carrier
  - Baseband is signal pre-modulation
  - Keying is the *digital* form of modulation (equivalent to coding but using modulation)

Passband Modulation (2)

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



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

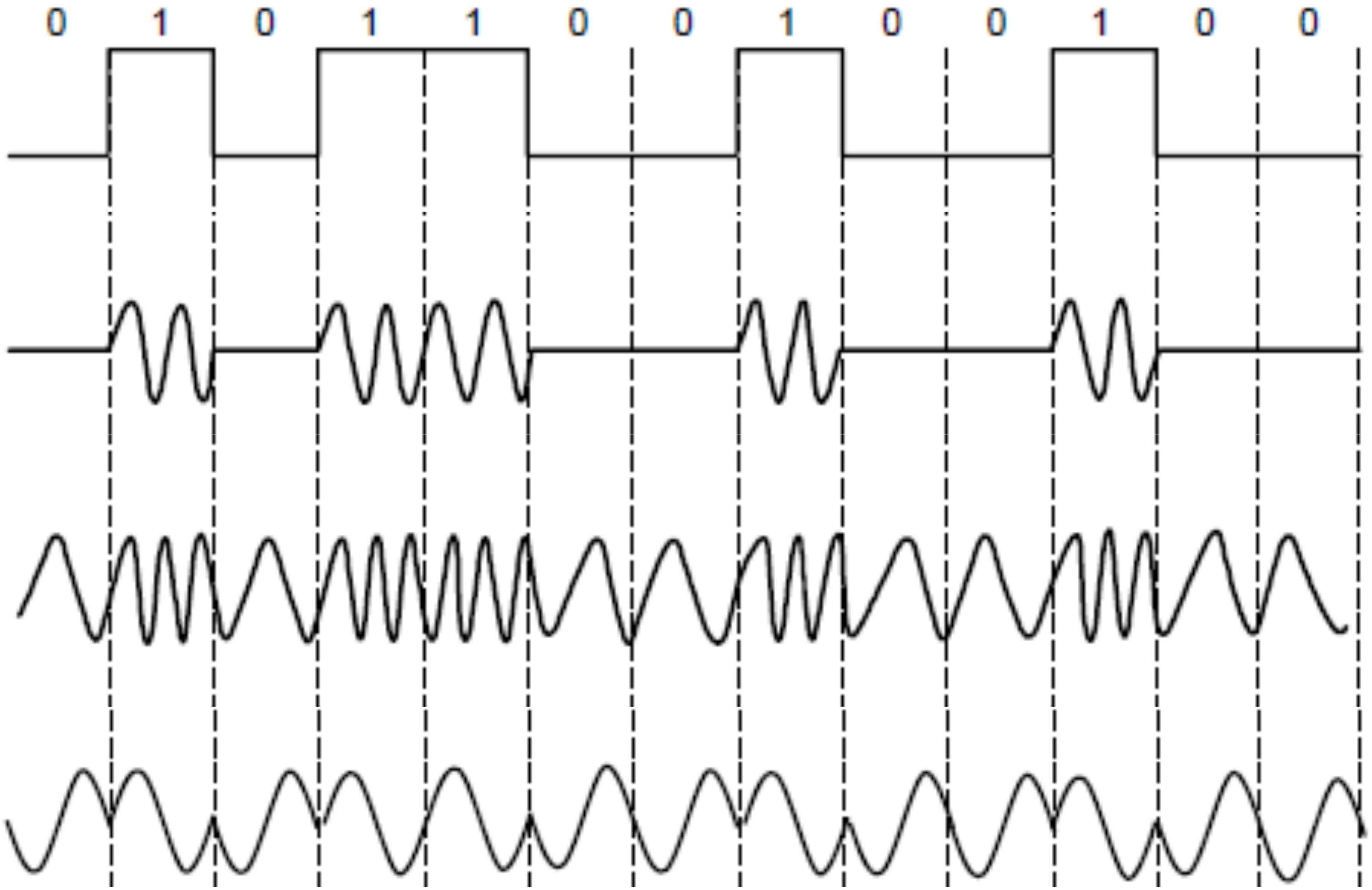
Comparisons

NRZ signal of bits

Amplitude shift keying

Frequency shift keying

Phase shift keying



Remember: Everything is ultimately analog

- Even digital signals
- Digital information is a *discrete* concept represented in an analog physical medium
    - A printed book (analog) vs.
    - Words conveyed in the book (digital)

Media

Types of Media

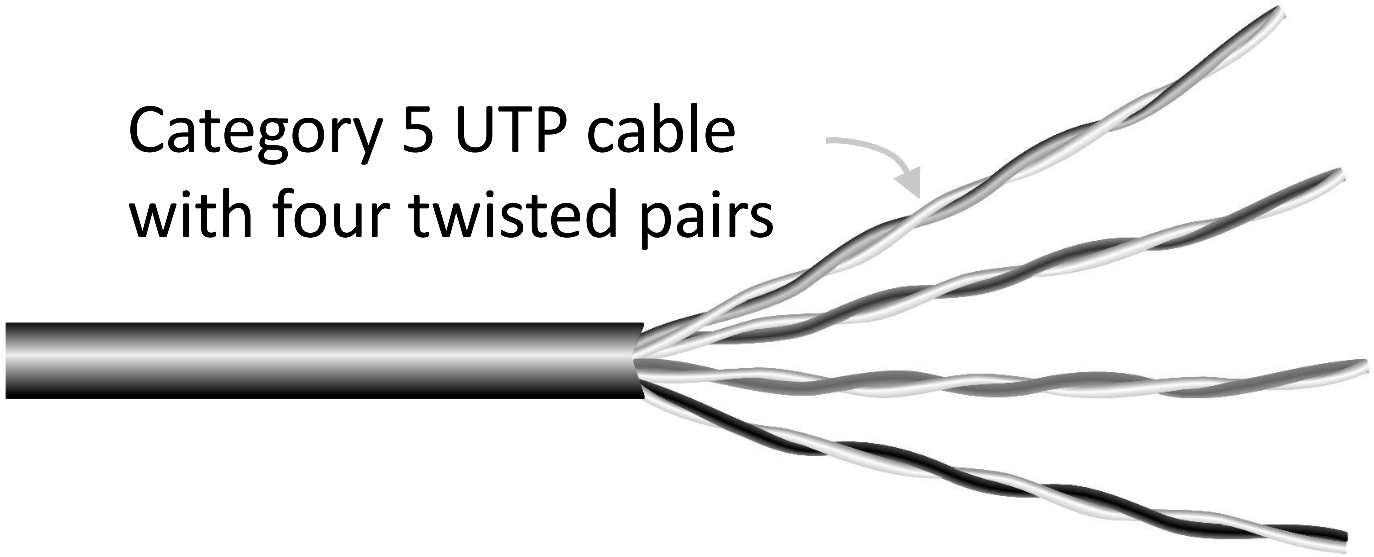
- Media propagate signals that carry bits

- Some common types:
  - Wires
  - Fiber (fiber optic cables)
  - Wireless

Wires – Twisted Pair

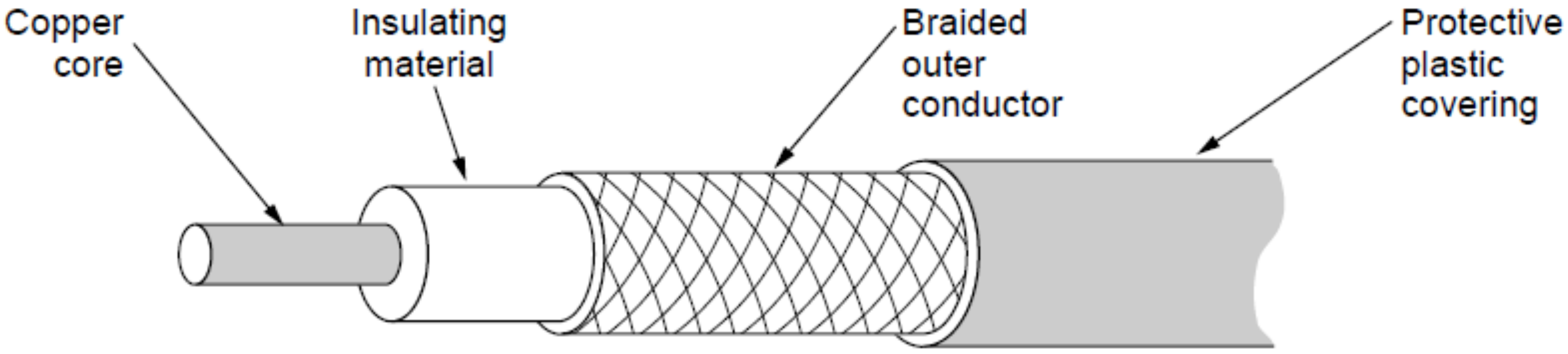
- Very common; used in LANs and telephone lines

Category 5 UTP cable
with four twisted pairs



Wires – Coaxial Cable

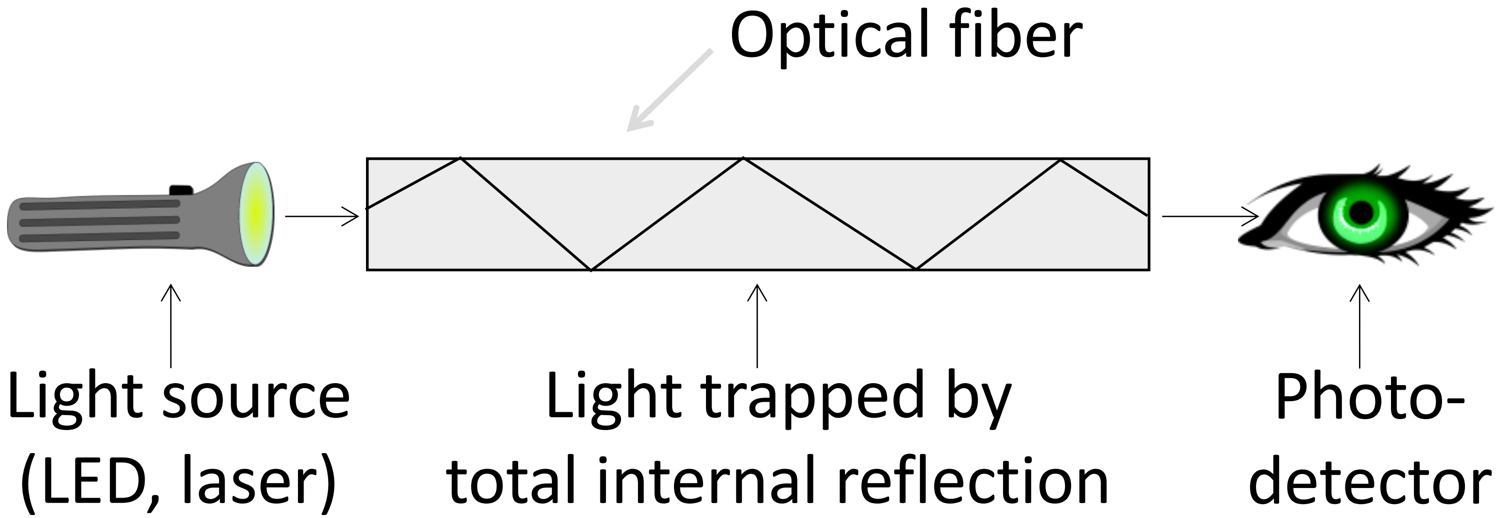
- Also common. Better shielding for better performance



- Other kinds of wires too: e.g., electrical power (§2.2.4)

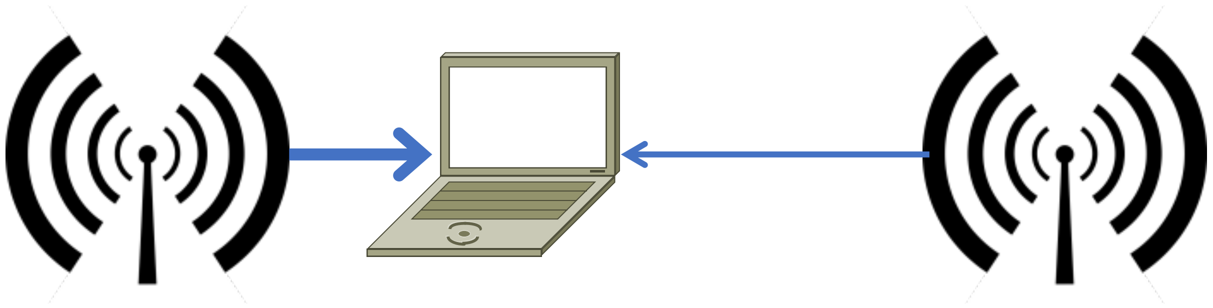
Fiber

- Long, thin, pure strands of glass
  - Enormous bandwidth (high speed) over long distances

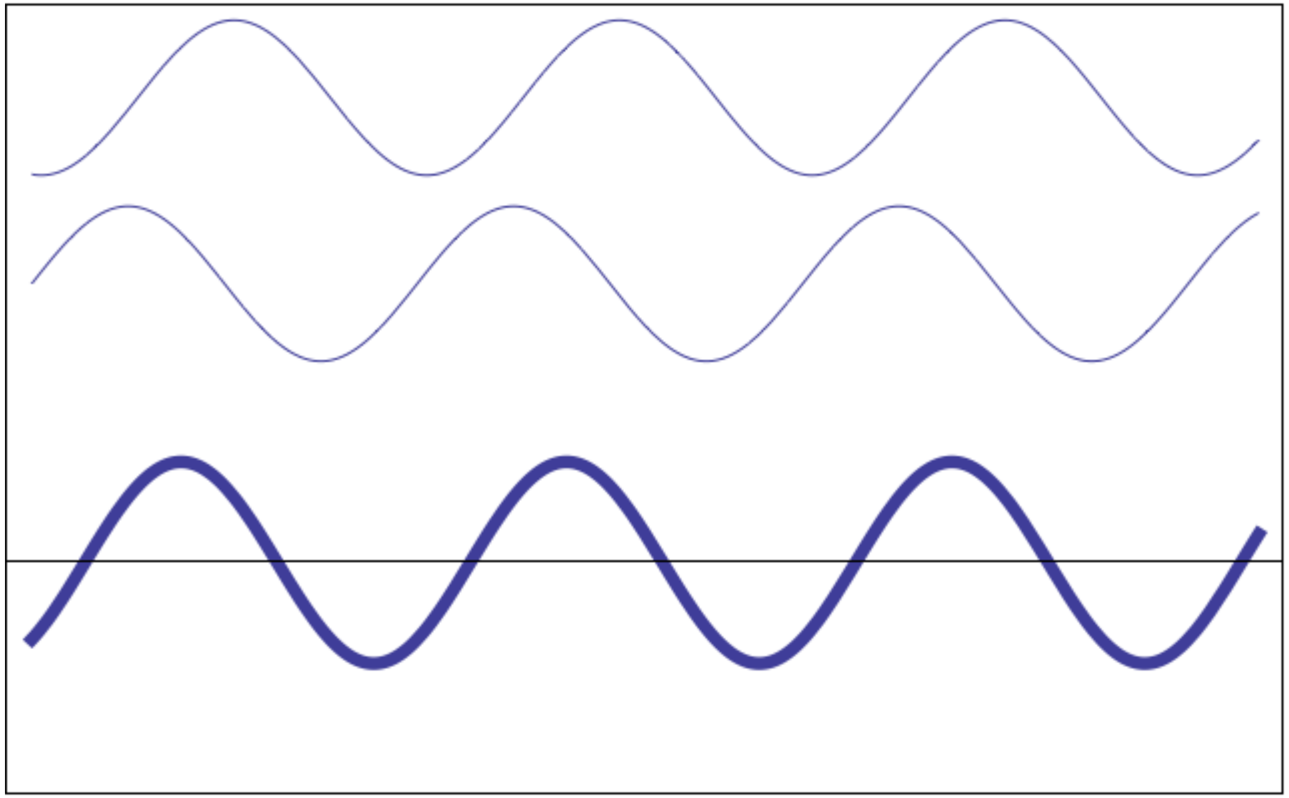


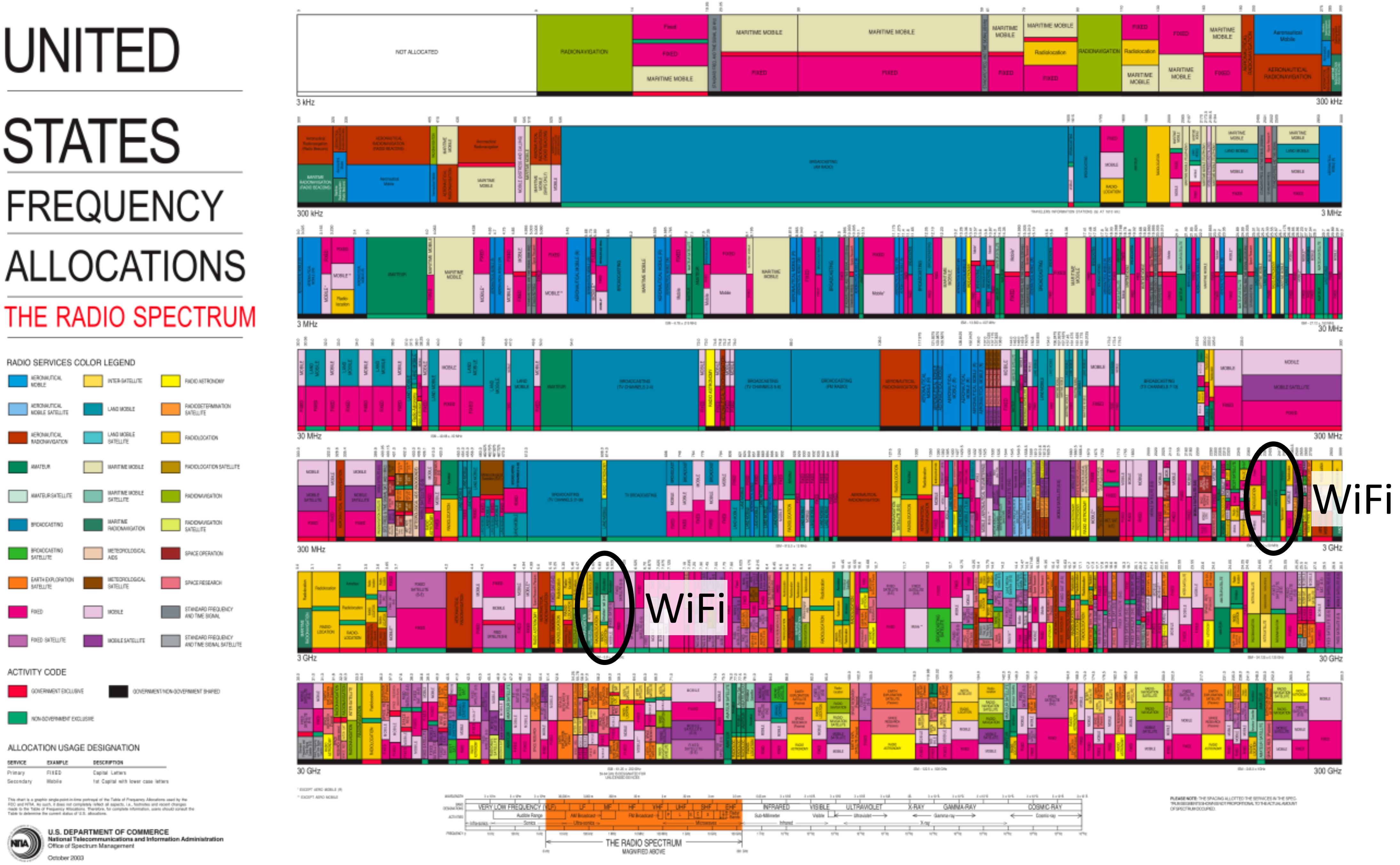
Wireless

- 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



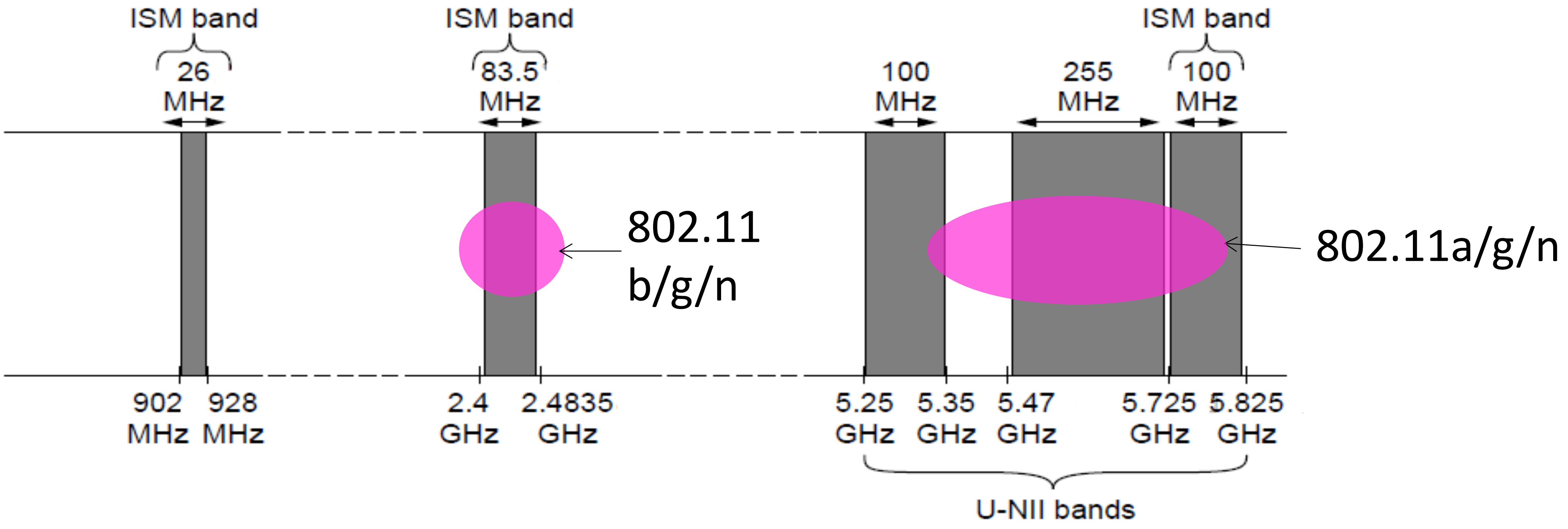
Wireless Interference




UNITED
STATES
FREQUENCY
ALLOCATIONS
THE RADIO SPECTRUM
RADIO SERVICES COLOR LEGEND
ACTIVITY CODE
ALLOCATION USAGE DESIGNATION
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003
3 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz
THE RADIO SPECTRUM
WiFi
WiFi

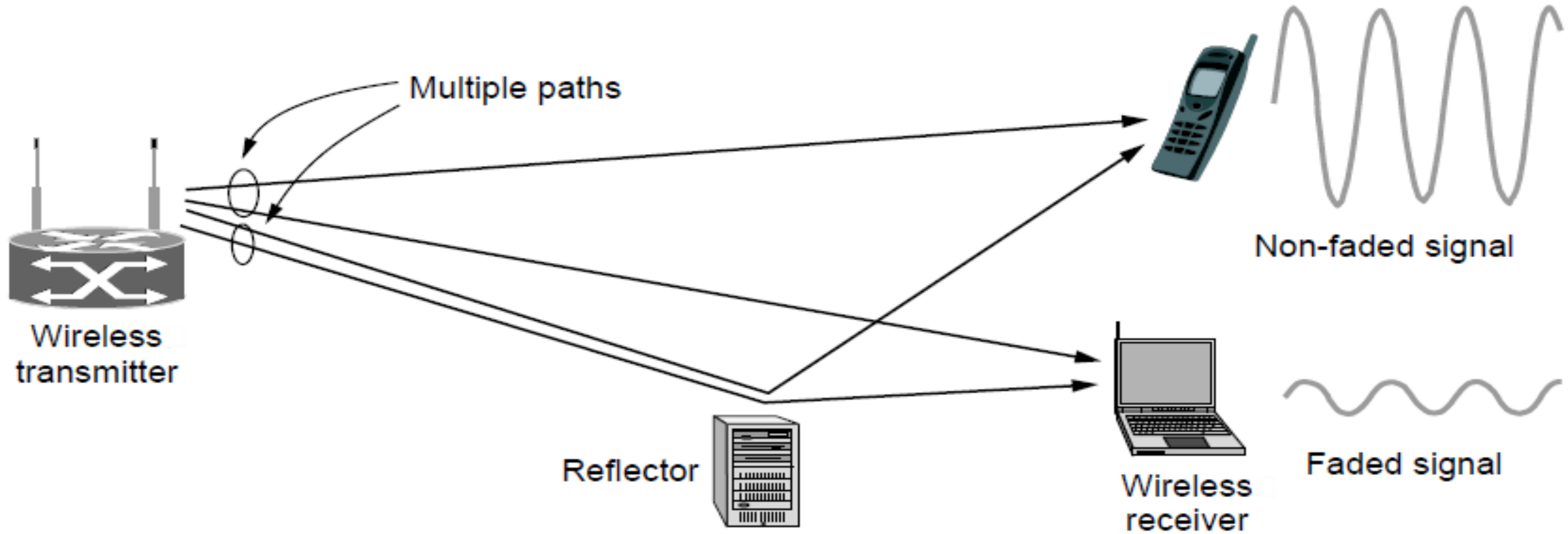
Wireless Bands

- Unlicensed (ISM) frequencies, e.g., WiFi, are widely used for computer networking



Multipath

- Signals bounce off objects and take multiple paths
  - Some frequencies attenuated at receiver, varies with location



Many Other Wireless Effects

- Wireless propagation is complex, depends on environment

- Some key effects are highly frequency dependent,
  - E.g., <u>multipath</u> at microwave frequencies

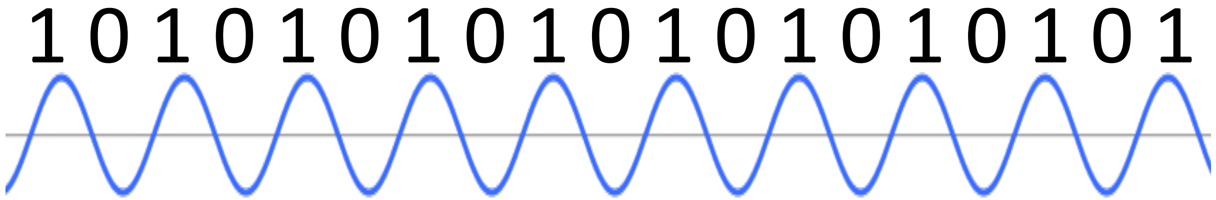
Fundamental Limits

How much data can we send over a link?

- Key channel properties
  - B: Bandwidth (hertz)
  - S: Signal strength
  - N: Noise
- B limits the rate of transitions, and S/N limits how many signal levels we can distinguish
  - Nyquist limit (~1924), Shannon capacity (1948)

Nyquist Limit

- The maximum symbol rate is 2B



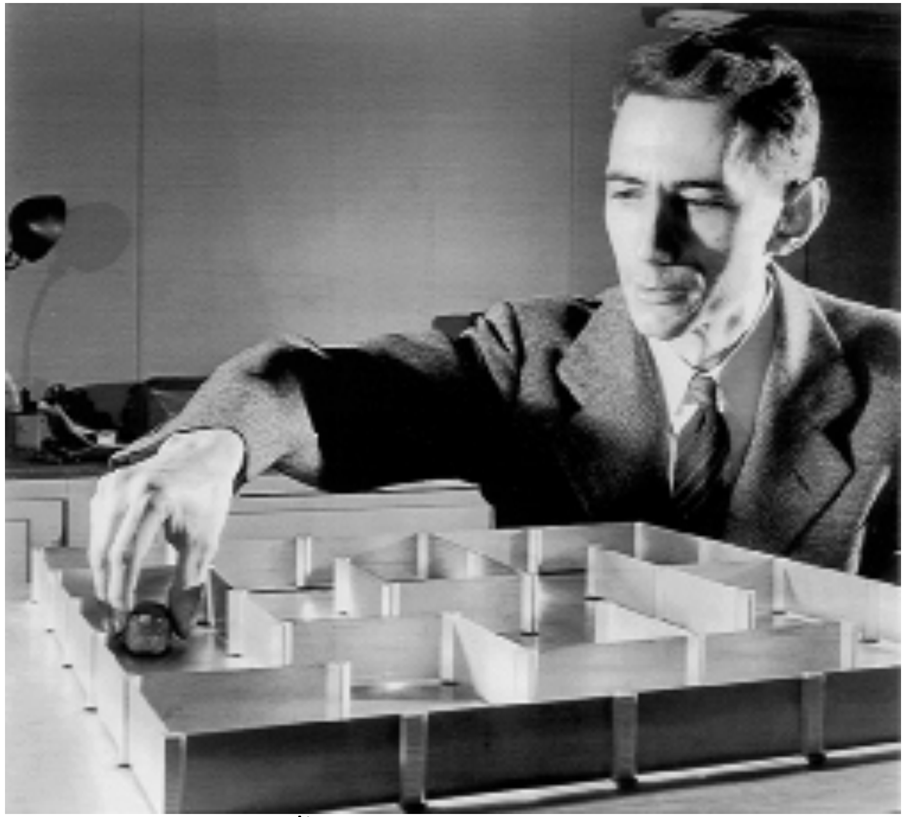
- Thus if there are V signal levels, ignoring noise, the maximum bit rate is:

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

Claude Shannon (1916-2001)

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

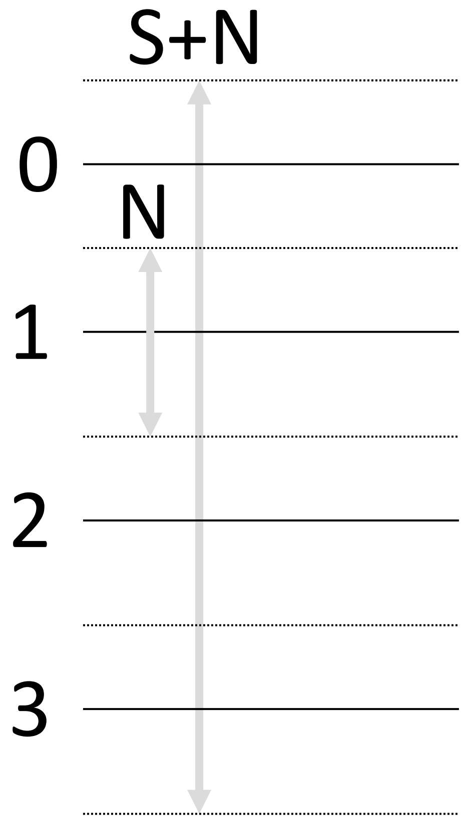
Electromechanical mouse that "solves" mazes!



Credit: Courtesy MIT Museum

Shannon Capacity

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



Shannon Capacity (2)

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

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

Shannon Capacity Takeaways

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

- There is some rate at which we can transmit data **without loss** over a random channel
- Assuming noise fixed, increasing the signal power yields diminishing returns : (
- Assuming signal is fixed, increasing bandwith increases capacity linearly!

Wired/Wireless Perspective (2)

- Wires, and Fiber
  - Engineer link to have requisite SNR and B

  →Can fix data rate

Engineer SNR for data rate

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

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

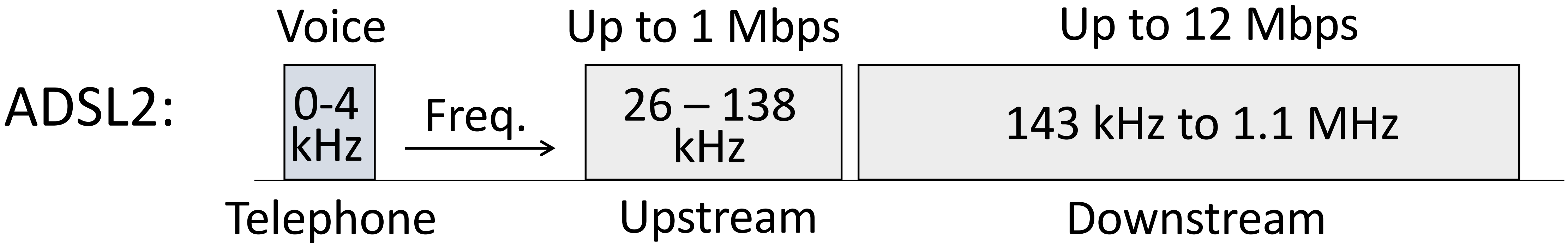
Adapt data rate to SNR

Putting it all together – DSL

- Digital Subscriber Line is widely used for broadband
  - Many variants offer 10s of Mbps
  - Reuses twisted pair telephone line to the home
    - Has ~2 MHz of bandwidth but voice uses only lowest ~4 kHz

DSL (2)

- Separate bands for upstream and downstream (larger)
- Modulation varies both amplitude and phase (QAM)



Phy Layer Innovation Still Happening!

- **Backscatter** “zero power” wireless
- **mm wave** 30GHz+ radio equipment
- Free space optical (**FSO**)
- Cooperative **interference management**
- **Massive MIMO** and beamforming
- Powerline Networking